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THESIS

ESTABLISHMENT OF MODELS AND DATA TRACKING FOR SMALL UAV RELIABILITY

by

Marinos Dermentzoudis

June 2004

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This thesis lays the foundation for a Navy-wide SUAV reliability program.

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ESTABLISHMENT OF MODELS AND DATA TRACKING FOR SMALL UAV RELIABILITY

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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To my one-year old son, Stephanos, who brought joy to my life, I would like to express my gratitude because he made me realize through his everyday achievements that I had to bring this research effort to an end.

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EXECUTIVE SUMMARY

Small UAVs will be used with growing frequency in the near future for military operations. As SUAVs progress from being novelties and toys to becoming full members of the military arsenal, their reliability and availability must begin to approach the levels expected of military systems. They currently miss those levels by a wide margin.

The military has wide experience with the need for reliability improvement in systems, and in fact developed or funded the development of many of the methods discussed in this thesis. These methods have not yet been applied to SUAVs.

The projection of reliability experience from manned piloted aviation to UAVs has led to overestimation of the UAV reliability. Real and urgent operational demands in the Persian Gulf, Kosovo, and Afghanistan have highlighted the very low levels of reliability of UAVs compared to manned air vehicles.

To make a decision, one needs analytical support. Analytical support requires models. Models require good data. Good data requires systems to collect and archive it for easy retrieval. When I began this thesis, I thought that good data on SUAV reliability would be easily available for analysis. I was mistaken. That is why the majority of this thesis has discussed data collection systems and argued that some (but not all) need to be applied to SUAVs. For ease of implementation, we adapted forms from commercial use for FMECA and FRACAS systems for SUAVs, and constructed a very detailed FTA for a typical SUAV. This work is more typical of a reliability engineering thesis, but was necessary to enable any operational analysis.

With the existing crude data on one UAV system, I was able to perform a crude analysis using a reliability growth model based on Duane’s postulate. With good data, the Navy will be able to do much more, as outlined in the thesis.

The DoD Reliability Primer is currently under extensive revision. In the meantime, this thesis can serve as a survey of the reliability methods that are applicable to SUAVs and as template for the implementation of FMECA, FTA, and FRACAS

methods for reliability improvement for SUAVs. As with all surveys, it has depended on the work of the original authors, which I have borrowed liberally and documented extensively. The adaptation of these methods for SUAVs is the original contribution of this thesis.

I observed developmental tests of SUAVs in the course of writing this thesis. I can personally attest that no appropriate methods of data collection, archival, or analysis are currently being used, and that these methods are desperately needed by the SUAV community if it is to progress beyond the novelty stage. I strongly recommend their adoption by NAVAIR.

This thesis makes an initial examination of the real problem of SUAV reliability. Primarily it is a qualitative approach, which illuminates some of the problem's aspects. Collecting real data from SUAV systems will formulate reliability databases. Quantitative reliability analysis may then follow and result in detailed information about reliability improvement, but only if the collection systems outlined here are implemented to provide the data for analysis.

I. INTRODUCTION

A. BACKGROUND (UAVS, SUAVS)

1. UAV – Small UAV

One hundred years after the Wright brothers' first successful airplane flight, aircraft have been proven invaluable in combat. Unfortunately, airplanes have also contributed to the loss of operator life. Many pilots have been killed attempting to accomplish their mission, to become better pilots, and to test new technologies. The development of uninhabited or unmanned aerial vehicles (UAVs) raises the possibility of more efficient, secure, and cost effective military operations.[1]

> The UAV puts eyes out there in places we don't want to risk having a manned vehicle operate. Sometimes it's very dull, but necessary work—flying a pattern for surveillance or reconnaissance. UAVs can go into a dirty environment where there's the threat of exposure to nuclear, chemical or biological warfare. They are also sent into dangerous environments—battle zones: Dull, Dirty, Dangerous. The primary reason for the UAV is the Three D's.[2]

The history of UAVs started in 1883 when Douglas Archibald attached an anemometer to the line of a kite. Archibald managed to obtain differential measures of wind velocity at altitudes up to 1,200 feet. In 1888, Arthur Batat made the first aerial photograph in France, after installing a camera on a kite. The first use of UAVs built for military purposes was during WWII by the Germans. The well-known *flying bombs* V-I and V-II showed that unmanned aircraft could launch against targets and create a destructive effect. In the 1950s, the US developed the *Snark*. It was an unmanned intercontinental range aircraft designed to supplement Strategic Air Command's manned bombers against the Soviet Union. *Snark*, V-I and V-II destroyed themselves as they hit their targets. In fact, these were early versions of today's cruise and ballistic missiles.[3]

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[1] Clade, Lt Col, USAF, "Unmanned Aerial Vehicles: Implications for Military Operations," July 2000, Occasional Paper No. 16 Center for Strategy and Technology, Air War College, Air University, Maxwell Air Force Base.

[2] Riebeling, Sandy, *Redstone Rocket Article*, Volume 51, No.28, "Unmanned Aerial Vehicles," July 17, 2002, Col. Burke John, Unmanned Aerial Vehicle Systems project manager, Internet, February 2004. Available at: http://www.tuav.redstone.army.mil/rsa_article.htm

[3] Carmichael, Bruce W., Col (Sel), and others, "Strikestar 2025," Chapter 2, "Historical Development and Employment," August 1996, Department of Defense, Internet, February 2004. Available at: http://www.au.af.mil/au/2025/volume3/chap13/v3c13-2.htm

In the US, the need to perform reconnaissance (RECCE) missions by UAVs came after the realization that these missions are extremely dangerous and mentally fatiguing for the pilot. The U2 *Dragon Lady* planes used to be the state-of-the-art platforms for RECCE missions. They were slow, with a maximum speed of 0.6 Mach, and cruised at an altitude between 70 and 90,000 feet.[4] In May 1960 the Soviets captured a U2 plane. The pilot, Gary Powers, confessed to the *black bird* program, created by President Eisenhower to monitor the development of Soviet intercontinental ballistic missiles after the launch of Sputnik-I. The U2 flights over Russia were suspended. Spy satellites filled their gap. In 1962, another U2 was hit by a Soviet anti-air missile while on a RECCE mission in Cuba. The pilot was killed in the crash. As a result of these incidents, the first unmanned RECCE "drone", the AQM-34 *Lighting Bug*, was made by the Ryan Aeronautical Company in 1964. The term "drone" became slang among military personnel for early-unmanned vehicles. It was a byword of the DH.82B *Queen Bee*, which was a dummy target for anti-aircraft gunner training.[5]

The *Lightning Bug* was based on the earlier *Fire Bee*. It operated from 1964 until April 1975, performing a total of 3,435 flight hours in RECCE missions that were too dangerous for manned aircraft, especially during the Vietnam War. Some of its most valuable contributions were photographing prisoner camps in Hanoi and Cuba, providing photographic evidence of SA-2 missiles in North Vietnam, providing low-altitude battle assessment after B-52 raids, and acting as a tactical air launched decoy.[6]

In 1962, Lockheed Martin began developing the D-21 supersonic RECCE drone, the *Tagboard*. It was designed to be launched from either the back of a two-seat A-12, which was under development at the same time, or from the wing of a B-52H. The drone could fly at speeds greater than 3.3 Mach, at altitudes above 90,000 feet and had a range

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[4] The Global Aircraft Organization, US Reconnaissance, "U-2 Dragon Lady," Internet, February 2004. Available at: http://www.globalaircraft.org/planes/u-2_dragon_lady.pl

[5] Clark, Richard M., Lt Col, USAF, "Uninhabited Combat Aerial Vehicles, Airpower by the People, For the People, But Not with the People," CADRE Paper No. 8, Air University Press, Maxwell Air Force Base, Alabama, August 2000, Internet, February 2004. Available at: http://www.maxwell.af.mil /au/aupress/CADRE_Papers/PDF_Bin/clark.pdf

[6] Ibid.

of 3,000 miles. The project was canceled in 1971 together with the A-12 development due to numerous failures, high cost of operations, and bad management.[7]

In addition to the RECCE role, Teledyne Ryan experimented with strike versions of the BQM-34 drone, the *Tomcat*. They investigated the possibility of arming the *Lightning Bug* with Maverick electro-optical-seeking missiles or electro-optically-guided bombs *Stubby Hobo*. Favorable results were demonstrated in early 1972 but the armed drones were never used during the Vietnam War. Interest in the UAVs was fading by the end of the Vietnam War.[8]

In the 1973 Yom Kippur War, the Israelis used UAVs effectively as decoys to draw antiaircraft fire away from attacking manned aircraft. In 1982, UAVs were used to obtain the exact location of air defenses and gather electronic intelligence information in Lebanon and Syria. The Israelis also used UAVs to monitor airfield activities, changing strike plans accordingly.[9]

2. The Pioneer RQ-2[10]

The US renewed its interest in UAVs in the late 1980s and early 90s, with the start of the Gulf War. Instead of developing one from scratch, the US acquired and improved the *Scout*, which was used by the Israelis in 1982 against the Syrians. The outcome was the *Pioneer*, which was bought by the Navy to provide cheap unmanned over the horizon targeting (OTHT), RECCE, and battle assessment. The Army and Marines bought the *Pioneer* for similar roles and six *Pioneer* systems were deployed to SW Asia for Desert Storm.

Compared to the *Lightning Bug,* the *Pioneer* is slower, larger, and lighter, but cheaper. The average cost of the platform was only $850K, which was inexpensive relative to the cost of a manned RECCE aircraft.[11] With its better sensor technology, the

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[7] Carmichael.

[8] Ibid.

[9] Ibid.

[10] The material of this section is taken (in some places verbatim) from GlobalSecurity.org, “Pioneer Short Range (SR) UAV,” maintained by John Pike, last modified: November 20, 2002, Internet, May 2004. Available at: http://www.globalssecurity.org/intell/systems/pioneer.htm

[11] National Air and Space Museum, Smithsonian Institution, “Pioneer RQ-2A,” 1998-2000, revised 9/14/01 Connor R. and Lee R. E., Internet, May 2004. Available at: http://www.nasm.si.edu/research /aero/aircraft/pioneer.htm

Pioneer can deliver real-time battlefield assessment in video stream, a huge improvement compared to the film processing required for the *Lightning Bugs.*

By 2000, after 15 years of operations, the *Pioneer* had logged more than 20,000 flight hours. Apart from Desert Storm it was used in Desert Shield, in Bosnia, Haiti, Somalia, and for other peacekeeping missions. The Navy used the *Pioneer* to monitor the Kuwait and Iraqi coastline and to provide spotting services for every 16-inch round fired by its battleships.

Pioneer can give detailed information about a local position to a battalion commander. Joint force commanders wanted to see a bigger, continuous picture of the battlefield, but space-based and manned-airborne RECCE platforms could not satisfy their demand for continuous situational awareness information. In response to that need and in addition to tactical UAVs (TUAVs) like the *Pioneer,* the US began to develop a family of endurance UAVs.

Three different platforms compose the endurance UAV family: *Predator, Global Hawk, and Dark Star.*

a. The Predator RQ-1[12]

Predator is a by-product of the CIA-developed *Gnat 750*, also known as the TierII or medium altitude endurance (MAE) UAV. It is manufactured by General Atomics Aeronautical Systems and costs about $3.2M to $4.5M per platform.[13] Its endurance was designed to be greater than 40 hours with a cruising speed of 110 knots and operational speed of 75 knots using a reciprocating engine with a 25,000-foot ceiling and 450-pound payload. *Predator* can carry electro-optical (EO) and infrared (IR) sensors. It also collects full-rate video imagery and transmits it in near real-time via satellite, other UAVs, manned aircraft or line-of-sight (LOS) data link. More importantly, *Predator* is highly programmable. It can go from autonomous flight to manual control by a remote pilot.

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[12] The material for this section is taken (in some places verbatim) from: Carmichael.

[13] Ciufo, Chris A., “UAVs:New Tools for the Military Toolbox,” [66] *COTS Journal*, June 2003, Internet, May 2004. Available at: http://www.cotsjournalonline.com/2003/66

Except for *Pioneer, Predator* is the most tested and commonly used UAV. It was first deployed to Bosnia in 1994, next in the Afghan War of 2001, and then in the Iraqi war of 2003.

Used as a low altitude UAV, *Predator* can perform almost the same tasks as *Pioneer*: surveillance, RECCE, combat assessment, force protection, and close air support. It can also be equipped with two laser-guided *Hellfire* missiles for direct hits at moving or stationary targets. During operation Enduring Freedom in Afghanistan, *Predators* were considered invaluable to the troops for scouting around the next bend of the road or over the hill for hidden Taliban forces.

Used as a high altitude UAV, the *Predator* can perform surveillance over a wide area for up to 30 to 45 hours. In Operation Iraqi Freedom, *Predators* were deployed near Baghdad to attract hostile fire from the city's anti-air defense systems. Once the locations of these defense systems were revealed, manned airplanes eliminated the targets.

b. The Global Hawk RQ-4[14]

A TierII+ aircraft, *Global Hawk* is a conventional high-altitude endurance (CHAE) UAV by Teledyne Ryan Aeronautical. A higher performance vehicle, it was designed to fulfill a post-Desert Storm requirement for high resolution RECCE of a 40,000 square nautical mile area in 24 hours. It can fly for more than 40 hours and over 3,000 miles away from its launch and recovery base carrying a synthetic aperture radar (SAR) and an EO/IR payload of 2,000 pounds at altitudes above 60,000 feet at a speed of 340 knots. The cost of a Global Hawk is about $57M per unit.[15]

c. The Dark Star RQ-3[16]

The Tier III stealth or low observable high altitude endurance (LOHAE) RQ-3 UAV was the Lockheed-Martin/Boeing *Dark Star*. Its primary purpose was to image well-protected, high-value targets. Capable of operating for more than eight hours at altitudes above 45,000 feet and a distance of 500 miles from its launch base, it was designed to meet a $10M per platform unit cost. Its first flight occurred in March 1996;

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[14] The material for this section is taken (in some places verbatim) from: Carmichael.

[15] Ciufo.

[16] The material for this section is taken (in some places verbatim) from: Carmichael.

however, a second flight in April 1996 crashed due to incorrect aerodynamic modeling of the vehicle flight-control laws. The project was cancelled in 1999.[17]

For the characterization code RQ-3 the "R" is the Department of Defense designation for reconnaissance; "Q" means unmanned aircraft system. The "3" refers to it being the third of a series of purpose-built unmanned reconnaissance aircraft systems.[18]

3. RQ-5 Hunter[19]

Initially engaged to serve as the Army's short range UAV system for division and corps commanders at a cost of $1.2M per unit,[20] the RQ-5 *Hunter* can carry a 200 lb load for more than 11 hours. It uses an electro-optical infrared (EO/IR) sensor, and relays its video images in real-time via a second airborne *Hunter* over a line-of-site (LOS) data link. It deployed to Kosovo in 1999 to support NATO operations. Production was cancelled in 1999 but the remaining low-rate initial production (LRIP) platforms remain in service for training and experimental purposes. *Hunter* is to be replaced by the *Shadow 200* or RQ-7 tactical UAV (TUAV).

4. RQ-7 Shadow 200[21]

The Army selected the RQ-7 *Shadow 200* in December 1999 as the close range UAV for support to ground maneuver commanders. It can be launched by the use of a catapult rail and recovered with the aid of arresting gear, and remain at least four hours on station with a payload of 60 lbs.

5. RQ-8 Fire Scout[22]

The RQ-8 *Fire Scout* is a vertical take-off and landing (VTOL) tactical UAV (VTUAV). It can remain on station for at least three hours at 110 knots with a payload of 200 lb. Its scouting equipment consists of an EO/IR sensor with an integral laser

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[17] GlobalSecurity.org, "RQ-3 Dark Star Tier III Minus," maintained by John Pike, last modified: November 20, 2002, Internet, May 2004. Available at: Available at: http://www.globalsecurity.org /intell/systems/darkstar.htm

[18] Ibid.

[19] The material for this section is taken (in some places verbatim) from: Office of the Secretary of Defense (OSD), "Unmanned Aerial Vehicles Roadmap 2000-2025," April 2001, page 4.

[20] Ciufo.

[21] The material for this section is taken (in some places verbatim) from: OSD 2001, page 5.

[22] The material for this section is taken (in some places verbatim) from: OSD 2001, page 5.

designator rangefinder. Data is relayed to its ground or ship control station in real time over a LOS data link and a UHF backup that could operate from all air capable ships.

6. Residual UAVs Systems[23]

The US military maintains the residual of several UAV programs that are not current programs for development but have recently deployed with operational units and trained operators. BQM-147, *Exdrones*, is an 80-lb delta wing communications jammer and was deployed during the Gulf War. From 1997 to 1998 some of them were rebuilt and named *Dragon Drone* and deployed with Marine Expeditionary units. Air Force Special Operations Command and Army Air Maneuver Battle Lab are also conducting experiments with *Exdrones*.

Some hand-launched, battery powered FQM-151 *Pointers* have been acquired by the Marines and the Army since 1989 and were employed in the Gulf War. *Pointers* performed as test platforms for various miniaturized sensors and have performed demonstrations with the Drug Enforcement Agency, National Guard and Special Operations Forces.

7. Conceptual Research UAV Systems[24]

The various service laboratories have developed a number of UAVs to research special operational needs and concepts. The Marine Corps Warfighting Laboratory is exploring three such concepts. The *Dragon Warrior* or *Cypher II* is intended to fly over the shore on fixed-wing mode flight and then, after removing its wings, converts into a hovering land platform design for urban operations.

Marines have converted a *K-Max* helicopter to a UAV in order to explore the Broad Area Unmanned Responsible Resupply Operations. This concept is for ship-to-shore resupply by UAVs.

Battery-powered *Dragon Eye* is a mini-UAV (2.4 foot wingspan and 4 lbs) developed as the Navy’s version for the Over-The-Hill RECCE Initiative and the Marines’ Interim Small Unit Remote Scouting System requirement. The Dragon Eye can be carried in a backpack, and hence is given the name of Backpack UAV.

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[23] Ibid, page 6.

[24] Ibid, pages 7-8.

Sponsored by the Defense Threat Reduction Agency, the Counterproliferation (CP) Advance Concept Technology Demonstrations (ACTD) envisions deploying several mini-UAVs like the *Finder* from a larger *Predator* UAV to detect chemical agents and relay the results back through *Predator*.

> The CP ACTD is designed to address the growing need to provide a military capability for "precision engagement" of weapons of mass destruction (WMD) related facilities. In order to accomplish this objective, the CP ACTD will develop, integrate, demonstrate and transition to the warfighters, operationally mature technologies that potentially address the unique requirements to enhance the joint counterforce mission to hold WMD-related facilities at risk. The driving CP counterforce requirements include enhancing the ability to predict and to control collateral effects and to provide prompt response and reliable kill.[25]

Besides the *Dragon Eye* and *Finder* mentioned above, the Naval Research Laboratory (NRL) has built and flown several small and micro-UAVs. Definition for these airframes will follow. The Naval Air Warfare Centre Aircraft Division (NAWC/AD) maintains a small UAV test and development team and also operates various types of small UAVs.

8. DARPA UAV Programs[26]

The Defence Advanced Research Projects Agency (DARPA) is sponsoring five major creative UAV programs:

a. The Air Force X-45 UCAV, which was awarded to Boeing in 1999. The mission for the UCAV is Suppression of the Enemy Air Defences (SEAD). The platform will cost one third as much as a Joint Strike Fighter (JSF) to acquire and one quarter as much to operate and support (O&S). The X-45A, with a maximum speed of 1000km/h, was designed to carry two 500 kg bombs using radar absorbing materials, and was first flown in June 2002.

b. The UCAV-Navy X-46/X-47 is a similar program for the equivalent Navy version of a UCAV that can be carrier-based. Apart from SEAD missions, RECCE and strike will be among the platform's capabilities. The X-47A *Pegasus* by Northrop

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[25] Department of Defense, Director of Operational Test & Evaluation, "Missile Defense and Related Programs FY 1997 Annual Report," February 1998, Internet, February 2004. Available at: http://www.fas.org/spp/starwars/program/dote97/97cp.html

[26] The material for this section is taken (in some places verbatim) from: OSD 2001, pages 8-9.

Grumman successfully flew in March 2003 using modified GPS coordinates for navigation.

c. The Advanced Air Vehicle (AAV) program includes two rotorcraft projects:

(1) The *Dragon Fly* Canard Rotor Wing, which will demonstrate vertical take-off-and-land (VTOL) capability and then transition to fixed wing flight for cruise.

(2) The A160 *Hummingbird,* which uses a hingeless rigid rotor to perform high endurance flight of more than 24 hours at a high altitude of more than 30,000 feet.

d. DARPA is exploring various designs of micro-air vehicles (MAVs), which are less than six inches in any dimension. The Lutronix *Kolibri* and the Microcraft *Ducted Fan* rely on an enclosed rotor for vertical flight, while the Lockheed Martin Sanders *Microstar* and the AeroVironment *Black Window* and *E-Wasp* are fixed-wing horizontal fliers.

9. Other Nation's UAVs

In FY00 some 32 nations manufactured more than 150 models of UAVs, and 55 countries operate some 80 types of UAVs, primarily for RECCE missions.

Derivatives of the Israeli designs are the *Crecerelle* used by the French Army, the Canadair CL-289 used by the German and French Armies and the British *Phoenix*. The Russians use the VR-3 *Reys* and the Tu-300 and the Italians the *Mirach 150.*[27]

10. NASA

In the civilian sector, NASA has been the main agency concerned with developing medium and high-altitude long endurance UAVs. The agency has been involved with two main programs "Mission to Planet Earth" and "Earth Science Enterprise" for environmental monitoring of the effects of global climatic change. During the late 80s, NASA started to operate high-altitude manned aircraft, but later decided to develop a UAV for high-altitude operations. NASA constructed the propeller driven

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[27] Petrie, G., *Geo Informatics,* Article "Robotic Aerial Platforms for Remote Sensing," Department of Geography &Topographic Science, University of Glasgow, May 2001, Internet, February 2004. Available at: http://web.geog.gla.ac.uk/~gpetrie/12_17_petrie.pdf

Perseus between 1991 and 1994 and *Theseus*, which was a larger version of *Perseus,* in 1996.

In 1994 NASA started its Environmental Research Aircraft and Sensor Technology (ERAST) program. As a result, NASA has operated the Altus and Altus II since 1998. Their operating ceilings are 45,000 to 65,000 feet using turbocharged engines.

The development of solar powered UAVs is also being supported and funded by NASA. The idea, development, and construction was initiated by the Aerovironment company, which has been involved in the construction of solar-powered aircraft for 20 years. *Solar Challenger*, HALSOL, *Talon*, *Pathfinder*, *Centurion*, and *Helios* with a wingspan of 247 feet, were among the solar-powered UAVs during those efforts.[28]

New technologies like regenerative fuel-cell-powered UAVs are underway. These allow UAVs to fly for weeks or months, reducing the costs of missions so as to deliver a maximum return on investment per flight. NASA will also support the development of such technology.[29]

11. What Is a UAV?[30]

The distinction between cruise missile weapons and UAV weapon systems is sometimes confusing. Their main differences are:

a. UAVs are designed to be recovered at the end of their flight while cruise missiles are not.

b. A warhead is tailored and integrated into a missile's airframe while any munitions carried by UAVs are external loads.

According to 1-02 DoD Dictionary, a UAV is

> A powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a

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[28] Ibid.

[29] *UAV Rolling News*, "New UAV work for Dryden in 2004," June 12, 2003, Internet, February 2004. Available at: http://www.uavworld.com/_disc1/00000068.htm

[30] The material for this section is taken (in some places verbatim) from: Office of the Secretary of Defense (OSD), "Unmanned Aerial Vehicles Roadmap 2002-2027," December 2002, Section 1, "Introduction."

> lethal or non-lethal payload. Ballistic or semi ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles.[31]

12. Military UAV Categories

UAVs can be classified according to different criteria such as mission type, sensor type, performance, and control system. Remote Piloted Vehicles (RPVs) and autonomous UAVs are two distinct groups based on their different control systems. They have many common features but the main difference is that an RPV follows the data-link commands of a remote station for the specific air mission. In other words, it is a “dumb” vehicle, which can carry sensors and relay data. UAVs can be further classified according to their mission as Reconnaissance Surveillance and Target Acquisition (RSTA) UAVs, Combat UAVs (UCAVs), and others. According to the way they are launched, they can be classified as hand-launched, rail-launched, rocket-launched and airfield-launched.

We also classify military UAVs in three main categories, considering their ceiling as their driver characteristic: Tactical UAVs (TUAVs), Medium-Altitude Endurance UAVs (MAE UAVs), and High-Altitude Endurance UAVs (HAE UAVs).[32]

a. Tier I or TUAVs are inexpensive with an average cost of 100K$FY00, with a limited payload of around 50 kg, a LOS permitted range of the ground control station, and endurance of approximately four hours. In general, they are rather small with an average length of two meters and their maximum ceiling is around 5,000 feet. *Pioneer* is a typical example. This category is also referred to as “Battlefield UAVs” and can be divided in three subcategories:

(1) Micro UAVs (MUAVs) are very small UAVs in sizes 6 to 12 inches.[33] The Aerovironment *Wasp* is an example of this category.[34]

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[31] Ibid.

[32] Tozer, Tim, and others, “UAVs and HAPs-Potential Convergence for Military Communications,” University of York, DERA Defford, undated, Internet, February 2004. Available at: http://www.elec.york.ac.uk/comms/papers/tozer00_ieecol.pdf

[33] Pike, John, Intelligence Resource Program, “Unmanned Aerial Vehicles (UAVS),” Internet, March 2004. Available at: http://www.fas.org/irp/program/collect/uav

[34] The material for this part of section is taken (in some places verbatim) from: OSD 2002, *Section2*, “Current UAV programs.”

(2) Mini UAVs have a span up to four feet. They provide the company/platoon/squad level with an organic RSTA capability out to 10 Km. The Aerovironment *Dragon Eye* is an example of this category.[35]

(3) Small UAVs (SUAVs) have a size greater than four feet in length. "SUAV is a low-cost and user-friendly UAV system." It is a highly mobile air vehicle system that among other potentials allows the small warfighting unit to set the foundation to exploit battlefield information superiority.[36]

b. Tier II or MAE UAVs are larger than TUAVs, more expensive, with an average cost of 1M$FY00, and have enhanced performance. Their payload can reach 300 kg, their endurance is 12 or more hours, and their ceiling is up to 20,000 feet. *Predator* is a typical example of a MAE UAV.

c. Tier II Plus or HAE UAVs can be large craft with an endurance of more than 24 hours, payload capacities of more than 800 Kg and a ceiling of more than 30,000 feet. Their average cost is about 10M$FY00. *Global Hawk* is a typical example of HAE UAV.

d. Tier III Minus or LOHAE UAVs can be large crafts with an endurance of more than 12 hours, payload capacities of more than 300 Kg, and a ceiling of more than 65,000 feet. *Dark Star* was a typical example of LOHAE UAV.

13. Battlefield UAVs

Here are two descriptions of the use of UAVs in training and combat.

a. Story 1. Training at Fort Bragg

> "FDC this is FO adjust fire, over". "FO this is FDC adjust fire, out". "FDC grid 304765, over". "FO grid 304765, out". "FDC two tanks in the open, over". "FO that's two tanks in the open, out". Then about 30 seconds later, "FO shot, over". "FDC shot, out". "FO splash, over". "FDC splash, out". Fort Bragg, N.C. (April 5, 2001).
>
> Communications like these can normally be heard during a live-fire training exercise between the forward observers (FO) and the Marines at the fire direction control centre (FDC), but during exercise Rolling

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[35] Ibid.

[36] NAVAIR, "Small Unmanned Aerial Vehicles," undated, Internet, February 2004. Available at: http://uav.navair.navy.mil/smuav/smuav_home.htm

Thunder, the 3rd Battalion, 14th Marines used a different type of forward observer.

Instead of a few Marines dug in a forward position, a UAV controlled by the Marines from the Marine fixed-Wing Unmanned Vehicle Squadron 2 (VMMU-2), Cherry Point, N.C., gave the calls for fire.

The UAV is a remote-controlled, single-propeller plane with a wing span of 17 feet and an overall length of 14 feet. Inside the body of the plane is a camera that allows the pilots to see and to identify targets, according to Cpl. Tim Humbert, team non-commissioned officer, VMU-2.

“This was an excellent training opportunity for us,” said Capt. Konstantine Zoganas, battalion fire direction officer, 3rd Bn., 14th Marines, Philadelphia, Pa. “There aren’t many units who get the opportunity to train with this equipment.”

For this mission, the UAV, which was flying at around 6,000 to 8,000 feet, was used to identify targets. They then looked at that data and turned it into a fire mission, which was sent to the Marines on the gun line. Once the Marines on the gun line blasted their round toward the target, the UAV was used to adjust fire. “After using the UAV, I think it is equal to, if not better than, a forward observer,” said Zoganas. “A forward observer has a limited view depending on where he is at, but a UAV, being in the air, has the ability to cover a lot more area,” said Zoganas. “I think the UAV’s capabilities are underestimated, it is a great weapon to have on the modern battlefield.”[37]

2. Story 2. Desert Shield/Storm Anecdote

Surrenders of Iraqi troops to an unmanned aerial vehicle actually happened. All of the UAV units at various times had individuals or groups attempt to signal the *Pioneer*, possibly to indicate a willingness to surrender. However, the most famous incident occurred when USS Missouri (BB 63), using her *Pioneer* to spot 16-inch gunfire, devastated the defences of Faylaka Island off the coast of Kuwait City. Shortly thereafter, while still over the horizon and invincible to the defenders, the USS Wisconsin (BB 64) sent her *Pioneer* over the island at low altitude. When the UAV came over the island, the defenders heard the obnoxious sound of the two-stroke engine since the air vehicle was intentionally flown low to let the Iraqis know that they were being targeted. Recognizing that with the “vulture” overhead, there would soon be more of those 2,000-pound naval gunfire rounds landing on their positions with the same accuracy, the Iraqis made the right choice and, using

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[37] Zachany, Bathon A., Marine Forces Reserve, “Unmanned Aerial Vehicles Help 3/14 Call For and Adjust Fire,” Story ID Number: 2001411104010, April 5, 2001, Internet, February 2004. Available at: http://www.13meu.usmc.mil/marinelink/mcn2000.nsf/Open document

> handkerchiefs, undershirts, and bed sheets, they signalled their desire to surrender. Imagine the consternation of the *Pioneer* aircrew who called the commanding officer of Wisconsin and asked plaintively, “Sir, they want to surrender, what should I do with them?”[38]

14. Battlefield Missions

Reconnaissance is a “mission undertaken to obtain, by visual or other detection methods, information about the activities and resources of an enemy; or to secure data concerning the meteorological, hydrographical geographical characteristics of a particular area.” This task is about gathering general information about an enemy or an area. Surveillance is the “specific and systematic observation of a particular area or target for a short or extended period of time.”[39]

UAVs have been used for the above missions since their inception. They can also be used for target acquisition, target designation and battle damage assessment (BDA). Due to their small size, they can operate more discreetly than their manned counterparts, allowing target acquisition to occur with less chance of counter-detection. “The surveillance UAV can be used to designate the target for a precision air and/or artillery or missile strike while providing near real-time battle damage assessment to the force or mission commander.”[40] In that way, useless repeat attacks on a target could be avoided as well as wastage of munitions.

Battlefield UAVs are appropriate UAVs for all of the above missions. In the beginning of the 1950s, UAVs like the Northrop *Falconer* had been developed for battlefield reconnaissance with little or no combat service. Later the Israelis were the early developers of the operational use of battlefield UAVs in the early 1980s in southern Lebanon operations. Their successes with battlefield UAVs drew international attention.[41]

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[38] The Warfighter’s Encyclopedia, Aircraft, UAVs, “RQ-2 Pioneer,” August 14, 2003, Internet, February 2004. Available at: http://www.wrc.chinalake.navy.mil/warfighter_enc/aircraft/UAVs/pioneer.htm

[39] Ashworth, Peter, LCDR, Royal Australian Navy, Sea Power Centre, Working Paper No6, “UAVs and the Future Navy”, May 2001, Internet, February 2004. Available at: http://www.navy.gov.au/spc/workingpapers/Working%20Paper%206.pdf

[40] The material for the above part of section is taken (in some places verbatim) from: Ashworth.

[41] Goebel, Greg,/ In the Public Domain, “[6.0] US Battlefield UAVs (1),” Jan 1, 2003, Internet, February 2004. Available at: http://www.vectorsite.net/twuav6.html

We can distinguish two broad categories of battlefield UAVs; the "combat surveillance" UAV and the "tactical reconnaissance" UAV.

a. Combat Surveillance UAVs[42]

The function of combat surveillance UAVs is to observe everything on a battlefield in real-time, flying over the battle area, and relaying intelligence to a ground-control station. In general, they are powered by a small internal combustion two-stroke piston engine, known as a "chain saw" because of its characteristic noise. An autopilot system with a radio control (RC) back-up for manual operations directs the platform from pre-takeoff programmed sets of waypoints. In most cases, the program is set up by displaying a map on a workstation, entering the coordinates, and downloading the program into the UAV. Navigation is always verified by a GPS and often by an INS system as well.

Combat surveillance UAVs normally use the autopilot to get on station (above the operating area) and then operate in manual mode by RC to find or detect potential targets. As a result, only LOS ranges are permitted, due to the limitations of the RC transmitter signals.

Sensors are generally housed in a turret underneath the platform and/or are integrated into the platform's fuselage. They usually feature day-night imagers and in many case a laser designator, SIGINT packages, or Synthetic Aperture Radar (SAR).

Larger UAVs have fixed landing gear that are used for takeoff and landing purposes on small airstrips. Larger UAV can also be launched by special rail launcher boosters and recovered by parachute, parasail or by flying into a net. Smaller UAVs may be launched by a catapult and recovered in the same way or by landing in plain terrain without any use of landing gear.

b. Tactical Reconnaissance UAVs[43]

Tactical Reconnaissance (TR) UAVs are usually larger and in some cases jet powered with extended range and speed. Like the combat surveillance UAVs, they are equipped with an autopilot with RC backup. Their primary mission is to fly over

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[42] The material for this section is taken (in some places verbatim) from: Goebel.

[43] Ibid.

predefined targets out of line of sight, and take pictures or relay near real-time data to the ground-control station via satellite links.

A UAV of this type can usually carry day-night cameras and/or Synthetic Aperture Radar (SAR). The necessary communication equipment is usually located on the upper part of the platform's fuselage. A TR UAV can also be launched from runways or small airstrips, an aircraft, and/or by special rail launcher boosters, and be recovered by parachute.

The exact distinction between the two types of battlefield UAVs and other types of UAVs is not clear. Some types are capable of both missions. A small combat surveillance UAV may be the size of "a large hobbyist RC model plane." It can be "used to support military forces at the brigade or battalion level and sometimes they are called 'mini UAVs.' Their low cost makes them suitable for 'expendable' missions."

B. PROBLEM DEFINITION

1. UAVs Mishaps

According to the Office of Secretary of Defense "UAV Roadmap" the mishap rate for UAVs is difficult to define:

> Class A mishap rate (MR) is the number of significant vehicle damages or total losses occurring per 100,000 hours of fleet flight time. As no single U.S. UAV fleet has accumulated this amount of flying time, each fleet's MR represents its extrapolated losses to the 100,000-hour mark. It is expressed as mishaps per 100,000 hours. It is important to note that this extrapolation does not reflect improvements that should result from operational learning or improvement in component technology.[44]

> A Pentagon report said that crashes and component failures are increasing the cost of UAVs and restrict their availability for military operations.[45]

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[44] OSD 2002, Appendix J, page 186.

[45] Peck, Michael, *National Defense Magazine, May 2003*, Feature Article, "Pentagon Unhappy About Drone Aircraft Reliability, Rising Mishap Rates of Unmanned Vehicles Attributed to Rushed Deployments," Internet, February 2004. Available at: http://www.nationaldefensemagazine.org/article.cfm?Id=1105

The reliability issue has sparked controversy and concern that UAVs are becoming too expensive. There is a wide-spread notion that UAVs are simply expendables and cheap vehicles, something like diapers that are used once and discarded. The truth is that these are costly components of expensive systems.

To get a view of the problem, we see that the 2002 crash rate for *Predator* was 32.8 crashes per 100,000 flight hours, and for 2003 it was 49.6 until May. The accident rate for the *Global Hawk* was 167.7 per 100,000 flight hours on May 2003.[46]

Nevertheless, commanders can take greater risks with UAVs without worrying about loss of life. These risks would not be taken with manned aircrafts. For example, the recently updated MR for the F-16 was 3.5 per 100,000 flight hours. According to DoD data, the MR for the RQ-2A *Pioneer* was 363 while the MR for the RQ-2A dropped to 139. For the RQ-5 *Hunter* it was 255 for pre-1996 platforms, and has dropped to 16 since then. For the *Predator* RQ-1A, it was 43 and for the RQ-1B it was 31.[47]

2. What is the Problem?

Currently a network experiment series named Surveillance and Tactical Acquisition Network (STAN) is being conducted by the Naval Postgraduate School (NPS) at Camp Roberts, with SUAVs as the sensor platforms and the primary source of information. SUAV programs are currently of great interest to the Fleet, Special Forces, and other interested parties and are receiving large amounts of funding. There is a great deal of concern about the reliability of SUAVs because a lot of problems have emerged in testing. Reliability must be improved.

This thesis documents these problems. At the CIRPAS site at McMillan Field in Camp Roberts on September 11 and 12, 2003, I observed flight, communication, search and detection, and target acquisition tests, using two different types of SUAV platforms, XPV-1B *TERN* and *Silverfox,* an experimental program funded by the office of Naval Research. Incidents regarding reliability that occurred during that time include:

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[46] Peck, Michael, *National Defense Magazine, May 2003,* Feature Article, “Pentagon Unhappy About Drone Aircraft Reliability, Rising Mishap Rates of Unmanned Vehicles Attributed to Rushed Deployments,” page 1, Internet, February 2004. Available at: http://www.nationaldefensemagazine.org /article.cfm?Id=1105

[47] Peck.

a. During the pre-takeoff checks in the runway end, an engine air-intake filter failed (due to broken support lock wire hole). The problem was obviously due to engine vibrations. There was no spare part filter or any other means to repair the failure, so it was replaced with another *TERN* platform's air filter.

Result: the mission was delayed for thirty minutes.

b. During the start engine procedure, a starting device failed. The failure was due to a loose bolt and the starting device could not start the engine. After ten minutes delay, the bolt was tightened.

Result: the procedure was delayed for ten minutes.

c. After two and a half hours of flight operation on a *TERN* platform and while in flight, the engine stalled at 500 feet. The SUAV ran out of fuel.

Result: loss of one *TERN* platform.

d. At the pre-takeoff checks on a *Silverfox* platform, recalibration of an engine's rpm was necessary (probably because it was during the initial flight after replacing the old engines with new).

Result: five-minute delay.

e. During the operations on *Silverfox* platforms, many bad sensor signals were received (especially using the CCD camera) probably due to ground-control station antennas or due to LOS constraints.

Result: Missions lost their search and detection capability

f. After *Silverfox's* landings (calculated crashes) in the field (not on a runway), extensive cleaning of the interior of the platform due to weeds, soil and debris that entered the vehicle from the front engine opening was needed.

Result: At least twenty minutes cleaning was needed after such landings.

The next step for STAN experiment was at the CIRPAS site at McMillan Field in Camp Roberts from May 2 to May 6, 2004. I observed flight, communication, search and detection, and networking tests, using the XPV-1B *TERN on May 2 and 3*. Incidents regarding reliability that occurred during that time include:

a. During the assembly checks in the hangar on May 2, major software problem was detected. Repairing was not possible by the team members.

Result: the platform was unable to operate at all.

b. During the test flight operation of the next platform the same day, the engine stalled at 1000 feet and led to a platform crash.

Result: loss of platform.

c. On May 3, after one hour of flight operation, the third platform and while in flight, an autopilot software malfunction was occurred that led to a platform auto hard landing in the ground.[48]

Result: loss of one more *TERN* platform.

d. During landing of the next *TERN* platform and after two hours in flight operation the front tire delaminated on May 5.[49] Probably due to operator error, the damage was impossible to be repaired by the team members.

Result: loss of platform.

e. On May 6, after one hour of operation flight and while in flight, a right-wing servo failure occurred that result in loss of platform control and then to a platform crash.[50]

Result: loss of platform.

3. What is the Importance of the Problem?

It is most notable that SUAVs are not technologically sophisticated enough to warn the operator that the vehicle is under attack and/or under critical failure (such as out of fuel), cannot operate under unfavorable weather conditions, and have a low level of reliability, which degrades their role in military operations. Even though SUAVs cost very little compared to other systems, such as observers, helicopters, planes and satellites, it is essential that small UAV missions be carried out with an acceptable level of

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[48] Gottfried, Russell, LCDR (USN), *Unmanned Vehicle Integration TACMEMO, 5-6 May Recap*, e-mail May 7, 2004.

[49] Ibid.

[50] Ibid.

reliability, operability, and reusability. In that way, they can become dependable systems and be used in the battlefield with other systems.

4. How Will the Development Teams Solve the Problem without the Thesis?

Trial and error and/or test, analyze and fix (TAAF) are the methods being used to overcome failures for the *Silverfox* system. Being in the experimental phase, it is the easiest but most time consuming way.

For the other system (*TERN*) that has been operational for almost two years, an extended trial period is presently being conducted. From it, conclusions can be made for future system improvements and operational usages. Other experimental systems can also contribute to quantitative assessments of readiness and availability.

5. How Will This Thesis Help?

This thesis provides a tool to consider reliability issues by developing a system for tracking data that could be improve reliability for SUAV systems.

6. How Will We Know That We Have Succeeded

Verification and validation of the proposed solutions and methods by NAVAIR and the other interested parties will indicate the accuracy and the effectiveness of the framework suggested by this thesis.

7. Improving Reliability

UAV reliability is the main issue preventing the FAA from relaxing its restrictions on UAVs flying in civilian airspace and for foreign governments to allow overflight and landing flights. Improved reliability or simply knowing actual mishap rates and causes will enable risk mitigation and eventual flight clearance.

Efforts toward improving UAV reliability are required, but how can this best be accomplished? The answer is by spending money, but we can be more specific. More redundancy of flight control-systems may increase reliability, but there is another trade off. The absence of components needed for manned aircraft makes UAVs cheaper, but this also degrades their reliability. If reliability is sacrificed, then high attrition will increase the number of UAVs needed and so the cost will rise again.

By focusing on flight control systems, propulsion, and operator training, which account for approximately 80% of UAVs mishaps, we can increase reliability.[51] Redundancy in on-board systems is not easily added, especially to small UAVs. Weight and volume restrictions are very tight and that can lead to expensive solutions. But then if we make UAVs too expensive, we cannot afford to lose them.

We can categorize UAVs by their volume, by their usage, by their endurance or by their capabilities and type of operations, but we can also view each UAV system as a unique case. We can analyze the system according to its functional components and do a Failure Mode and Effect Analysis (FMEA). That is the first step for further implementation of a reliability tracking and improvement method such as FRACAS, Failure Mode Effect and Criticality Analysis (FMECA) or even an implementation of MSG-3, if it is more suitable. I discuss these methods, in details, later.

Reliability by itself is a measure of effectiveness (MOE). In order to keep track of reliability I develop some measures of performance (MOP), and by using them we can determine the results of our reliability corrective actions, if any. We can also keep track of our system's ability to be maintained, and if we consider the operational requirements and logistic data, then we can evaluate its availability as well. Definitions and a discussion of reliability are included in Appendix D.

8. Area of Research

This study provides a basis for conducting reliability tracking for SUAVs to improve techniques and methodologies that increase SUAVs readiness. To achieve this, existing methodologies of controlling reliability, FMEA and reliability centered maintenance (RCM) with maintenance steering group-3 (MSG-3) are analyzed and compared. Finally, a criticality analysis provides a method for SUAV operators to account for and to mitigate risk during operations.

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[51] Peck.

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II. RELATED RESEARCH

A. EXISTING METHODS

The following section, presents and analyzes existing general methods of failure tracking and analysis, as well as the existing reliability centered maintenance method that has been used by the civil aviation industry. A comparison between them, focusing on small UAV (SUAV) application, is also presented.

1. General: FMEA, FMECA and FTA

a. Introduction to Failure Mode and Effect Analysis (FMEA)

Well-managed companies are interested in preventing or at least minimizing risk in their operations, through risk management analysis. “The risk analysis has a fundamental purpose of answering the following two questions:

- What can go wrong?
- If something does go wrong, what is the probability of it happening and what are the consequences?”[52]

To answer these questions, previously forensic techniques were used. Today the focus has changed. “The focus is on prevention.”[53]

FMEA is one of the first systematic techniques for failure analysis. “An FMEA is often the first step of a system’s reliability study.”[54] It incorporates reviewing components, assemblies and subsystems to identify failure modes, causes and effects of such failures. FMEA is a systematic method of identifying and preventing product and process failures before they occur. It is focused on preventing defects, enhancing safety, and increasing customer satisfaction.

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[52] Stamatis, D. H., *Failure Mode and Effect Analysis: FMEA from Theory to Execution*, American Society for Quality (ASQ), 1995, page xx. The above part of section is a summary and paraphrase (in some places verbatim) of “Introduction.”

[53] Ibid, page xxi.

[54] Hoyland, A., and Rausand, M., *System Reliability Theory: Models and Statistics Methods*, New York: John Wiley and Sons, 1994, page 73.

The purpose of FMEA is preventing process and product problems before they occur.[55] Used in the design and manufacturing process, FMEAs reduce cost and efforts by identifying product and process improvements early in the development phase when it is easier, faster and less costly to make changes. Formal FMEAs were first conducted in the aerospace industry in the mid 60's, when looking at safety issues. Industry in general (automotive particularly) adapted the FMEA for use as a quality improvement tool.

"FMEA is a specific methodology to evaluate a system, design, process or service, for possible ways in which failures (problems, errors, risks, and concerns) can occur."[56] For each of the failures identified, an estimate is made for its occurrence, severity, and detection. Then an evaluation is made for the necessary action to be taken, planned, or ignored. The effort focuses on minimizing the probability of failure or the effect of failure. This approach can be technical or nontechnical. Technical is the quantitative way, in other words, the way in which we determine, express, and measure the quantity of something. Nontechnical is the qualitative way, which is relative to, or involves the quality of something. For both ways, the focus is on the risk one is willing to take. In that way, FMEA becomes a systematic technique using engineering knowledge, reliability, and organizational development techniques.[57]

b. Discussion

FMEA, as a qualitative analysis, is better carried out during the design stages of the system. "The purpose is to identify design areas where improvements are needed to meet reliability requirements."[58] It provides an important basis for design reviews and inspections. It can be carried out using the bottom-up or the top-down approach. With the bottom-up approach or hardware approach, FMEA starts at the component level and expands upward. When the expansion is from the system level downwards, then the top-down or functional approach is being used. Most FMEA are

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[55] McDermott, E. R., Mikulak, J. R, and Beauregard, R. M., *The Basics of FMEA*, Productivity Inc., 1996, page 4.

[56] Stamatis, page xxi.

[57] Stamatis, page xxii. The above part of section is a summary and paraphrase (in some places verbatim) of "Introduction."

[58] Hoyland, page 74.

carried out according to the bottom-up approach. However, for some systems adopting the top-down approach can save time and effort.[59]

In order to have a formal FMEA process, accurate data is key. Given accurate data, one can make the proper assumptions and calculations, producing an accurate FMEA process. Accurate data presume a comprehensive quality system implementation. Without accurate data "on a product or process, the FMEA becomes a guessing game, based on opinions rather than actual facts". Implementing a quality system assures standard procedures and proper documentation and thus yields reliable data.[60]

"The basic questions to be answered by FMEA are

(1) How can each part of the system possibly fail?

(2) What mechanisms might produce these modes of failure?

(3) What could the effects be if the failures did occur?

(4) Is the failure in the safe or unsafe direction?

(5) How is the failure detected?

(6) What inherent provisions are provided in the design to compensate for the failures?"[61]

There are at least four prerequisites we must understand and must consider while conducting FMEA:

(1) All problems are not the same and not equally important.

(2) Know the customer (end user).

(3) Identify the function's purpose and objective.

(4) When doing an FMEA, it must be prevention oriented.[62]

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[59] Hoyland, page 76. The above part of section is a summary of "Bottom-up versus Top-down Approach."

[60] McDermott, page 4. The above part of section is a summary of "Part of a Comprehensive Quality System."

[61] Hoyland, page 76.

[62] Stamatis, page xxii-xxiii.

Definitions of terms related to failure and failure modes are presented in Appendix C.

c. FMEA: General Overview

For a system, a FMEA "is an engineering technique used to define, identify and eliminate known and/or potential failures" before they reach the end user.[63] A FMEA may take two courses of action. First, using historical data there may be an analysis of data for similar products or systems. Second, inferential statistics, mathematical modeling, simulations, and reliability analysis may be used concurrently to identify and define the failures. A FMEA, if conducted properly and appropriately, will provide the practitioner with useful information that can reduce the risk load in the system. It is one of the most important early preventive actions in a system, which can prevent failures from occurring and reaching the user. "FMEA is a systematic way of examining all the possible ways in which a failure may occur. For each failure, an estimate is made of its effect on the system, of its seriousness of its occurrence, and its detection." As a result, corrective actions required to prevent failures from reaching the end user will be identified, thereby assuring the highest durability, quality and reliability possible in the system. [64]

d. When is the FMEA Started?[65]

As a methodology used to maximize the end user's satisfaction by eliminating and/or reducing known or potential problems, FMEA must begin as early as possible, even if all the facts and information are not yet known. After FMEA begins, it becomes a living document and is never really complete. It uses information to improve the system and it is continually updated as necessary. Therefore, an FMEA should be available for the entire system life.

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[63] Stamatis, page 25.

[64] Stamatis, page 26. The above part of section is a summary and paraphrase (in some places verbatim) of "FMEA: A General Overview."

[65] The material from this section is taken (in some places verbatim) from: Stamatis, page 29, "When is the FMEA Started?"

e. Explanation of the FMEA[66]

Identification and prevention of known and potential problems from reaching the end user is the essence of an FMEA system. One of the assumptions that must be made is that problems have different priorities. Finding or setting priorities is important because that is the main issue, which drives the methodology. Three components help define the priority of failures: occurrence, severity and detection.

> Occurrence is the frequency of the failure. Severity is the seriousness (effects) of the failure. Detection is the ability to detect the failure before it reaches the customer. To define the value of these components, the usual way is to use numerical scales called risk-criteria guidelines. These guidelines can be qualitative and/or quantitative.[67]

If the guideline is qualitative, then it must follow the theoretical expected behavior of the potential component. For occurrence the expected behavior follows a normal distribution because frequencies tend to be like that over time. For severity, the expected behavior is lognormal. This is due to the fact that failures, which do occur, should cause annoyance, and they are not usually critical or catastrophic. So the guideline should follow a right-skewed distribution. For detection, the expected behavior is that of a discrete distribution. This is expected due to the fact that there is more concern if the failure is found by the end user than finding it during the manufacturing phase in the production facilities. So the guideline should follow a distribution with a gap between values.

If the guideline is quantitative, it must be specific. It is not necessary for the guideline to follow a theoretical distribution.

Ranking for the criteria usually has a value based on 1 to 10 scales. It provides ease of interpretation, accuracy, and some precision in the quantification of the ranking. Ranking using scales from 1 to 5, if used, offers convenience but does not give an accurate “quantification because it reflects a uniform distribution.”[68]

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[66] The material from this section is taken (in some places verbatim) from: Stamatis, page 33, ”Interpretation of FMEA.”

[67] Stamatis, page 33.

[68] Stamatis, page 35.

The failure's priority is represented through the risk priority number (RPN), which is the product of occurrence times severity times detection. The value of RPN is used only to rank order the concerns of the system. If there are more than two failures with the same RPN, we first address the failure with the higher severity and then with the higher detection. Severity comes first because it has to do with the effects of the failure. Detection is next because user dependency is more important than the failure frequencies.

The objective for product/design FMEAs is to reveal product problems that will result in safety hazards, malfunctions or shortened product life. FMEAs can be conducted at each phase in the design process (initial design, prototype, final design) or at the production process while it is occurring. "How can the product fail?" is the basic question asked in design FMEAs.[69]

f. The Eight Steps Method for Implementing FMEA[70]

The eight steps of the method are:

(1) Select the team: The team should be "cross-functional and multidisciplinary and the team members must be willing to contribute." After the team has been identified, it prioritizes the opportunities for improvement.

(2) Do the functional block diagram: The first step for every attempt to solve any problem is to become familiar with the subject to ensure that everyone on the FMEA team has the same understanding of the process and the production phases. A blueprint, an engineering drawing, or a flowchart review is necessary. If it is not available, the team needs to create one. Team members should see the product or a prototype and walk through the production process exactly. A block diagram of the system provides an overview and a working model of the relationships and interactions of the system's subsystems and components.

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[69] McDermott, page 25. The above part of section is a summary and paraphrase (in some places verbatim) of "Product/Design."

[70] The material from this section is taken (in some places verbatim) from Stamatis, pages 42-44, "The Process of Conducting an FMEA," and McDermott, pages 28-42, "The FMEA Worksheet."

(3) Collect data: The team begins to collect and categorize data. Then they should start filling the FMEA forms. The failures identified are the failure modes of the FMEA.

(4) Brainstorm and prioritize potential failure modes: Important issues of the problem are recognized by the team. The team can now begin thinking about potential failure modes that could affect the product function, quality or manufacturing. Brainstorm sessions place all ideas out on the table. The objective is to create dozens of ideas. The ideas should be organized by grouping them into similar categories. Grouping can be done by the type of failure, (e.g. mechanical, electrical, communication etc) or the seriousness of the failure. At that step, the FMEA team reviews the failure modes and identifies the potential effects of any failure. This step is like an “if-then statement” process. If that failure occurs, then what are the consequences?

(5) Analysis: Assign a severity, occurrence and detection rating for each effect and failure mode. The sequence from data to information to knowledge to decision is followed. The analysis could be qualitative or quantitative and anything may be used (cause and effect analysis, mathematical modeling, simulation, reliability analysis etc). At this step, severity, occurrence, and detection ratings must be estimated. Those ratings are based on a 10-point scale, with number 1 being the lowest and 10 the highest in importance. Establishing clear and concise descriptions for the points on each of the scales is important so that all team members have the same understanding of the ratings.

(a) The severity rating estimates how serious the effect would be if a given failure did occur. Each effect should be given its own severity rating, even if there are several effects for a single failure mode.

(b) The most accurate way to determine the occurrence rating is by using actual failure data from the product. When this is not possible, failure mode occurrence must be estimated. Knowing the potential cause of failure can produce a better estimate. Once the potential causes have been identified for all of the failure modes, an occurrence rating can be assigned, even without failure data.

(c) By assigning the detection rating, we estimate how likely we are to detect a failure or the effect of a failure. We start by identifying controls that may detect a failure or the effect of a failure. In case there are no controls, the likelihood of detection will be low and the item would receive a high rating (9-10).

(6) Results: Results are derived from the analysis. RPNs must be calculated and all FMEA forms are completed. The RPN is the product of severity, times occurrence, times detection for all of the items. The total RPN is the sum of all RPNs. This number is used as a metric to compare the revised total RPN against the original RPN, once the recommended actions have been introduced. From the highest RPN to the smallest, we can now prioritize the failure modes. A Pareto Chart or other diagram helps to visualize the differences between the various ratings and enables decision regarding on which items to work. Usually it is useful to set a threshold RPN such that everything above that point is addressed.

(7) Confirm, evaluate and measure: After the results have been recorded, confirmation, evaluation, and measurements of the success or failure are done. Using an organized process, we can identify and implement actions to eliminate or reduce the problem of high-risk failure modes. It is very common to manage a reduction on a high-risk failure mode. After doing that, we refer back to the severity occurrence and detection ratings. Often the easiest approach to make a process or product improvement is to increase detectability of the failure, thus lowering the detection rating. This is not the best approach because increasing failure-detectability only makes it easier to detect failures once they occur. Reducing severity is important, especially in situations leading to injuries. The best way for improvement is by reducing the likelihood of the occurrence of the failure. And if it is highly unlikely that a failure will occur, there is less need for detection measures. Evaluation answers the question: “Is the situation better, worse or the same as before?”

(8) Do it all over again: The team must pursue improvement until the failures are completely eliminated, regardless of the answer from Step 7, because FMEA is a process of continual improvement. The long-term goal is to eliminate or mitigate every failure completely. The short-term goal is to minimize the effects of the

most serious failures, if not eliminate them. Once action has been taken to improve the product, new ratings should be determined and a resulting RPN calculated. For the failure modes that have been corrected, there should be a reduction in the RPN. Resulting RPNs and total RPNs can be organized in diagrams and compared with the original RPNs. There is no target RPN for FMEAs. It is up to the organization to decide on how far the team should pursue improvements. Failures happen sooner or later. The question is how much relative risk the team is willing to take. The answer, again, depends on management and the seriousness of failure.

g. FMEA Team

"A team is a group of individuals who are committed to achieving common organizational objectives." They meet regularly to identify, to solve problems, and to improve processes. They work and interact openly and effectively together and produce the desired results for the organization. "Synergy," which means that "the sum of the total is greater than the sum of the individuals," is the characteristic of a team. [71]

"One person typically is responsible for coordinating the FMEA process but all FMEAs are team-based." Team members "bring a variety of perspectives and experiences to the project." They are "formed when needed and disbanded" after the FMEA is completed. [72] The first priority for the team is to define the scope of FMEA. A clear definition of the product or process to be studied should be written and understood by all team members.

h. Limitations Applying FMEA[73]

(1) "FMEA analysis may be very effective when applied to a system in which system failures most probably are the results of single-component failures." In that way, "each failure is considered individually as an independent occurrence." So, an FMEA is not the best approach for analyzing systems with a fair degree of redundancy (dependency). For such systems, a Fault Tree Analysis (FTA) is a better alternative.

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[71] Stamatis, pages 85-88. The above part of section is a summary and paraphrase (in some places verbatim) of "What Is a Team?" and "Why Use a Team?"

[72] McDermott, page 15. The above part of section is a summary and paraphrase (in some places verbatim) of "The FMEA Team."

[73] Hoyland, page 80, the above part of section is a summary of "Applications."

(2) FMEA gives inadequate attention to human errors because the focus is on hardware failures.

(3) The amount of insignificant work that must be done is also a disadvantage. Component failures, including those with insignificant consequences, are examined and documented. For large complex systems with a high degree of redundancy, the amount of trivial and unnecessary work is huge.

i. FMEA Types

Generally there are four types of FMEA: System, design, process and service. In the SUAV case, we deal with the system and design FMEA. Failure modes are caused by system deficiencies in the functions of the system. Deficiencies include interactions among subsystems and elements of the system.

j. System and Design FMEA[74]

We focus on system/design FMEA once we begin to analyze the reliability for SUAVs. A system FMEA is usually accomplished in steps, which "include conceptual design, detailed design and development, and testing and evaluation." Establishing a system FMEA, uses a system engineering process as well as a product development methodology, or research and development, or a combination of all these. During the early stages of development, the main focus is to

- Turn an operational need into a demand for system performance parameters and system configuration through "the use of an interactive process."
- "Integrate related technical parameters and assure compatibility of physical, functional, and program interfaces" optimizing the total system.
- "Integrate reliability, maintainability, engineering support, human factors, safety, liability, security, and other related specialties into the total engineering effort."

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[74] The material from this section is taken (in some places verbatim) from: Stamatis, pages 101-129, "System FMEA," "Design FMEA."

The first step in conducting the system FMEA is a feasibility study to find solutions to a problem. The outcome of the system FMEA is an initial design with a baseline configuration and operational specifications.

Design FMEA is a method of “identifying potential or known failure modes and providing corrective actions” before the production line starts. Initial sample runs or prototype runs and trial runs are excluded. The milestone for the first production run is important because after that point any modification and/or change in the design it would be a major problem due to the amount of effort, time and cost required to do the changes in that stage. The design FMEA is a “dynamic process” involving the implementation of numerous “technologies and methods to produce an effective design.” This result will be an input for the process, and/or the service FMEA.

The first step in conducting the design FMEA should be a “feasibility study and/or a risk-benefit analysis.” The objective of this early stage is to optimize the system, which means to maximize the system quality, reliability and maintainability, and minimize cost. The outcome of the design FMEA is a preliminary design, which can be used as baseline configuration and functional specifications.

k. Analysis of Design FMEA[75]

There are two main methods of design: design-to-cost and design-to-customer requirements. In the first approach, the main goal of the design is to keep costs within a certain budget. This is also called value-engineering analysis and it is suitable for commercial products with minimum safety standards. In the design-to-customer requirements approach, the primary designer’s concern is to satisfy the customer’s requirements and safety and regulatory obligations. This is common for products related with military applications and with high safety standards.

A design FMEA starts with two requirements:

- Identifying the appropriate form, and
- Identifying the rating guidelines

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[75] Stamatis, page 129-130.

The form and the rating guidelines for the design FMEA (or any kind of FMEA) are not standardized. Each one performing FMEA makes his own forms and rating guidelines, which correspond to the project’s special requirements and characteristics, as well as the designer’s vision and experience.

There are also two ways that the rating guidelines can be formulated: The qualitative method and the quantitative method. In both cases, the numerical values can be from 1 to 5 or 1 to 10, which is most common.

An example of design FMEA form is in Table 1. The form is divided into three parts. The first part with item numbers from 1 to 10 is the introduction part. The second part of the form includes items 11 to 24 which are the body items of any design FMEA. The third part items 25 and 26 concern authority and responsibility of the FMEA team. Definition of terms is in Appendix A.

(1) Subsystem Name	**(4) Supplier Involvement**	**(8) FMEA Date**
(2) Design Responsibility	**(5) Model/Product**	**(9) FMEA Revision Date**
(2A) The Head of the System Design Team	**(6) Engineering Release Date**	**(10) Part Name**
(3) Involvement of Others	**(7) Prepared by**	**Page___of___Pages**

(11) Design Function	**(12)** Potential Failure Mode	**(13)** Potential Effect(s) of Failure	**(14)** Critical Characteristics	**(15)** SEV	**(16)** Potential Cause(s) of Failure	**(17)** OCC	**(18)** Detection Method	**(19)** DET	**(20)** RPN	**(21)** Recommended Action	**(22)** Responsible Area or Person and Completion Date	Actions Results **(24)**				
												(23) Action Taken	SEV	OCC	DET	RPN

(25) Approval Signatures	**(26) Concurring Signatures**

Table 1. An Example of Design FMEA (From Stamatis, page 131)

l. FMEA Conclusion

Technology can develop complex systems today. UAVs are an example of the increased automation built into a complex system. To be able to develop these systems efficiently, a number of appropriate system development processes can be used. Implementing such a process from the early stages of design is important for total development, cost, and time.

The objective of a FMEA is to look for all the ways a system or product can fail. Failure occurs when a product or system does not function as it should, or when the user makes a mistake. Failure modes are ways in which a product or process can fail. Each failure mode has a potential effect. Some effects are more likely to occur than others. Each effect has a risk associated with it. The FMEA process is a way to identify failure modes effects and risks within a process or product, and eliminate or reduce them.

The most important reason for conducting an FMEA is the need to improve. FMEAs have a positive impact because of their preventive role. The purpose of FMEA is preventing system and product problems before they occur. Used in the design and manufacturing process, they reduce cost and efforts by identifying product and system improvements early in the development phase when it is easier, faster and cheaper to make changes.

m. Other Tools[76]

(1) Fault Tree Analysis (FTA). This is a reasoned-conclusion "analytical technique for reliability and safety analysis used for complex dynamic systems." It provides an "objective basis" for further analysis and changes. It was developed in 1961 by Bell Telephone Company and is widely used in many applications in industry. FTA is a logical tree in which the "various combinations of possible events" are represented graphically. It shows the "cause and effect relationships" between a single failure and its causes. At the top of the tree is the failure, and the various contributing causes are at the bottom branches of the tree. "The FTA always supplements the FMEA."

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[76] The material from this section is taken (in some places verbatim) from Stamatis, pages 51-67, "Relationships of FMEA and Other Tools."

This thesis develops a FTA for SUAVs. FTA process outline follows:

(a) Identify the system fault state(s) or undesired events. The top event must be quantifiable, definable, noticeable, controllable and inclusive from the lower events.

(b) Proceed with Fault tree construction. Determine the level to which the examination should be conducted and fully describe all events that immediately caused this event. With each lower level fault, describe its immediate causes until a component level failure or human error is exposed.

(c) Fault tree analysis is the last step in which we must determine the minimal cut sets for tree simplification and the probability of each input event. For the AND logic gates the probability of the output is the product of the inputs probabilities while for the OR logic gates it is the sum if and only if the events are mutually exclusive. Finally we must determine the top event probability.

(2) Functional flow diagrams or block diagrams "illustrate the physical or functional relationships" within a system under analysis. They are used to give a quick and comprehensive view of the system design requirements illustrating series and parallel relationships, hierarchy and other relationships among the system's functions. The types of block diagrams used in FMEA are:

(a) System Diagrams, used for identifying relationships between major components and other system components in large systems composed of several assemblies or subsystems,

(b) Detail Diagrams, used for identifying relationships between each part within an assembly or subsystem, and

(c) Reliability Diagrams, used for identifying the series dependence or independence of major components, subsystems or detail parts in achieving required functions.

(3) FMA. "Failure mode analysis (FMA) is a systematic approach to quantify failure modes, failure rate and root causes of known failures." FMA is based

only on historical field and process data. It is a diagnostic tool because it concerns itself with only known and/or occurred failures. “Both FMA and FMEA deal with failure modes and causes.” FMA may be conducted first and then the outcome becomes input for the FMEA.

(4) FMECA, FAMECA. An FMEA becomes (FMECA or FAMECA) Failure Mode, Effects and Critically Analysis if criticalities are assigned to the failure mode effects.[77] An analysis like that identifies any faulty components in the system so their reliability, or safety of operation, can be improved early enough so the designer can make corrections and set limitations in the design. FMECA results may also be useful when modifying the system and for maintenance planning. In a complex system all components cannot be redesigned. The most critical components are scientifically selected, and only these should be improved. FMECA is usually conducted during the design phase of a system.

(5) FMCA. “Failure mode and critical analysis (FMCA) is a systematic approach to quantify failure modes, rates and root causes from a criticality perspective.[78]” It is similar to the FMEA in all other details. An FMCA analysis is used “where the identification of critical, major and minor characteristics is important.” By focusing on criticality one can identify the single-point failure modes, which are a human error or hardware failure that can result in an accident.

(6) QFD. Quality function deployment (QFD) is a systematic methodology that unites the various working groups within a corporation and guides them to focus on customer’s choices, demands and expectations. QFD “encourages a comprehensive, holistic approach to product development.” It is a tool that interprets the customer’s requirements, through specific characteristics, manufacturing operations and production requirements. QFD and FMEA have much in common. They both target continual improvement by eliminating failures and looking for customer satisfaction. Usually, QFD occurs first and based on the results FMEA follows.

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[77] Hoyland, page 74.

[78] Stamatis, page 62.

(7) RCM.[79] Reliability-centered maintenance (RCM) has its roots in the aviation industry.[80] Airlines and airplane manufacturers developed the RCM process in the late 1960's. The initial development work was started by North American civil aviation industry. The airlines at that time began to realize that existing maintenance philosophies were not only too expensive but very dangerous as well. In 1980, an international civil aviation group developed an inclusive basis for different maintenance strategies. This basis is known as the Maintenance Steering Group-3 (MSG-3) for the aviation industry.[81]

The earliest view of failure in the 1930's was that as products aged, due to wear and tear, they were more likely to fail. So the best way to optimize system reliability and availability was by providing maintenance on a routine basis. During World War II, awareness about infant mortality led to the widespread belief in the "bathtub curve". In that case, overhauls or component replacements should be done at fixed time intervals to optimize system reliability and availability. This is based on the assumption that most systems operate reliably for a period of "X" and then wear out. Keeping records on failures enables us to determine "X" and take preventive actions just before deterioration starts. This model is true for certain types of simple systems and some complex ones with age-related failure modes. However, after 1960, due to complexity of the systems, research revealed that six failure patterns actually occur in practice. Data collection and analysis will enable NAVAIR to determine which apply to SUAVs.

(a) The bathtub curve. It begins with high occurrence/incidence of failure, which is the infant mortality, followed by constant or gradually increasing conditional probability of failure, and ends up in a wear-out zone due to age.

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[79] The material from this subsection is taken (in some places verbatim) from: Aladon Ltd, Specialists in the application of Reliability-Centered Maintenance, "Reliability Centred Maintenance-An Introduction," Internet, February 2004. Available at: www.aladon.co.uk/10intro.html

[80] Hoyland, page 79.

[81] Aladon Ltd, Specialists in the application of Reliability-Centered Maintenance, "About RCM," Internet, February 2004. Available at: www.aladon.co.uk/02rcm.html

(b) Constant or slowly increasing conditional probability of failure, ending in a wear-out zone.

(c) Slowly increasing conditional probability of failure, but no recognizable wear-out zone.

(d) A low conditional probability of failure when the system is new and then a rapid increase to a constant level.

(e) A constant conditional probability of failure at all ages.

(f) A high infant mortality during the early period and then constant or slowly decreasing conditional probability of failure.

The above six failure patterns are illustrated in the next figure.

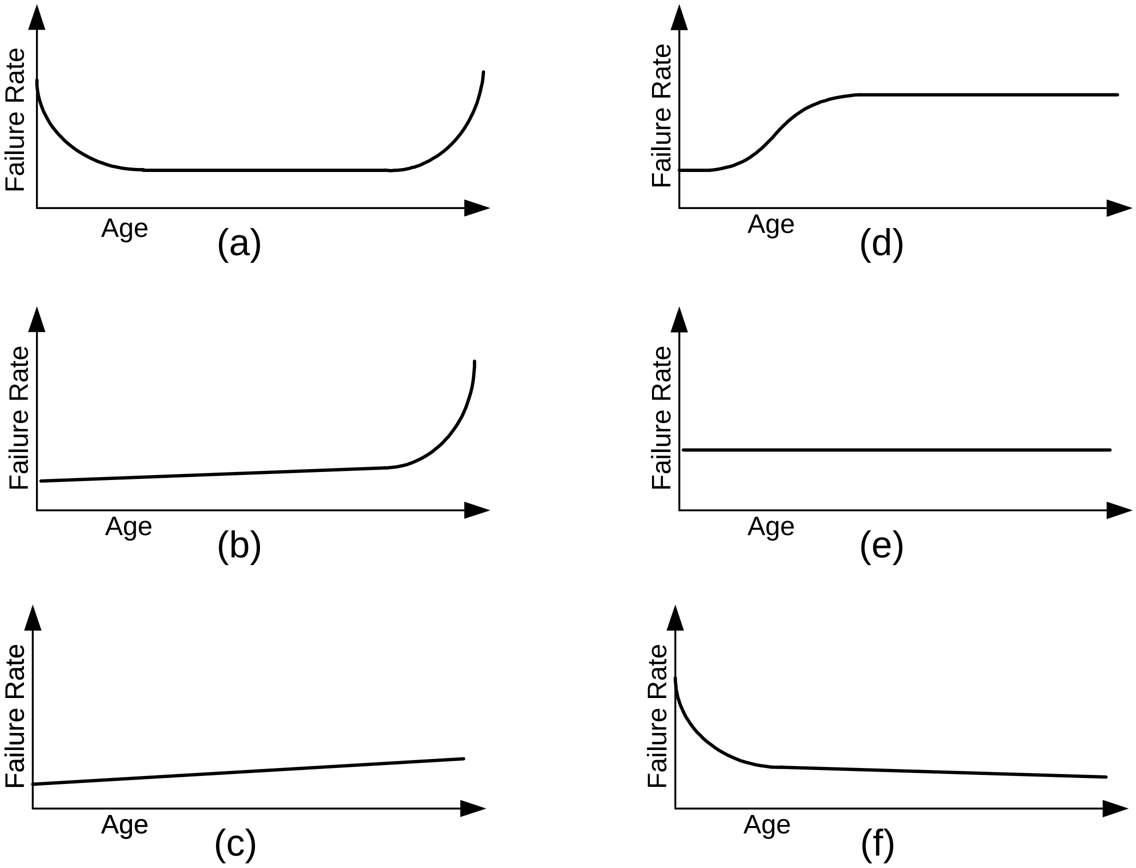

Figure 1. The Six Failure Patterns

The idea of RCM is based on the realization that what users want depends on the operating context of the system. So RCM is “a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context.” The RCM process asks seven questions about the system under review. Any RCM process should ensure that all of the following seven questions are answered satisfactorily in the sequence shown below:

- What are the functions and associated desired performance standards of the system in its present operating context? (Functions).
- In what ways can it fail to fulfill its functions? (Functional failures).
- What causes each functional failure? (Failure modes)
- What happens when each failure occurs? (Failure effects).
- In what way does each failure matter? (Failure ramifications)
- What should be done to predict or prevent each failure? (Proactive tasks and task intervals).
- What if a convenient solution cannot be found? (Default actions)

Definitions of terms related to functions, functional failures, failure modes, and failure effects are presented in appendix C.

(8) TAAF. The Test-Analyze And Fix (TAAF) philosophy is accomplished in an iterative manner by conducting tests, collecting data, analyzing data, making the appropriate modifications and starting the tests again. The process starts by conducting tests on the prototypes. The failure data are collected and the causes are sought. Corrective actions are then taken to reduce the occurrence of future failures. The same process is repeated until the tests results are acceptable.

Some characteristics of TAAF process are

- All failures are fully analyzed.
- Actions are taken in the design and/or production phase to ensure that failures do not recur.

- Tests are done at high level since improvements at that level have the maximum effect on system reliability.
- Corrective actions must be taken as soon as possible on all components in the development program.

In general, TAAF is a time consuming and costly reliability growth process, which resembles the spiral method of project development.[82]

(9) FRACAS. A Failure Reporting Analysis and Corrective Action system (FRACAS)[83] or Data Reporting Analysis and Corrective Action System (DRACAS) is commonly referred as a "closed loop reporting system." Implemented for a program during production, integration, testing, and field deployment phases, it allows for the collection and analyses of reliability and maintainability data for the hardware and software items. For a successful reliability improvement program, all failures should be considered. Every hardware and software failure, including the most simplistic ones, such as those caused by loose nuts and bolts or loose cables, should be investigated. Corrective action for each one should be developed. The manufacturer can use FRACAS results to "incorporate the corrective actions into the product." [84] We develop a FRACAS for SUAVs in this thesis.

2. Manned Aviation Specific: RCM, MSG-3

a. Introduction to RCM

Reliability centered maintenance (RCM) originated in the aviation industry in the late 60s. In the mid 70s, the US Department of Defense wanted to know more about aviation maintenance. As a result, Stanley Nowlan and Howard Heap of the United Airlines wrote a report titled "Reliability Centered Maintenance." It was published in 1978, and it is still one of the most important documents in the history of physical asset management.[85] RCM is "a process used to determine what must be done to

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[82] Blischke, R. W., and Murthy D. N. Prabhakar, *Reliability Modeling, Prediction, and Optimization*, John Wiley & Sons, 2000, page 547-548.

[83] Pecht, M., *Product Reliability Maintainability and Supportability Handbook*, CRC Press, 1995, page 322.

[84] Ibid, page 324.

ensure that any physical asset continues to do what its users want it to do in its present operating context."

b. The Seven Questions

The RCM process answers seven questions about the system under review. Any RCM process should ensure that all of the following seven questions are answered satisfactorily and are answered in the sequence shown below:

(1) What are the functions and associated desired performance standards of the system in its present operating context (functions).

(2) In what ways can it fail to fulfill its functions? (Functional failures)

(3) What causes each functional failure? (Failure modes)

(4) What happens when each failure occurs? (Failure effects)

(5) In what way does each failure matter? (Failure ramifications)

(6) What should be done to predict or prevent each failure?

(7) What if a preventative approach cannot be found? (Default actions)

While defining the functions and desired standards of performance of a system, the objectives of maintenance are defined. Defining functional failures enables exact explanation of the meaning of failure. The functions and functional failures were addressed by the first two questions of the RCM process. The next two questions identified the failure modes, which are more likely to cause each functional failure, and to find out the failure effects associated with each failure mode. This is done by performing an FMEA for each functional failure.[86]

c. RCM-2[87]

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[85] Moubray, John summarized by Sandy Dunn, Plant Maintenance Resource Center, "Maintenance Task Selection-Part 3," Revised September 18, 2002, Internet, May 2004. Available at: http://www.plant-maintenance.com/articles /maintenance_tak_selection_part2.shtml

[86] The material from this part of section is taken (in some places verbatim) from: Aladon Ltd, "Introduction."

[87] The material from this section is taken (in some places verbatim) from: Aladon Ltd, "About RCM."

Nowlan and Heap's report and MSG-3 have been used as a basis for various military RCM standards and for non-aviation derivatives. Of these, by far the most widely used is RCM-2.

RCM-2 is a process used to decide what must be done to ensure that any physical asset, system or process continues to perform exactly as its user wants it to. The process defines what users expect from their assets in terms of

(1) Primary performance parameters such as output, throughput, speed, range and carrying capacity, and

(2) Risk (safety and environmental integrity), quality (precision, accuracy, consistency and stability), control, comfort, containment, economy, customer service and so on.

The second step in the RCM-2 process is to identify the ways the system can fail, followed by an FMEA to associate all the events that are likely to cause each failure.

The last step is to identify a suitable failure management policy for dealing with each failure mode. These policy options may include predictive maintenance, preventive maintenance, failure finding, or changing the design and/or configuration of the system.

The RCM-2 process provides rules for choosing which of the failure management policies is technically appropriate and presents criteria for deciding the frequency of the various routine tasks.

d. SAE STANDARD JA 1011

RCM-2 complies with SAE Standard JA 1011 or "Evaluation Criteria for Reliability-Centered Maintenance (RCM) Process." It was published in August 1999 by the Society of the Automotive Engineers (SAE). It is a brief document setting out the minimum criteria that any process must include to be called an RCM process when applied to any particular asset or system.[88]

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[88] The material from this section is taken (in some places verbatim) from: Aladon Ltd, "About RCM."

The standard says that in order to be called an "RCM" process, a process must get satisfactory answers to the seven questions above, which must be asked, in that particular order. The rest of the standard identifies the information that must be gathered, and the decisions that must be made in order to answer each of these questions satisfactorily. [89]

e. MSG-3[90]

In July 1968, Handbook MSG-1, "Maintenance Evaluation and Program Development," was developed by various airlines and air manufacturers' representatives. Decision logic and airline/manufacturer procedures for scheduled maintenance development for the new Boeing 747 were the main part of the document.

In the 1970's the "Airline/Manufacturer Maintenance Program Planning Document" or MSG-2 was released. It was a universal document that updated the decision logic for the latest aircraft.

In 1979, after a decade of MSG-2 implementation, "experience and events indicated" that MSG procedures needed updating. In addition, new generation aircraft maintenance requirements, new regulations on maintenance programs, the high price of fuel and spare parts greatly influenced maintenance program development. Various areas that where "most likely candidates for improvement" were the difficulty of the decision logic, the clarity of the difference between economic and safety issues, and the effectiveness of the hidden functional failures solutions.

With the participation and combined efforts of the Federal Aviation Authority (FAA), Civil Aviation Administration from the UK (CAA/UK), the American Engineering Association (AEA), US and European aircraft engine manufacturers, airlines, and the US Navy created the MSG-3 document.

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[89] The material from the above part of section is taken (in some places verbatim) from: Athos Corporation, Reliability-Centered Maintenance Consulting, "SAE RCM Standard: JA 1011, Evaluation Criteria for RCM Process," Internet, February 2004. Available at: http://www.athoscorp.com/SAE-RCMStandard.html

[90] The material from this section is taken (in some places verbatim) from: Air Transport Association of America, "ATA MSG-3, Operator/Manufacturer Scheduled Maintenance Development, Revision 2002.1," Nov 30, 2001, pages 6-8.

Some of the major improvements presented by MSG-3 as compared to MSG-2 were

(1) For systems and powerplant treatment:

(a) MSG-3 provides a “more rational procedure for task definition” and “linear progression through the decision logic.”

(b) “MSG-3 logic took a top-down or consequence of failure approach.” At the beginning, the functional failure was evaluated for the consequences of failure and was assigned one of two basic categories, safety or economic.

(c) Further classification established sub-categories based on “whether the failure was evident to or hidden from the operating crew.”

(d) “Task selection questions were arranged in a sequence” so that the “most easily accomplished task, was considered first.” If the task was not applicable or effective, then “the next task in sequence was considered, down to and including possible redesign.”

(2) Structures treatment, “fatigue, corrosion, accidental damage, age exploration” and other considerations were incorporated in the logic diagram.

(3) “MSG-3 recognized the new damage tolerance rules and the supplemental inspection programs and provided a method by which their purpose could be adapted to the Maintenance Review Board (MRB) process instead of relying on type data certificate restrains.” The MRB is discussed in Appendix B.

(4) MSG-3 logic was “task-oriented and not maintenance process oriented.” With the task-oriented concept, “one would be able to view the MRB document and identify the initial scheduled maintenance for a given item.” Definitions for the MRB are in appendix B.

(5) Servicing/lubrication was included as part of the logic diagram to emphasize its severity.

(6) Treatment of hidden functional failures was more thorough because of their distinct separation from the evident functional failures.

(7) "The effect of concurrent or multiple failures was considered."

(8) "Structures decision logic no longer contained a specific numerical rating system."

f. MSG-3 Revision[91]

In 1987, after seven years of MSG-3 experience, the first revision was undertaken and released, and in 1993 revision two followed. In 2001, MSG-3 revision 2001 was incorporated and in 2002, revision 2002 was issued and is now in effect.

> MSG-3 is intended to facilitate the development of initial scheduled maintenance. The remaining maintenance (that is non-scheduled or non-routine maintenance) consists of maintenance actions to correct discrepancies noted during scheduled maintenance tasks, other non-scheduled maintenance, normal operation or data analysis.

The analysis process identifies all scheduled tasks and intervals based on the aircraft's certificated operating capabilities.

"The management of the scheduled maintenance development activities" should be accomplished by an Industry Steering Committee (ISC), which consists of members from representatives of operators, and prime airframe and engine manufacturers. "The ISC should see that the MSG-3 process identifies 100% accountability for all Maintenance Significant Items (MSI's) and Structural Significant Items (SSI's)."

An MSI is an item that has been identified by the manufacturer whose failure

- can affect ground or flight safety, and/or
- is undetectable during operation time, and/or
- could have significant operational and/or economic impact.[92]

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[91] The material from this section is taken (in some places verbatim) from: ATA MSG-3, pages 9-13.

[92] ATA MSG-3, page 87.

A SSI is any “element or assembly,” related to significant flight, ground, pressure or control loads. An SSI failure could affect the structural integrity of the aircraft.[93]

“One or more working groups, composed of specialist representatives from the participating operators, the prime manufacturer and the Regulatory Authority, may be constituted.” The ISC will approve analyses, technical data and information, which will be “consolidated into a final report for presentation to the Regulatory Authority.”

g. General Development of Scheduled Maintenance[94]

For each new type of aircraft, it is necessary to develop scheduled maintenance prior to its introduction into airline service. The MSG-3 (revision 2002) document has the primary purpose “to develop a proposal to assist the Regulatory Authority in establishing initial scheduled maintenance tasks and intervals for new types of aircraft and/or powerplants.” The intention is to maintain and to enhance the inherent “safety and reliability levels of the aircraft.” As operating experience is gained, the operator may make additional adjustments to maintain and to enhance safety and reliability.

The objectives of efficient aircraft scheduled maintenance are

- To ensure the inherent safety and reliability levels of the aircraft;
- “To restore safety and reliability to their inherent levels when deterioration has occurred;”
- “To obtain the information needed for design improvement of those items whose inherent reliability proves insufficient;”
- To achieve the above goals at a minimum total cost.

From the above objectives, obviously, scheduled maintenance can only prevent deterioration of inherent levels. If the inherent levels are unsatisfactory, then redesign is necessary to achieve the desired safety and reliability levels.

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[93] Ibid, page 89.

[94] The material from this section is taken (in some places verbatim) from: ATA MSG-3, pages 14-16.

Scheduled maintenance consists of two groups of tasks:

(1) “A group of scheduled tasks to be accomplished at specified intervals. The objectives of these tasks are to prevent deterioration of the inherent safety and reliability levels of the aircraft.” They may include lubrication/servicing (LU/SV), operational/visual check (OP/VC), inspection/functional check (IN/FC), restoration (RS) and discard (DS).

(2) A group of non-scheduled tasks that result from the scheduled tasks accomplished at specified intervals, and reports of malfunctions usually created by the operating crew and data analysis. The objectives of these tasks are to bring the aircraft to a desired condition.

An efficient program schedules only those tasks necessary to meet the fixed objectives. Additional tasks, which will increase cost without any significant improvement in reliability, are not scheduled. The MSG-3 document “describes the method for developing the scheduled maintenance” using a “guided logic approach.” The logic flow of analysis is “failure-effect oriented” while the result must be a task-oriented program. Items with no scheduled task specified may be monitored by an operator’s reliability program. Finally, assumptions that can result in a change must be documented.

h. Divisions of MSG-3 Document[95]

The working portions of MSG-3 are contained in four sections. They are a section for System/Powerplant, including components and Auxiliary Power Units (APU’s); a section for aircraft structure; a section for zonal inspection; and finally a section for lightning/high intensity radiated field (L/HIRF) analysis. “Each section contains its own explanatory material and decision logic diagram, and it may be used independently of other MSG-3 sections.”

In the following sections (i through p), Aircraft Systems/Powerplant Analysis is further discussed because it obviously has the closest potential relationship with SUAVs applications.

i. MSI Selection[96]

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[95] The material from this section is taken (in some places verbatim) from: ATA MSG-3, page 16.

[96] The material from this section is taken (in some places verbatim) from: ATA MSG-3, pages 22-23.

Progressive logic diagram is the evaluation technique applied to each maintenance significant item (MSI) using the technical data available. An MSI may be a system, a subsystem, module, component, accessory, unit or part. In general, the evaluations are based on the item’s functional failures and causes of the failure.

Before MSG-3 logic can be applied to an item, the aircraft’s significant systems and components must be identified. Then using the top-down approach MSIs must be identified. To select MSIs, the process is as follows:

(1) The manufacturer divides the aircraft into the main functional areas, Air Transport Association (ATA) systems, and subsystems. This division continues “until all the aircraft’s replaceable components have been identified.”

(2) “The manufacturer establishes the list of items to which MSI selection questions will be applied.”

(3) Those questions applied to the items in the lists are

(a) “Could failure be undetectable or not likely to be detected by the operating crew during normal duties?” (Detectability)

(b) Could failure affect safety on ground or in flight? (Safety part of severity)

(c) “Could failure have a significant operational impact?” (Operational part of severity)

(d) “Could failure have a significant economic impact?” (Economic part of severity)

(4) Subsequent analysis.

(a) If at least one of the above four questions is answered with “yes,” MSG-3 analysis is required. “An MSI is usually a system or subsystem,” and in most cases is “one level above the lowest level identified” on (1). “This level is considered the highest manageable level; i.e. one that is high enough to avoid unnecessary analysis, but low enough to be properly analyzed.”

(b) For those items for which all four questions are answered with a “no,” MSG-3 analysis is not required. “The lower level items should be listed to identify those that will not be further assessed.” This list must be reviewed and approved by the Industry Steering Committee (ISC).

(5) The resulting list for the highest manageable level items is considered the “candidate MSI list” and is presented by the manufacturer to the ISC. The ISC reviews and approves this list, which is passed to the working groups (WGs).

(6) The WGs review the candidate MSI list in order “to verify that no significant items have been overlooked, and that the right level for the analysis has been chosen.” By applying MSG-3 analysis, the WGs can “validate the selected highest manageable level or propose modification of the MSI list to the ISC.”

j. Analysis Procedure[97]

For each MSI, the following must be identified:

- Function(s), the “normal characteristic actions of an item”
- Functional Failure(s), the failure of an item to perform its planned function(s)
- Failure Effect(s), the result of a functional failure
- Failure Cause(s), the reason for the functional failure occurrence

Analysis should take special care to “identify the functions of all protective devices,” and include economic and safety related tasks in order to “produce initial scheduled maintenance tasks and intervals.” Vendor recommendations (VR) that are available should be “considered and discussed in the WGs meetings and accepted if they are applicable and effective.”

A preliminary work sheet, prior to applying the MSG-3 logic diagram to an item, clearly defines the MSI, its function(s), functional failure(s), failure cause(s) and additional data for each item.

k. Logic Diagram[98]

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[97] The material from this section is taken (in some places verbatim) from: ATA MSG-3, pages 23-24.

[98] The material from this section is taken (in some places verbatim) from: ATA MSG-3, pages 24-25.

The decision logic diagram, illustrated in Figure 2 and 3, assists in analyzing systems in general and powerplant items in particular. The logic flow follows a top-down approach and answers the “yes” or “no” questions giving the direction of the analysis flow after each answer.

There are two levels in the decision analysis:

“(1) Level 1 requires the evaluation of each functional failure in order to determine the failure effect category; i.e. safety, operational, economic, hidden safety or hidden non-safety.

(2) Level 2 then takes the failure cause(s) for each functional failure into account for selecting the specific type of task(s).”

In Level 2, regardless of the answer to the first question about lubrication/servicing (LU/SV), the next task selection question must always be asked. When following the hidden or evident safety effects path, all successive questions must be asked. In the remaining categories that follow the first question, a “yes” answer permits exiting the logic.

Default logic concerns areas paths that do not affect safety. If there is no “adequate information to a clear ‘yes’ or ‘no’ to the questions in the second level, then default logic dictates a ‘no’ answer.” “No,” as an answer in most cases, provides a more conservative and/or costly task.

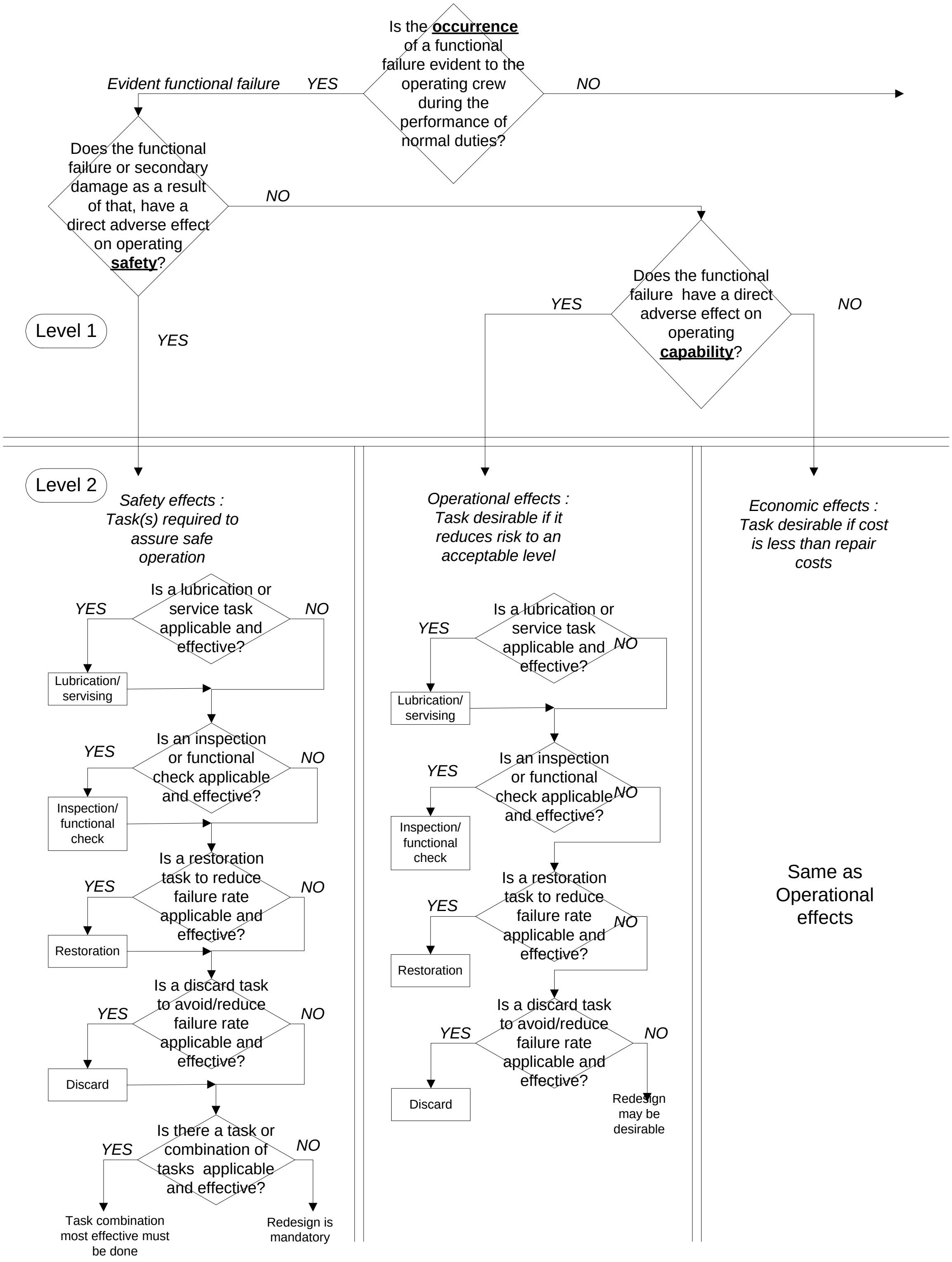

Figure 2. Systems Powerplant Logic Diagram Part1 (After ATA MSG-3, page 18)

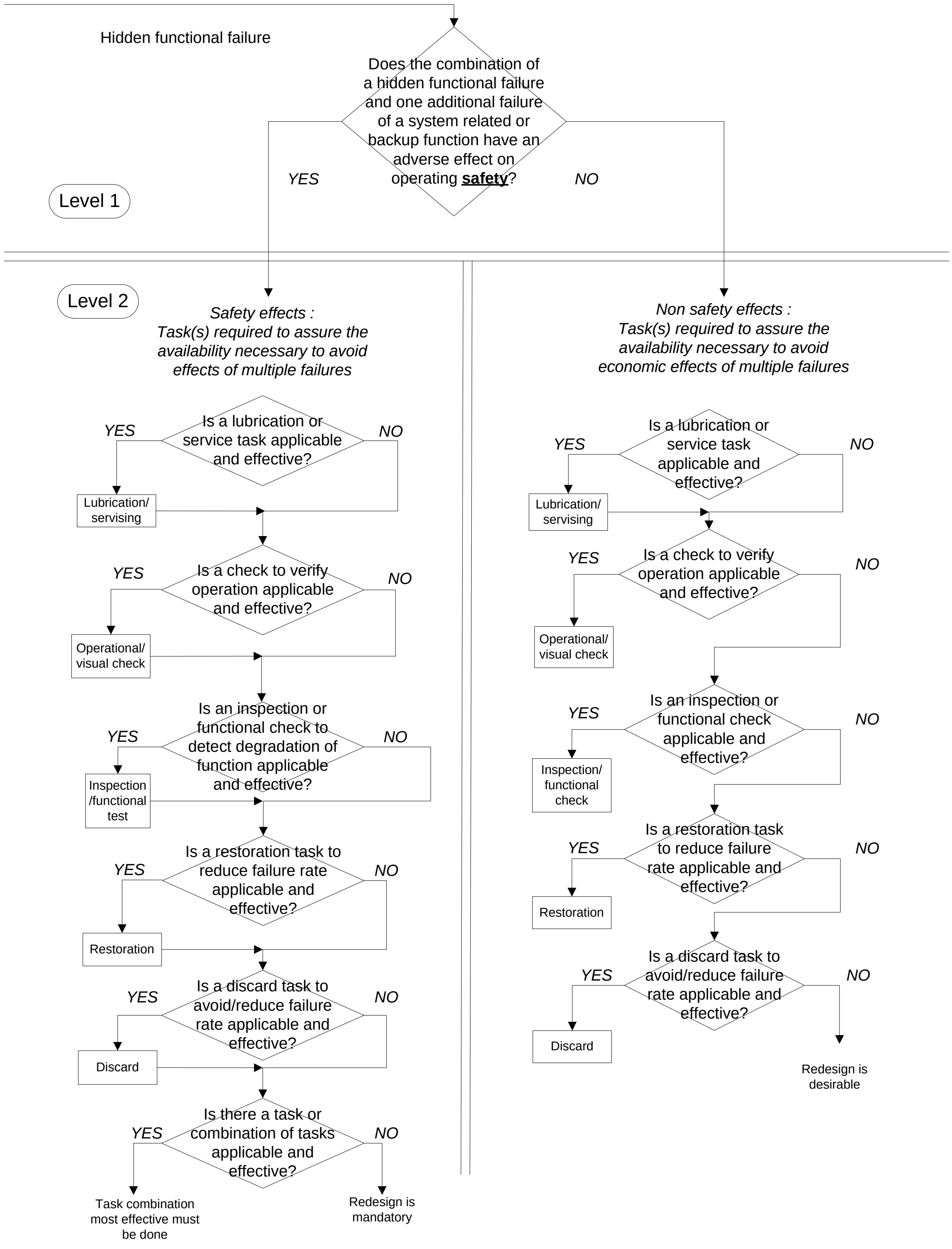

Figure 3. Systems Powerplant Logic Diagram Part2 (After ATA MSG-3, page 20)

l. Procedure

This procedure requires consideration of the functional failures, failure causes, and the applicability or effectiveness of each task. Each functional failure processed through the logic will be directed into one of five failure effect categories:[99]

- Safety
- Operational
- Economic
- Hidden safety
- Hidden non-safety[100]

m. Fault Tolerant Systems Analysis[101]

"In MSG-3 analysis, a fault tolerant system is one that has redundant elements that can fail without impacting safety or operating capability." These faults are not very noticeable to the operating crew and the aircraft's safety and airworthiness is not impaired. So, "functional failures, in fault tolerant systems, are hidden non-safety." The "fault-tolerant" faults can be "detected by interrogation of the system."

The method for analyzing MSIs that include fault-tolerant functions has the following steps:

- "The manufacturer identifies and lists all functions, highlighting those that are fault-tolerant."
- The basis for identifying fault-tolerant functions must be provided.
- "For non-fault-tolerant functions, the standard analysis process must be used."
- "For fault-tolerant functions, the WGs must determine and select an applicable and effective task and interval, based on the available data from the manufacturer."

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[99] ATA MSG-3, page 25.

[100] Ibid, page 21.

[101] The material from this section is taken (in some places verbatim) from: ATA MSG-3, page 26.

n. Consequences of Failure in the First level[102]

There are four first-level questions.

(1) Evident or Hidden Functional Failure. Question: “Is the occurrence of a functional failure evident to the operating crew during the performance of normal duties?”

The intention for this question is to separate the evident from the hidden functional failures. The operating crew is the pilots and air crew on duty. The ground crew is not part of the operating crew. A “yes” answer indicates the functional failure is evident and leads to Question 2. A “no” answer indicates the functional failure is hidden and leads to Question 3.

(2) Direct Adverse Effect on Safety. Question: “Does the functional failure or secondary damage resulting from the functional failure have a direct unfavorable effect on operating safety?”

A direct functional failure or resulting secondary damage “achieves its effect by itself, not in combination with other functional failures.” If the consequences of the failure condition would “prevent the continued safe flight and landing of the aircraft and/or might cause serious or fatal injury to human occupants,” then safety should be considered as unfavorably affected. A “yes” answer indicates that this functional failure must be considered within “the Safety Effects category” and task(s) must be developed accordingly. A “no” answer indicates the effect is either “operational or economic” and leads to question 4.

(3) Hidden Functional Failure Safety Effect. Question: “Does the combination of a hidden functional failure and one additional failure of a system related or back-up function have an adverse effect on operating safety?”

This question is asked of each hidden functional failure, identified in Question 1. A “yes” answer indicates that there is a “safety effect and task development must proceed in accordance” with the hidden-function safety-effects category. A “no” answer indicates that there is a “non-safety effect and will be handled in accordance” with hidden-function non-safety effects category.

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[102] The material from this section is taken (in some places verbatim) from: ATA MSG-3, pages 26-30.

(4) Operational Effect. Question: “Does the functional failure have a direct unfavorable effect on operating capabilities?”

In this question, considerations must be taken concerning the operating restrictions, correction prior to further dispatch, and abnormal or emergency procedures from the flight crew. A “yes” as an answer means that the effect of the functional failure has an unfavorable effect on operating capability, and task selection will be handled in evident operational effects category. A “no” as an answer means that there is an economic effect and should be handled in accordance with evident economic effects category.

o. Failure Effect Categories in the First Level[103]

After the analysts have answered the applicable first-level questions, “they are directed to one of the five effect categories.”

(1) Evident Safety: The Evident Safety Effect category concerns the safety operation assurance tasks. “All questions in this category must be asked.” In case no effective task(s) results from this category analysis, “redesign is mandatory.”

(2) Evident Operational: In this category, a task is “desirable if it reduces the risk of failure to an acceptable level.” Analysis requires the first question (LU/SV) to be answered and regardless of the answer, to proceed to the next level question. From that point a “yes” as an answer completes the analysis and “the resultant task(s) will satisfy the requirements.” If all answers are “no,” then no task has been generated and if operational penalties are severe, redesign may be desirable.

(3) Evident Economic: In that category, a task(s) is desirable if its cost is less than the repair cost. Analysis has the same logic as the operational category. If all answers are “no,” then no task has been generated and if economic penalties are severe, a redesign may be desirable.

(4) Hidden Safety: “The hidden function safety effect requires a task(s) to assure the availability necessary to avoid the safety effect of multiple failures.” All questions must be asked and “if there are no tasks found effective, then redesign is mandatory.”

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[103] The material from this section is taken (in some places verbatim) from: ATA MSG-3, pages 31-38.

(5). Hidden non-Safety: "The hidden function non-safety category indicates that a task(s) may be desirable to assure the availability necessary to avoid the economic effects of multiple failures." Analysis has the same logic as the operational category. If all answers are "no," no task has been generated and if economic penalties are severe, a redesign may be desirable.

p. Task Development in the Second level[104]

For each of the five-effect categories, task development is used in a similar manner. "It is necessary to apply the failure causes for the functional failure to the second level of the logic diagram" for the task resolution as in Table 2. There are six possible task follow-on questions in the effect categories.

(1) Lubrication/servicing (in all categories). Question: "Is the lubrication or servicing task applicable and effective?"

"Any act of lubrication or servicing for the purpose of maintaining the inherent design capabilities" is considered.

(2) Operational/visual check (hidden functional failure categories only). Question: "Is a check to verify operation applicable and effective?"

"The operational check is a task to determine that an item is fulfilling its intended purpose." It is a failure-finding task and does not require quantitative tolerances. "A visual check is an observation to determine that an item is fulfilling its intended purpose." It is also a failure-finding task and does not require quantitative tolerances.

(3) Inspection/functional check (All categories). Question: "Is an inspection or functional check to detect degradation of function applicable and effective?"

An inspection could be general and visual, detailed with surface cleaning or elaborate access procedures, special detailing with excess surface cleaning and substantial access and disassembly procedures. "A functional check is a quantitative check to determine if one or more functions of an item performs within specified limits."

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[104] The material from this section is taken (in some places verbatim) from: ATA MSG-3, pages 31-47.

(4) Restoration (All categories). Question: Is a restoration task to reduce the failure rate applicable and effective?

Restoration is the "work necessary to return the item to a specific standard." The scope of each assigned restoration task has to be clearly specified.

(5) Discard (All categories). Question: Is a discard task to avoid failures or reduce the failure rate applicable and effective?

Discard is the "removal from service of an item at a specified life limit." It is a typical task applied to single celled parts such as cartridges, canisters, filters, engine disks, etc.

(6) Combination (Safety categories only). Question: Is there a task or combination of tasks applicable and effective?

All possible paths must be analyzed since this is a safety category question.

Task	***Applicability***	***Safety Effectiveness***	***Operational Effectiveness***	***Economic Effectiveness***
Lubrication or Servicing	The replenishment of the consumable must reduce the rate of functional deterioration.	The task must reduce the risk of failure.	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective (i.e., the cost of the task must be less than the cost of the failure prevented)
Operational or Visual Check	Identification of failure must be possible.	The task must ensure adequate availability of the hidden function to reduce the risk of a multiple failure.	No applicable.	The task must ensure adequate availability of the hidden function, to avoid economic effects of multiple failures and must be cost effective.
Inspection or Functional Check	Reduced resistance to failure must be detectable, and there exists a reasonably consistent interval between a deterioration condition and functional failure.	The task must reduce the risk of failure to assure safe operation	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective
Restoration	The item must show functional degradation characteristics at an identifiable age, and a large proportion of units must survive to that age. It must be possible to restore the item to a specific standard of failure resistance.	The task must reduce the risk of failure to assure safe operation.	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective
Discard	The item must show functional degradation characteristics at an identifiable age, and a large proportion of units must survive to that age.	The safe life limit must reduce the risk of failure to assure safe operation.	The task must reduce the risk of failure to an acceptable level.	An economic life limit must be cost effective.

Table 2. Task Selection Criteria (After ATA MSG-3, page 46)

3. Comparison of Existing Methods

a. RCM

It is clear that maintenance activity must help ensure that the inherent levels of safety and reliability of the aircraft are maintained.

> The days of doing maintenance just for the sake of maintenance or because it makes us “feel good” are past. Studies have revealed that technicians performing maintenance based on “trivial knowledge” rather than the air carrier’s approved maintenance program have generated errors. In other cases, technicians performing approved maintenance that was not necessary have also generated maintenance errors. Each time we provide technicians access to an aircraft, we also provide the potential for that technician to inadvertently induce an error.[105]

We may say in simple words that the RCM goals are to:

- Ensure realization of the equipment’s inherent safety and reliability.
- Restore equipment’s safety and reliability to required levels when deterioration occurs.
- Obtain the information necessary for design improvements where inherent reliability is insufficient.
- Accomplish these goals at a minimum total life-cycle cost. [106]

The RCM logic is simply to:

- Determine the function of the system/component;
- Find out what the functional failures are;
- Evaluate the consequences of each failure; and,
- Assign the least expensive but adequate maintenance task to prevent each failure.[107]

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[105] Nakata, Dave, White paper, “Can Safe Aircraft and MSG-3 Coexist in an Airline Maintenance Program?”, Sinex Aviation Technologies, 2002, Internet, May 2004. Available at: http://www.sinex.com/products/Infonet/q8.htm

[106] The above part is taken (in some places verbatim) from: Nakata.

[107] The above part is taken (in some places verbatim) from: National Aeronautics and Space Administration (NASA), “Reliability Centered Maintenance & Commissioning,” slide 5, February 16, 2000, Internet, May 2004. Available at: http://www.hq.nasa.gov/office/codej/codejx/Intro2.pdf

b. Conducting RCM Analysis

Some managers, who see RCM as a quick, cheap and easy route to obtaining the particular maintenance policies they are seeking, frequently overrule junior staff taking part in RCM analysis. This is a poor approach to the conduct of any analysis. RCM is better conducted by a review group, which may involve senior staff alongside more junior staff. An experienced analyst with a developed background in RCM and in managing groups should lead it. If the group functioning is wrong, it is improper to blame RCM for what project management is failing to achieve.[108]

c. Nuclear Industry & RCM[109]

The initial maintenance programs in US nuclear power plants were developed in conventional fashion, mainly depending on vendor recommendations. "Continuing efforts to enhance safety and reliability" resulted in "utility management at some plants" questioning if the overall outcome was a "significant degree of over-maintenance." By the early 80s, the nuclear power industry seemed to be "faced with a choice of either generating power or doing the prescribed planned maintenance (PM)." They were seeking a way to reduce the PM workloads without impairing safety or reliability. This is the same type of question applicable to SUAV maintenance.

The Electric Power Research Institute (EPRI) became aware of the Nowlan & Heap report on RCM published in 1978. However, after the initial applications of RCM, many plants developed their own methods for maintenance optimization, which deviated from RCM principles. "They took the view that high levels of redundancy in their safety systems, high levels of regulations imposing failure-finding tasks, and the fairly simple mission of the power generating systems at such plants could validly support certain simplifications of the methodology." They also took the view that in older plants the existing experience had found all potential failure modes, and there was a very detailed record keeping conducted by the nuclear power industry. So "they felt that the function analysis and the FMEA steps embodied in the RCM process could be simplified."

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[108] The above part is taken (in some places verbatim) from: Clarke Phill, "Letter to the Editor of New Engineer Magazine regarding Professor David Sherwin at ICOMS 2000," question 10, August 2000, Internet, May 2004. Available at: http://www.assetpartnership.com/downloads.htm-13k

[109] The material from this section is taken (in some places verbatim) from: Moubray, page 3.

"The most abbreviated approach," recommended by EPRI in TR-105365 in September 1995, "modified the RCM process by setting up a list of simple functional questions," without further functional analysis, the question is whether the component failure leads to:

(1) plant trip (shutdown),

(2) power reduction of more than 5% (degradation),

(3) loss of a safety function,

(4) plant transient (recoverable),

(5) personnel hazard, or

(6) delay in start-up (mission delay)?

"These processes achieved their limited objectives in the nuclear industry" and they led to a very substantial reduction in the PM workload without impairing safety or reliability. Effects (1), (2), (3), and (5) are noticeable in SUAV operations. Event (4) is rarely tracked. Event (6) occurs routinely but rarely recorded.

d. RCM in NAVAIR[110]

"As reported by US Naval Air Command (NAVAIR), current operation and support (O&S) costs for naval aviation weapon systems consume 50 to 60 percent of the Navy's total operating account" with a tendency to increase every year by a rate of 5 percent.

NAVAIR, which was one of the sponsors of the original Nowlan & Heap report, found that some vendors were using all sorts of unique and custom-made processes, which they described as "RCM processes," to develop maintenance programs for equipment that they were selling to NAVAIR. "In this age of 'do more with less,' there is a problem that has infected the discipline of physical asset management. In the interest of saving time and money, corrupted versions of RCM, versions that

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[110] The material from this section is taken (in some places verbatim) from: Regan, Nancy, RCM Team Leader, Naval Air Warfare Center, Aircraft Division, "US Naval Aviation Implements RCM," undated, Internet, February 2004. Available at: http://www.mt-online.com/articles/0302_navalrcm.cfm

irresponsibly shorten the process, continue to flood the market. These tools are incorrectly called RCM."

These wayward RCM processes led NAVAIR to approach the Society of Automobile Engineers (SAE) as a recognized standard-setting institution with close relations to the US Military and to the aerospace industry, and SAE JA 1011 was published in August 1999. It is a brief document setting out all the minimum criteria that any process must include to be called an RCM process when applied to any particular asset or system.[111]

When NAVAIR initially implemented RCM in some systems, the economic savings included, on average:

- Scheduled maintenance reduced by 75 percent per year.
- Consumable usage decreased 88 percent per year.
- Disposal of hazardous material decreased 84 percent per year.

e. RCM in Industries Other Than Aviation and Nuclear Power[112]

RCM has been applied in many industrial sites in many countries. "These applications have embodied the performance of several thousand RCM analyses." RCM applications have not been successful in every case. It can be said to have failed in about one-third of the cases. None of the initiatives that failed was due to technical reasons but for organizational ones. The two most common reasons for failure are

(1) The head internal sponsor of the effort "quit the organization or moved to a different position before the new ways of thinking embodied in the RCM process" could be absorbed.

(2) The internal sponsor and/or the consultant, who was the acting change agent, "could not generate sufficient enthusiasm for the process," so it was not applied in a way which would yield results.

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[111] The material from the above part of section is taken (in some places verbatim) from: Aladon Ltd, "About RCM."

[112] The material from this section is taken (in some places verbatim) from: Moubray, page 5.

Of course, the other two-thirds have been successful. There is “a high correlation between the success rate of RCM-2 (MSG-3) applications and the change management capabilities of the consultants involved.” For example, the (British) Royal Navy (RN), which is a major user of SAE-compliant RCM, “has come to understand that the capabilities of individual consultants are as important as the track record of their employers.” So the “RN now insists on interviewing at great length every RCM consultant that is at their disposal” to verify the commercial sincerity of the employers.

When discussing RCM, both the economic benefits and the question of risk are considerations. For the economic benefits in some cases, “the payback period has been measured in days and sometimes one or two years.” The normal period is weeks to months. “These economic benefits flow from improved plant performance” mostly, although in some cases users (especially military) have achieved very substantial “reductions in direct maintenance costs”.

It is often said that RCM “is a good tool for developing maintenance programs in ‘high risk’ situations” and that “some equipment items have such low impact on business risk that the effort required to perform RCM analysis on them is greater than the potential benefits.” The truth is that “no physical asset or system can be deemed to be ‘low risk’ unless it has been subjected at the very least to a zero-based FMECA” that proves it is in fact low risk.

(1) From the results of thousands of RCM-2 (MSG-3) analyses that are being performed around the world, and incidents in supposedly “low risk,” some industries have avoided very serious business consequences.

(2) On average about 4% of the failure modes have direct safety or environmental implications. Frequently, findings showed that as many as 25% of the failure modes are not currently receiving any form of preventive maintenance. Most of those failure modes concern protective devices that had not been receiving proper attention prior to the RCM-2 analysis.

About the supposedly “low risk” industries: automobile and food plants are frequently said to be “low risk,” and therefore not worth strict and rigorous analysis.

The truth is that you cannot characterize these industries as low risk as the following examples indicate:

(1) The boiler that exploded during a maintenance inspection at Ford's River Rouge plant in Detroit in February 1999, killing six and shutting the plant down for 10 days,

(2) The failure of the Firestone tires on Ford Explorers, which has been charged to the design, the operating pressure and to manufacturing process failures. These failures put the existence of Firestone as a company at risk,

(3) The failure of a filter used in the Perrier water bottling in France, leading to the recall of thousands of Perrier products and an enormous cost to the company.

Although rare events, it is wrong to characterize a task or a component or a failure as "low risk," especially if all failure modes had not being considered.

f. FMEA and RCM[113]

"An FMEA, usually conducted in the design phase of an equipment or system, can also be used as a tool for analysis in RCM." While defining the functions and desired standards of performance of an asset, the objectives of maintenance with respect of that asset are defined. Defining functional failures enables us to explain what we mean by "failed." These two issues were addressed by the first two questions of the RCM process. The next two questions seek to identify the failure modes that are reasonably likely to cause each functional failure and to find out the failure effects associated with each failure mode. This is done by performing an FMEA for each functional failure. An FMEA contains:

- Description and detection for each failure mode
- Cause and effects of each failure
- Probability of failure (occurrence)
- Criticality of failure (severity)

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[113] The material from this section is taken (in some places verbatim) from: NASA, slide 13.

- Corrective/preventive measures

FMEA is the key to a successful commissioning program. For newly developed systems with not much experience gained by the developing parties, insufficient oversight, and many unknown potential circumstances, requirements are not standard and certain. Requirements in systems under development, like the UAVs, are a matter of research, experience and technology advances.

g. FMECA

Trying to perform an FMEA to a new system under development, such as SUAVs, is not an easy task because a lot of details keep changing. Instead, an FMECA is better since critical issues are those considered first priority. FMECA is a first-step effort that can be done in such a case.

h. FTA, FMEA, FMECA[114]

"The question to be addressed when considering the most appropriate system analysis tool is whether to conduct a FMECA/FMEA or a FTA." The most obvious answer to that decision making question is "it depends". The "criticality of a mission and/or personnel safety" matters are the primary driving concern and the initial reason for a FTA. The FTA's target is "finely focused" to a point compared to that of a FMECA's which is not focused only to one point but to a broader area.

"If there are many different areas of concern and all of them need to be revealed, then a FMECA is more effective because it has a greater chance of finding the critical failure modes." If only a single event or a few events that can be clearly defined are of crucial concern, then FTA is favored.

The desire for either a qualitative and/or a quantitative analysis is not the distinguishing factor for selecting a FTA or a FMECA/FMEA. Either approach can give qualitative or quantitative results. The following table gives guidance for choosing between FTA and FMECA/FMEA.

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[114] The material from this section is taken (in some places verbatim) from: Reliability Analysis Center (RAC), *Fault Tree Analysis (FTA) Application Guide*, 1990, pages 8-10.

FTA vs FMECA Selection Criteria	**FTA Preferred**	**FMECA/ FMEA Preferred**
Safety of personnel or public as the primary concern	**X**	
A small number of explicitly defined “top events”	**X**	
Inability to clearly define a small number of “top events”		**X**
Mission completion is of critical importance	**X**	
Any number of successful missions		**X**
“All possible” failure modes are of concern		**X**
“Human errors” contributions are of concern	**X**	
“Software errors” contributions are of concern	**X**	
A numerical “Risk evaluation” is the primary concern	**X**	
System is highly complex and interconnected	**X**	
System with linear architecture and little human or software intervention		**X**
System is not repairable	**X**	

Table 3. FTA and FMECA/FMEA (After RAC *FTA*, page 10)

i. FTA[115]

For any reliability program, FTA is an effective tool. It is a quick way of “understanding the causes of a system’s inherent problems” and also a way to “identify potential safety hazards during the design phase.”

Tailoring the FTA to fit the specific type of analysis that is necessary for a certain scope requires two decisions. The selection of the “top event,” which is the target upon which the FTA is to focus is the first decision, and the concern of whether the analysis is about to yield qualitative or quantitative or both types of results is the second decision.

j. RCM Revisited

“RCM is better in the operating and support phase of the life cycle of a system” This is true when considering how and why RCM was created. For example, airplanes were used from the beginning of the previous century. The general concept of the airplane has been known for many years. Legal requirements and special regulations controlling manned-aviation have also been in place for many years. Thus, in this case,

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[115] The material from this section is taken (in some places verbatim) from: RAC *FTA*, pages 9-11.

RCM provided solutions to certain manned-aviation problems mainly related to operations and maintenance issues with safety and economics as backgrounds. Similarly, many other industries also employed RCM to solve such problems.

By definition, RCM is a methodology for determining the most cost-effective maintenance strategy for a given item of equipment taking into account its operating environment. When a product is in design phase, the designers have little historical experience so the whole effort is focused on developing something that works and is not focused on cost-effective strategies. The following table gives guidance for choosing between MSG-3 and FMEA/FMECA.

FMEA/FMECA vs MSG-3 Selection Criteria	**MSG-3 Preferred**	**FMEA/ FMECA Preferred**
Safety of personnel or public as the primary concern	**X**	
Top-down approach of failure analysis	**X**	
Bottom-up approach of failure analysis		**X**
System is highly complex and interconnected	**X**	
Early design and development phase		**X**
Implementation cost		**X**
Implementation timescale		**X**
Economy issues are of critical importance	**X**	
“All possible” failure modes are of concern	**X**	**X**
“Human errors” contributions are of concern	**X**	**X**
“Software errors” contributions are of concern	**X**	
Systems with little human and a lot of software intervention	**X**	
First tool for initial failure analysis		**X**
Available for the entire system life-cycle (long-term)	**X**	
Available for the entire system life-cycle (short-term)		**X**
Implementation effort		**X**
Operational phase	**X**	
Conducted by experienced personnel	**X**	
Training requirements	**X**	
Extensive and conclusive	**X**	
System with linear architecture and little human or software intervention		**X**

Table 4. MSG-3 and FMECA/FMEA

k. UAVs, SUAVs versus Manned Aircraft

The primary difference between manned piloted aircraft and UAVs is that piloted aircrafts rely on the presence of humans to detect (sense) and respond to changes in the vehicle's operation. The human can sense the condition of the aircraft, say with unusual vibration that may indicate structural damage or impending engine failure. Humans can sense events within and outside the vehicle, gaining what is known as "situational awareness."

For manned military aviation the philosophy is pilot and aircraft-oriented. The valuable life of the pilot who spends so much time in studies, training, and gaining the experience of hundreds of flight hours, is the number one factor. The expensive, state-of-the-art multi-mission-capable aircraft is the number two factor. For UAVs, the philosophy is mission and cost-oriented. Different missions require different systems, different platforms with different capabilities. It is also desired that the cost should remain as low as possible. Technology helps to achieve both those goals for UAVs. Better, cheaper technologies can be adapted very easily and very quickly to UAVs.

UAVs can be remotely piloted ("controlled") from the ground. It is difficult for the pilot (operator) to feel and sense having the same or better situational awareness than if he was piloted a manned aircraft. For SUAVs, specifically, volume, weight, cost, duration of flight, and sensor capabilities are the primary factors of interest. Personnel safety is approached differently than manned aviation. With costs starting from $15K up to $300K per platform, SUAVs are considered expendables, but reusables, and treated accordingly. Thus SUAV reliability is low since they are designed to be inexpensive and have a relatively short life circle.

During the last few years, commanders no longer want their SUAVs to be "toys" that uncertainly expand their capabilities. Commanders want their SUAVs to be operationally effective assets to help win battles. "Operationally, the same case may be made for ensuring the missions are completed if we rely on UAVs to accomplish mission critical tasks once done using manned assets."[116]

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[116] Clough, Bruce, "UAVS-You Want Affordability and Capability? Get Autonomy!" Air Force Research Laboratory, 2003.

There are some facts about SUAV systems that require consideration:

(1) They are potentially valuable on battlefields.

(2) Unreliability creates operational ineffectiveness.

(3) SUAV design philosophy remains mission and cost oriented.

(4) Software and hardware reliability improvement is desirable.

(5) Tracking reliability of SUAVs provides insight on operational availability. Currently, there is not any system to track SUAVs reliability in use.

(6) Most of the SUAVs are not maritime systems; they are in design phase or operational testing.

(7) Sensor and miniaturization technology for SUAVs changes rapidly.

(8) Systems are not highly complex.

(9) The new unmanned aviation “community” has started to develop; experience operating SUAVs has just started to accumulate.

(10) Human factors for the GCS are critical since they are the linkage between the system and its effective employment.

l. Conclusions-Three Main Considerations about UAV- RCM

The reliability tracking and improvement system for SUAVs must be inexpensive, easily and quickly adapted, and implemented by a few, relatively inexperienced personnel. It must also cover the entire system’s issues of hardware, software and human factors. The safety requirements for personnel apply only to the ground operators and maintainers and the main source of data for hidden failures during flight can only be provided by telemetry. Finally, because sensor technology is rapidly developing and easily implemented due to low cost, the reliability tracking and improvement system for SUAVs must be easily adaptable to changes.

From the above we can construct the following table which summarizes the basic differences between the MSG-3 and FMEA/FMECA methods with respect to SUAVs:

	SUAVs	RCM MSG-3	FMEA/ FMECA
1	Reliability improvement needed	**X**	**X**
2	Mission and cost oriented		**X**
3	Operational testing and development phase		**X**
4	Rapid changes in technology		**X**
5	Inexpensive and easily adapted methodology		**X**
6	Telemetry is used a lot (Hidden failure difficult to identify)		**X**
7	Safety for operating personnel is not a critical issue		**X**
8	Experienced personnel difficult to find		**X**
9	Human factors for GCS is critical	**X**	**X**

Table 5. Comparing RCM MSG-3 and FMEA/FMECA for SUAVs.

So, the main considerations about RCM implementation for SUAVs are:

(1) Safety has an important role in RCM methodology because of the nature of civil aviation. The primary goal for civil aviation is to transport people and goods safely. Safety standards and strict rules are the top priority and, so they become a priority in RCM analysis. For industries where RCM has been applied, safety has almost the same role as in the aviation case because of strict regulations and standards for the operators and the employees. In the UAV case, however, there are no people onboard, so safety for travelers and crew is not as critical an issue.

(2) In the RCM process, the key factor for the initial identification of the hidden failure is the flight crew. In the UAV case, there is no crew aboard and so there is no chance for crew to sense hidden failures. The only indication that might be available is the platforms' control sensors reading while in-flight and the system's performance while a platform is tested on the ground prior to take-off.

(3) Experience gained in civil aviation cannot be applied directly to UAVs.

From the above it is clear that RCM MSG-3 is not suitable for SUAVs. These leaves fault tree analysis and FMEA as the remaining methods. We develop both in detail for the SUAV in the subsequent chapters of this thesis.

B. SMALL UAV RELIABILITY MODELING

During recent urban operations in Iraq and Afghanistan, SUAVs that provide over-the-hill or around-the-corner information were invaluable for operating teams. Some systems have been tested with very good results, but controversy surrounds the capabilities of such systems. A generic SUAV system must provide military forces with real-time around the clock surveillance, target acquisition, and battle assessment. Such a system must be capable of detecting any desired tactical information in a designated sector.

Each service component (Navy, Army, and Marines) requires versatile, easy to handle, and user-friendly systems that enable the commander to conduct reconnaissance on the battlefield in real-time. SUAVs are being seriously considered for this role. This entails a small-scale operation over a city block, or more extensive surveillance missions. Requirements of the system include locating and identifying targets, then relaying the information to a higher command. The detection accuracy should be sufficient to select and to deploy weapons, and then to maintain contact after engagement with such weapons. The system must be able to survey a large area rapidly using multiple platforms simultaneously. The configuration of the system should enhance the fighting capabilities of the force, minimizing the time for precise control movements and maximizing mobility, robustness and functionality. Due to previous experience with similar systems, reliability and interoperability are most important considerations.

1. System’s High Level Functional Architecture

As illustrated in Figure 4, SUAV battlefield systems high-level architecture consists of the following:

(1). Platform(s)

(a) Navigation with Global Positioning System (GPS) and Inertial Navigation System (INS)

(b) Flight control with remote manual, semi-auto, and full-auto (autonomous) mode of operation

(c) Onboard computer (OBC)

(d) Payload with the appropriate sensors for the type of mission

(2). Ground control station (GCS) with command, monitor and support capabilities.[117] This may be shipboard or land-based.

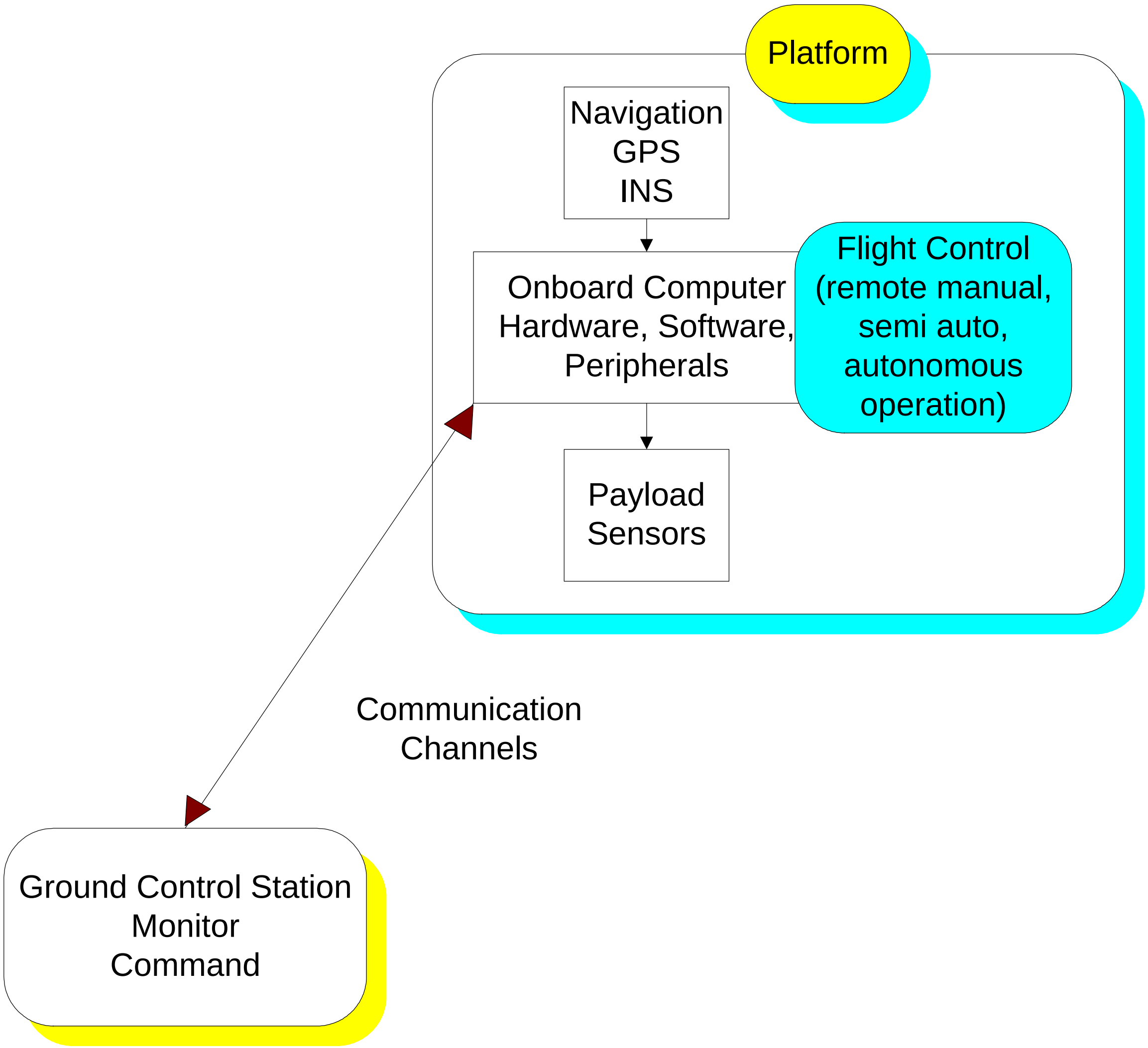

Figure 4. High Level Architecture of a SUAV System (After Fei-Bin)

For more detailed system architecture, refer to Figure 5:

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[117] Fei-Bin, Hsiao, and others, ICAS 2002, 23rd International Congress of Aeronautical Sciences, proceedings, Toronto Canada, 8 to 13 September, 2002, Article: "The Development of a Low Cost Autonomous UAV System", Institute of Aeronautics National Cheng Kung University Tainan, TAIWAN ROC.

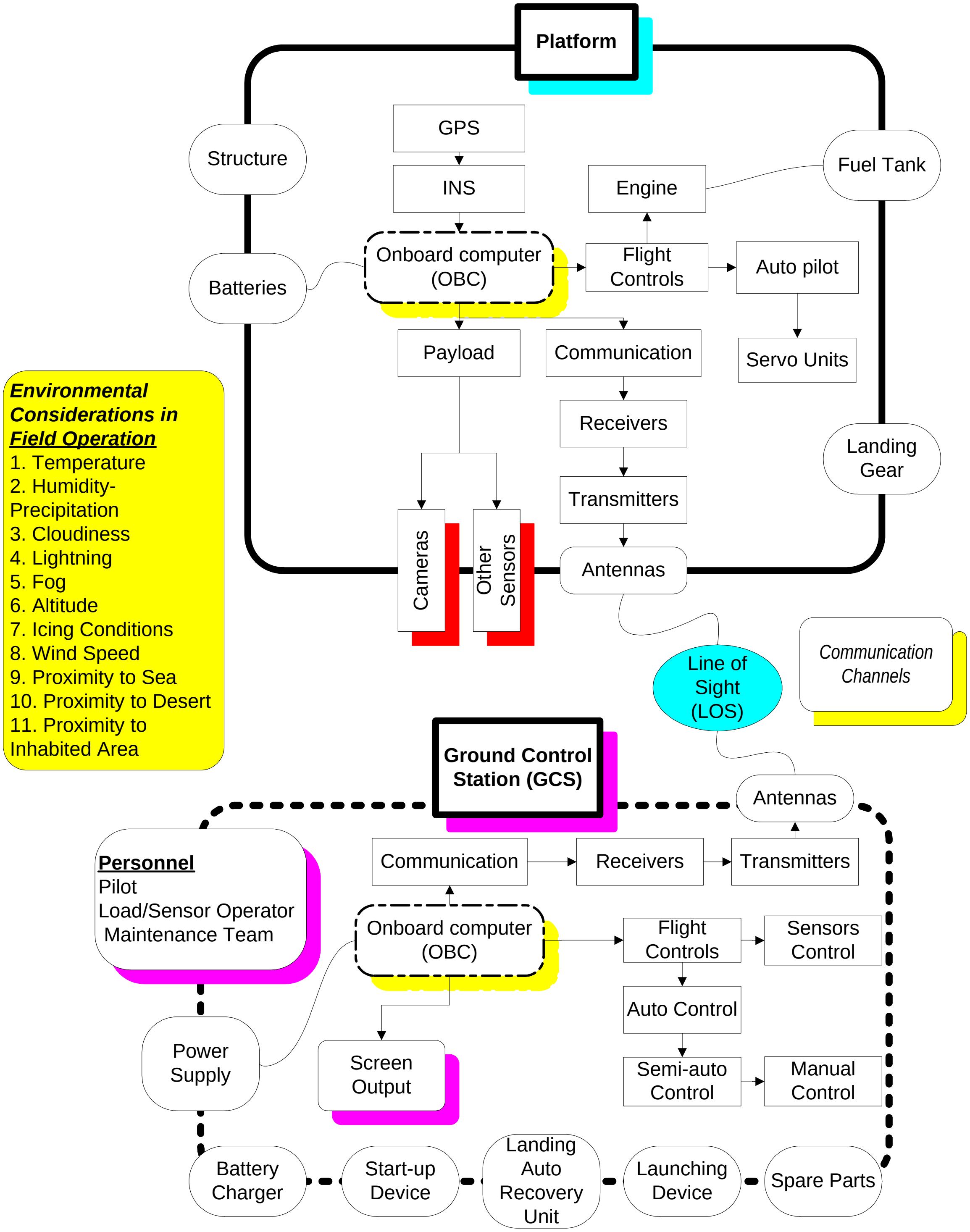

Figure 5. Simple Block Diagram of a SUAV System

For the platform's configuration, weight and volume are critical factors because of the limited size and the flight characteristics of the platform. The system is a complex one and reliability plays an important role for the operational effectiveness of the system. In general, there are two ways to increase reliability: Fault tolerance and fault avoidance.[118]

(1) Fault tolerance can be accomplished through redundancy in hardware and/or in software. The disadvantage is that it increases the complexity of an already complex system, as well as increasing equipment costs, volume, weight, and power consumption.

(2) Fault avoidance can be accomplished by improving reliability of certain components that constitute the system. In general, those components that contribute the most to reliability degradation are the most critical for fault avoidance.

The SUAV system cannot implement fault tolerance, at least for the platforms, so fault avoidance is the better approach. To achieve this, at first we must conduct an FMEA in order to define and to identify each subsystem function and its associated failure modes for each functional output.

In order to proceed in the FMEA, as analysts we will need the following:

(1) System definition and functional breakdown,

(2) Block diagram of the system,

(3) Theory of operation,

(4) Ground rules and assumptions,

(5) Software specifications.

As a second step, we conduct a criticality analysis in order to identify those mission critical elements that cause potential failures and weaknesses.

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[118] Reliability Analysis Center (RAC), *Reliability Toolkit: Commercial Practices Edition. A Practical Guide for Commercial Products and Military Systems Under Acquisition Reform*, 2004, page 115.

To perform these analyses, we will use the qualitative approach due to lack of failure rate data and a lack of the appropriate level of detail for part configuration.[119]

2. System Overview

The airborne system comprises the aerial platform and an onboard system. The ground system comprises a PC and a modem to communicate with the airborne system. All the onboard hardware is packed in a suitable model platform powered by a 1.5 kilowatts (kw) aviation fuel (JP-5) engine with a wingspan of 1.5 meters (m) and a fuselage diameter of 12 centimeters (cm). The sensor's payload is about two kilograms (kg).

The onboard computing system is being developed on a PC based single-board-computer. The onboard computer (OBC) is a multi-tasking real time operating system. The OBC can obtain data from the GPS, the INS, the communication system and the onboard flight and mission sensors. It computes the flight control and navigation algorithms, commands the sensor payload, and stores and downlinks data to the GCS in near real-time operation.

The GCS PC is the equivalent of a pilot's cockpit. It can display in near real time the status of the flying UAV or UAVs including:

- UAV(s) position and GCS position
- Speed
- Altitude
- Course
- Attitude and system health in visual pilot-like instruments
- The actual position can also be displayed on an electronic moving map.
- Output from the mission sensors such as near real time imagery displayed from various types of cameras like CCD, infrared (IR) and others.

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[119] Reliability Analysis Center (RAC), *Failure Mode, Effects and Criticality Analysis (FMECA)*, 1993, pages 9-13.

3. System Definition

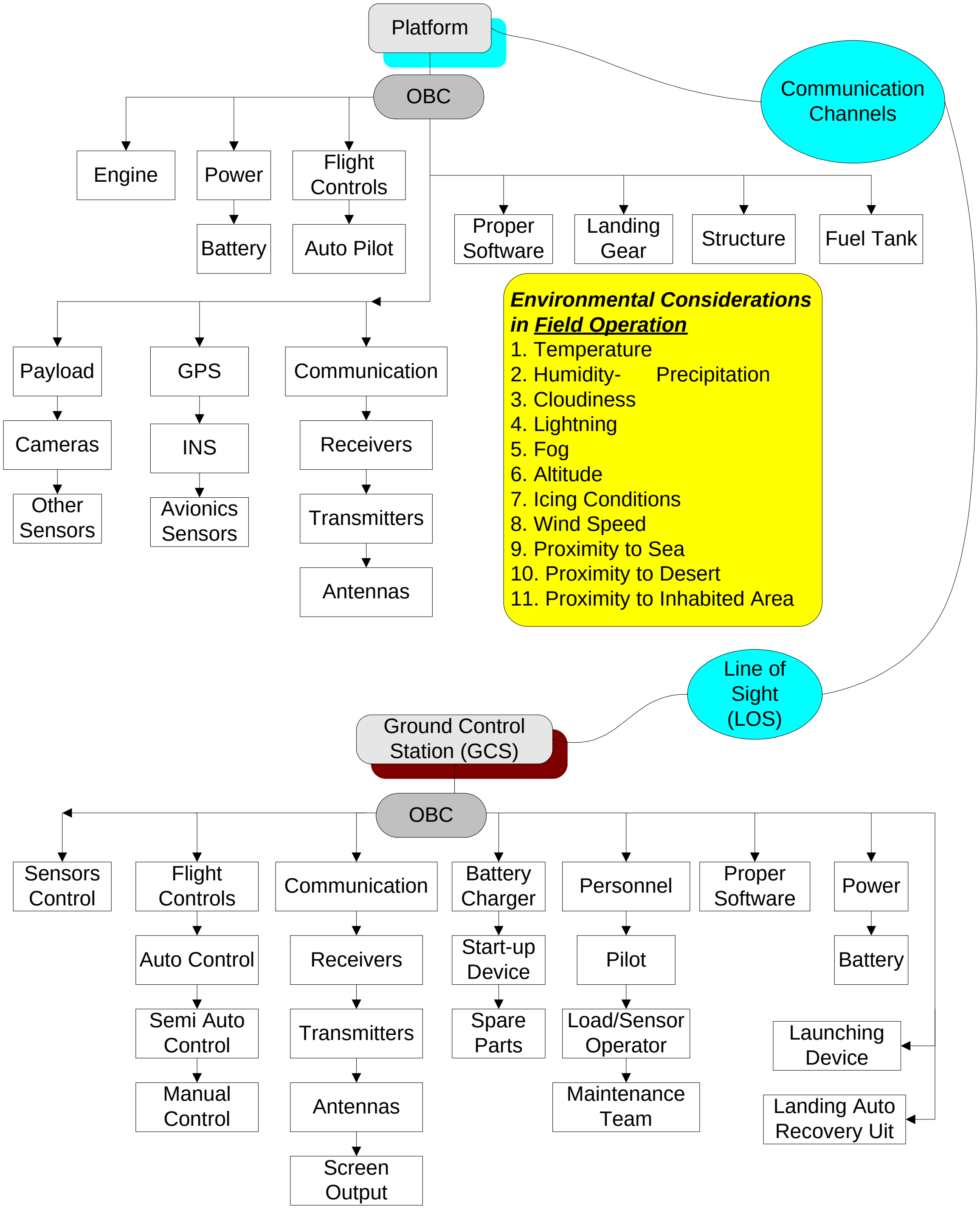

Figure 6. Simple Block Functional Diagram of a SUAV System

Using the diagram in Figure 6, we give the following functional definitions to each element in the diagram.

Platform Structure: The flying physical asset responsible for integration of all the necessary equipment for the mission profile.

Antennas: Responsible for conducting the transmitted and received signals to/from the GCS and passing them from/to transmitters or receivers and the appropriate communication hardware and software.

Payload, Cameras and Other Sensors: The actual physical assets for the type of desired mission consisting mainly of cameras and other special sensors like NBC agent detectors, magnetic disturbance, detectors, and much more.

GPS: The primary navigation system based on a satellite network known as the Global Positioning System.

INS: The support navigation system based on the inertial calculations of current speed and course in order to provide an accurate platform fix that will be used for piloting the platform and for target tracking.

Engine: The unit responsible for providing mechanical power be used in conjunction with the propeller to provide thrust to the platform.

Battery: The electric power supply asset for the entire platform’s equipment service.

Flight Controls: The necessary flight sensors, like pittot tubes, hardware, ailerons, elevators, rudder, the relevant servo units and the flight controller together with the right software for manual, semi-auto and autonomous flight.

Proper Software: The necessary software for platform mission control.

Landing Gear: Responsible for platform mobility in ground during takeoff and landing. Not mandatory for use.

Fuel Tank: Storage of fuel necessary for engine operation.

GCS: The manned shipboard or land-based component of the system responsible for command, control communication and support system center.

GCS Flight Controls: The GCS hardware and software for flight controls.

Sensors Control: Main factor responsible for mission performance. Manually operated with auto capabilities.

Screen Output: The outcome of the systems' performance presented on a monitor with all the relevant information for the mission and the system.

GCS Antennas: Conducts the transmitted and received signals to and from the platform and other centers related to the mission and passes them to/from transmitters or receivers and the appropriate communication hardware and software.

GCS Proper Software: The necessary software for GCS mission control.

Battery Charger: Charges the platform battery.

Start-up Device: Responsible for the initial start up of the engine's platform prior to takeoff.

Spare Parts: Necessary items for operating and supporting the system.

Power Supply: Generator and batteries that provide the GCS electric power.

Personnel: A pilot, a load/sensor operator, and maintainers who man the system for one shift.

Launching Device: Launches the platform.

Landing Auto Recovery Unit: Provides auto guidance to the platforms for auto-landings.

4. System Critical Functions Analysis

The SUAV essential functions analysis can be seen in Table 6.

Item	**Essential Functions**	**Mission Phases**						
		Stand-by	**Launch**	**Cruise to Area of Interest**	**On Station**	**Cruise Back to Base**	**Land**	**Off Station**
	Flight							
1	Provide structural integrity	x	x	x	x	x	x	x
2	Provide lift and thrust		x	x	x	x	x	
	Provide controlled flight							
3	Manual control		x	x	x	x	x	
4	Semi auto		x	x	x	x	x	
5	Auto		x	x	x	x	x	
6	Navigate			x	x	x	x	
7	Provide power to control and navigation equipment	x	x	x	x	x	x	
8	Withstand environmental factors (mainly wind)			x	x	x	x	
	Mission							
9	Start systems	x						
10	System's backup	x						x
11	Communications		x	x	x	x		
12	Line of sight			x	x	x	x	
13	Provide power to sensors and communications			x	x	x	x	
14	Detect, locate and identify targets			x	x	x		
15	Provide data			x	x	x		
16	Provide video image			x	x	x		
17	Monitor system's functions	x	x	x	x	x	x	x

Table 6. System's Essential Functions Analysis

5. System Functions

The mission phase consists of the following functions:

- Launch the platform
- Fly the platform
- Control, Command and Communicate with the platform
- Control, Command and Communicate with the platform sensors
- Perform surveillance and reconnaissance
- Detect targets
- Identify targets
- Classify targets
- Track targets
- Perform battle assessment
- Know platform's position
- Sustain flight mission for a certain time at a certain altitude at a certain speed and on a certain course
- Return to base and land safely
- Service the platform at a certain time and set it ready for the next mission

These functions are the primary drivers for software development and among the factors for the hardware selection.

6. Fault Tree Analysis

In the following fault-tree analysis of a SUAV system a top-down analysis has been used to reveal the failure causes. The sub-analyses end with a circle, which means that further analyses are needed at a more detailed level, or end with a diamond, which means that the analysis stops there. Due to a lack of data, only the mechanical engine failure has been analyzed at more than one level. Using that analysis we formulate a model to use as an example for further analysis.

7. Loss of Mission

The first attempt for the fault-tree analysis should be the loss of the mission tree. The reasons for mission loss may be:

(1) Loss of platform

(2) Loss of GCS

(3) Unable to locate platform (loss of platform's position)

(4) Inappropriate mission for the sensors (wrong choice of sensors)

(5) Sensor(s) failure

(6) Unable to launch platforms for various reasons, such as weather or launching device failure

(7) Unable to communicate with the platform

(8) Loss of the operator(s)

(9) Loss of the onboard platform's or GCS's computer

(10) For out-of-the system reasons, such as weather conditions or situational reasons.

Figure 7 illustrates the tree analysis for loss of mission.

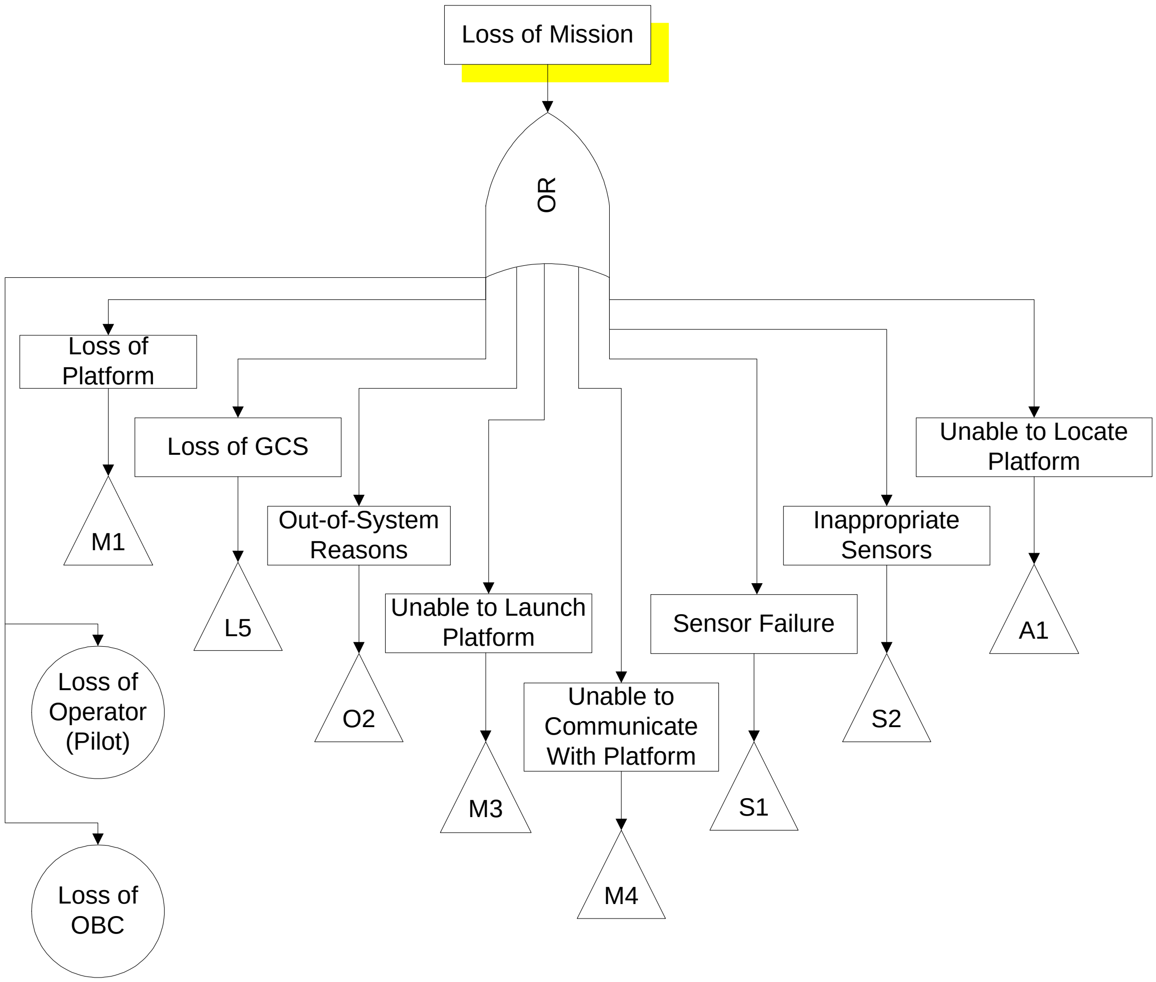

Figure 7. Loss of Mission

8. Loss of Platform

The reasons for loss of platform may be:

(1) Loss of platform’s structural integrity

(2) Loss of platform’s lift

(3) Loss of thrust

(4) Loss of platform’s control

(5) Loss of GCS

(6) Loss of platform’s position

Figure 8 illustrates the tree analysis for loss of platform.

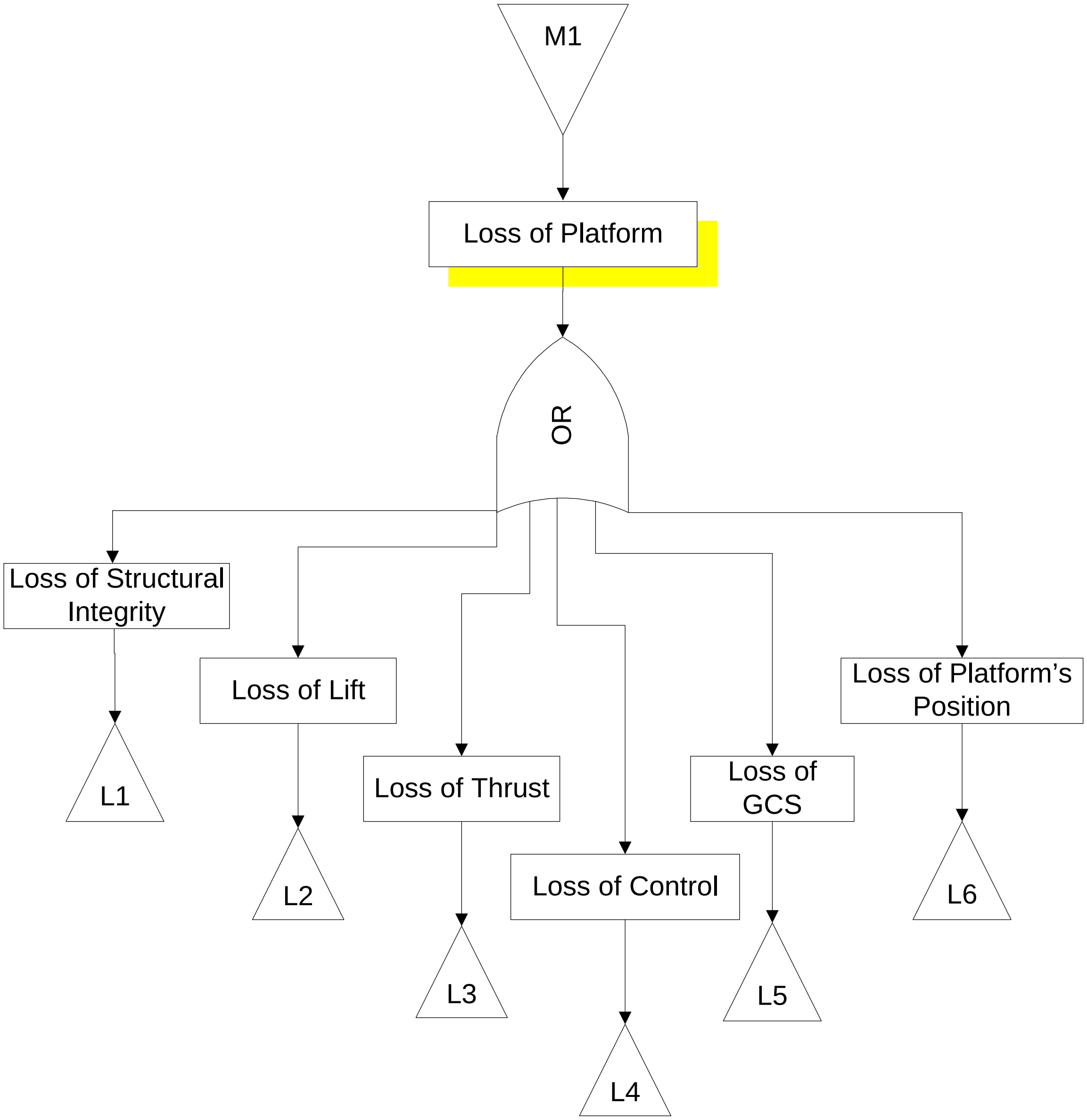

Figure 8. Loss of Platform

9. Loss of GCS

The reasons for loss of GCS may be:

(1) GCS software failure

(2) Loss of OBC

(3) Loss of GCS power

(4) Loss of GCS communication

(5) Loss of GCS personnel

(6) Environmental reasons (e.g. heavy weather conditions, earthquake)

(7) Fire

Figure 9 presents the tree analysis for loss of GCS.

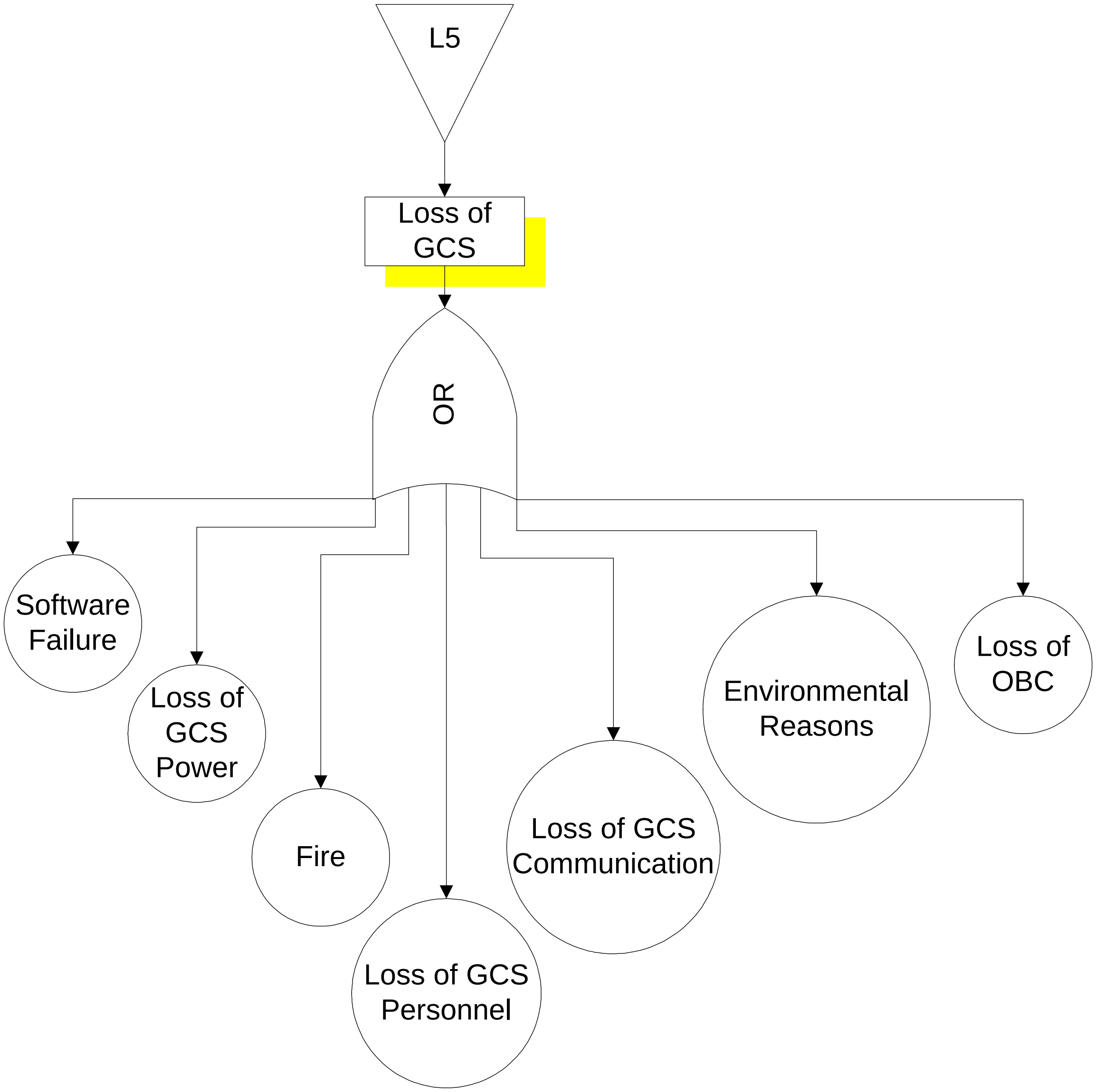

Figure 9. Loss of GCS

10. Loss of Platform’s Structural Integrity

The reasons for loss of platform’s structural integrity include fuselage, wing, or empennage related problems, which could be due to:

(1) Fracture

(2) Pressure overload

(3) Thermal weakening

(4) Delamination or fiber buckling

(5) Structural connection failure or

(6) Operator error.

Figure 10 contains the fault-tree analysis for loss of platform’s structural integrity.

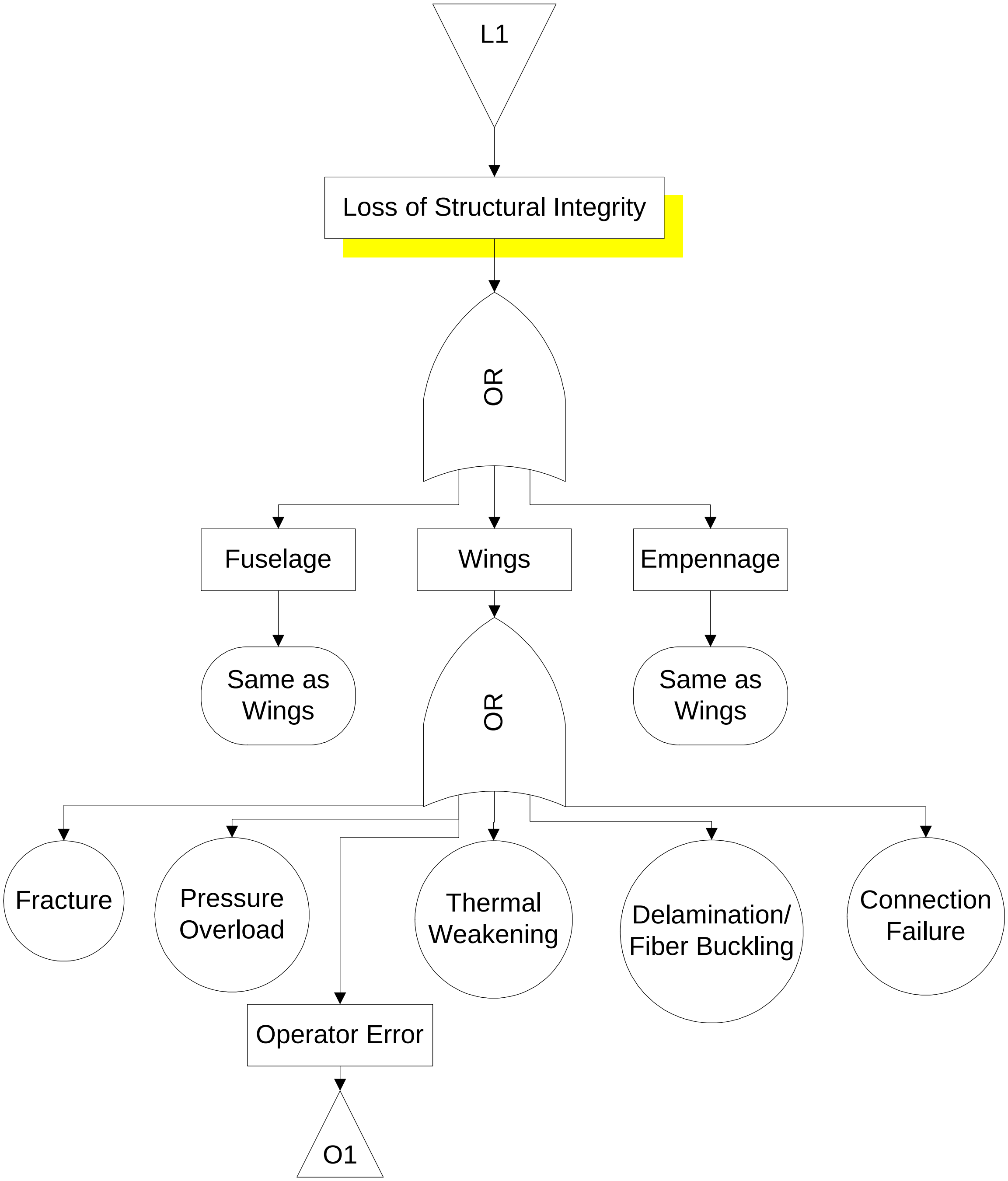

Figure 10. Loss of Structural Integrity

11. Loss of Lift

Reasons for loss of lift may be:

(1) Loss of thrust

(2) Operator error, or

(3) Loss of wing surface, which could be due to loss of right or left wing surface, which in turn could be due to:

(a) Fracture removal

(b) Pressure overload

(c) Thermal weakening

(d) Delamination or fiber buckling

(e) Structural connection failure or

(f) Operator error

Figure 11 shows the fault-tree analysis for loss of lift.

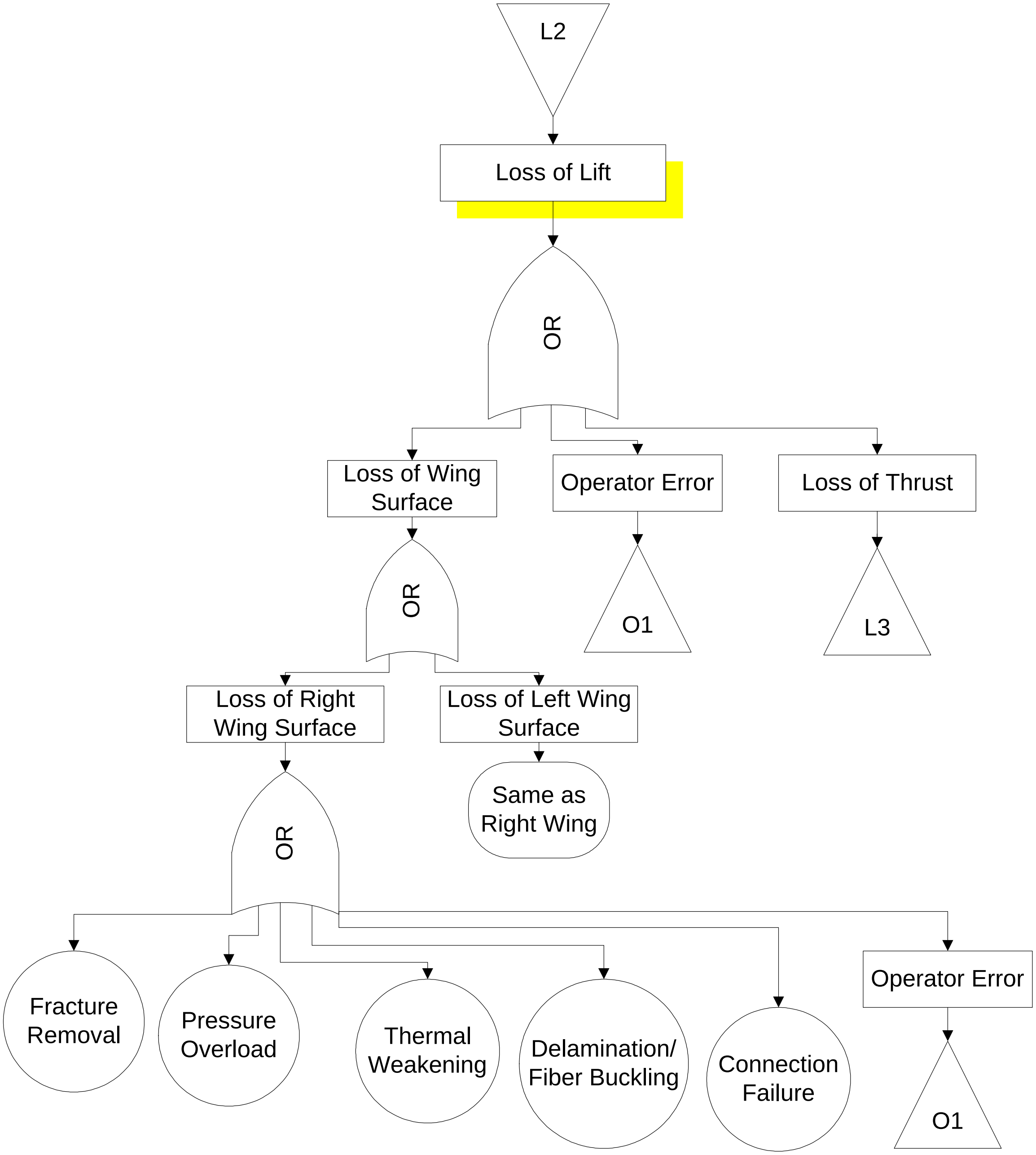

Figure 11. Loss of Lift

12. Loss of Thrust

Reasons for loss of thrust may be:

(1) Loss of engine control

(2) Operator error

(3) Loss of propeller that could be due to:

  (a) Propeller structural failure

  (b) Propeller disconnection

  (c) Operator error

(4) Loss of engine, which could be due to:

  (a) Engine failure

  (b) Engine stalling, which could be due to:

    ((1)) Failure of fuel system

    ((2)) Operator error

    ((3)) Air filter failure

    ((4)) Air filter clogged

    ((5)) Engine control failure

Figure 12 shows the tree analysis for loss of thrust.

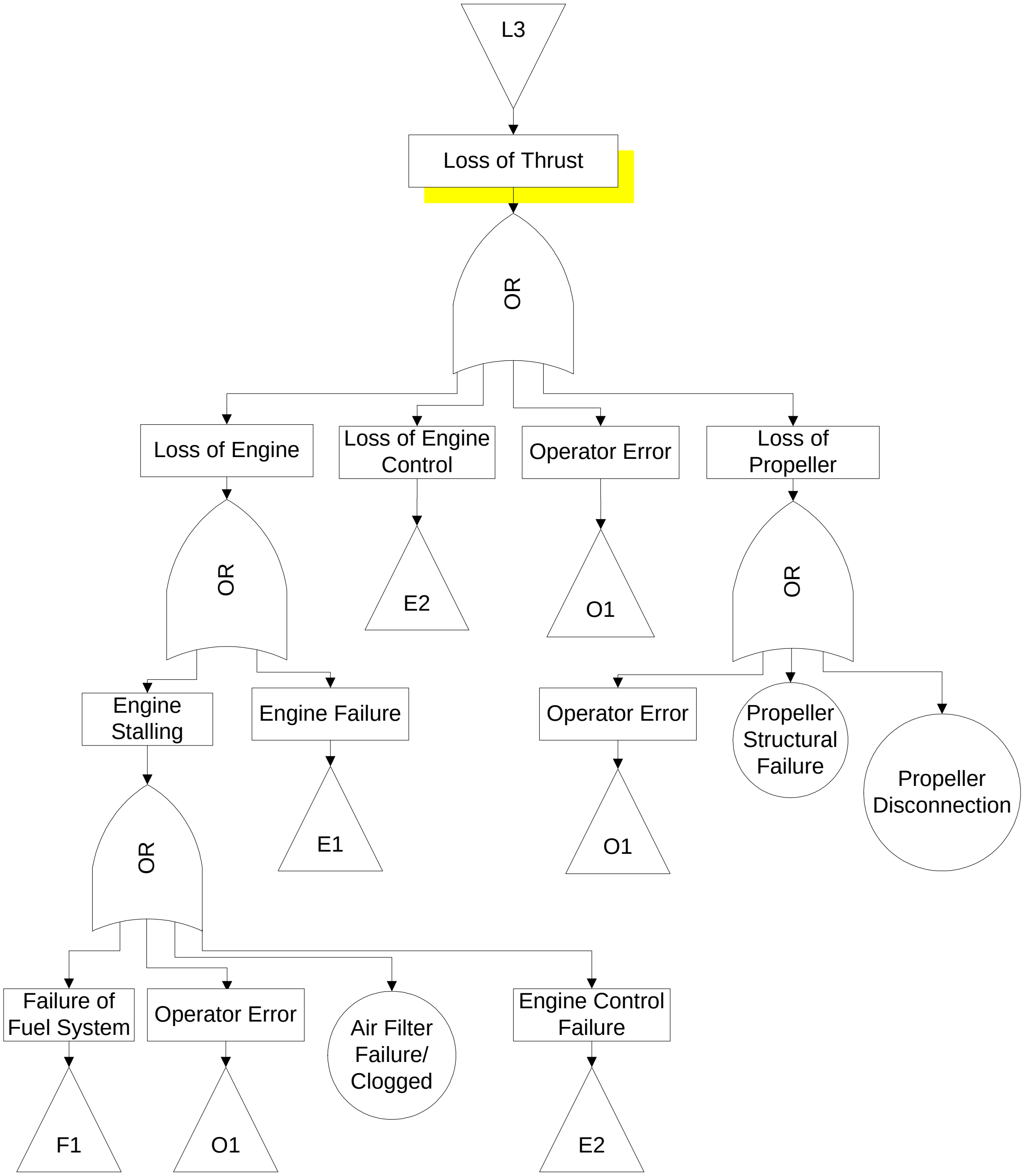

Figure 12. Loss of Thrust

13. Loss of Platform Control

Reasons for loss of control may be:

- (1) Loss of lift
- (2) Loss of control channel
- (3) Loss of power, which could be due to:
  - (a) Total loss of platform’s power
  - (b) Loss of control unit power
- (4) Loss of aileron forces that could be due to:
  - (a) Loss of left wing aileron force that could be due to:
    - ((1)) Loss of onboard computer (OBC)
    - ((2)) Disruption of control cables
    - ((3)) Loss of servo unit
    - ((4)) Loss of aileron surface
  - (b) Loss of right-wing aileron force for the same as the left-wing aileron reasons
- (5) Loss of rudder force for the same as the left-wing aileron reasons
- (6) Loss of elevator force for the same as the left-wing aileron reasons

Figure 13 illustrates the tree analysis for loss of platform’s control.

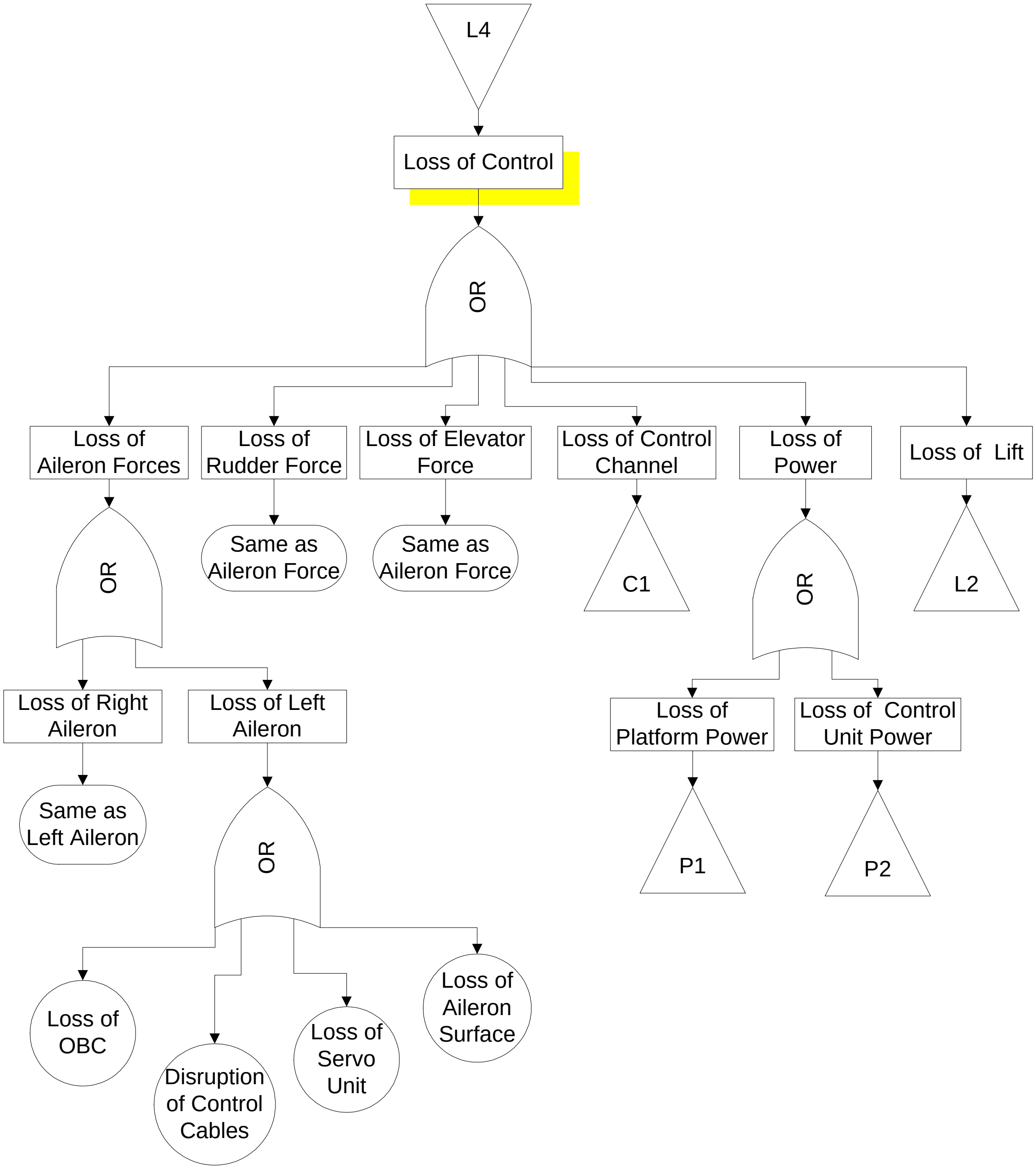

Figure 13. Loss of Platform's Control

14. Loss of Platform Position

Reasons for loss of platform position may be:

(1) Loss of line of sight (LOS)

(2) Loss of INS backup

(3) Loss of GPS unit

(4) Loss of GPS antenna

(5) Loss of GPS signal

(6) Platform failure to transmit

Figure 14 shows the tree analysis for loss of platform's position:

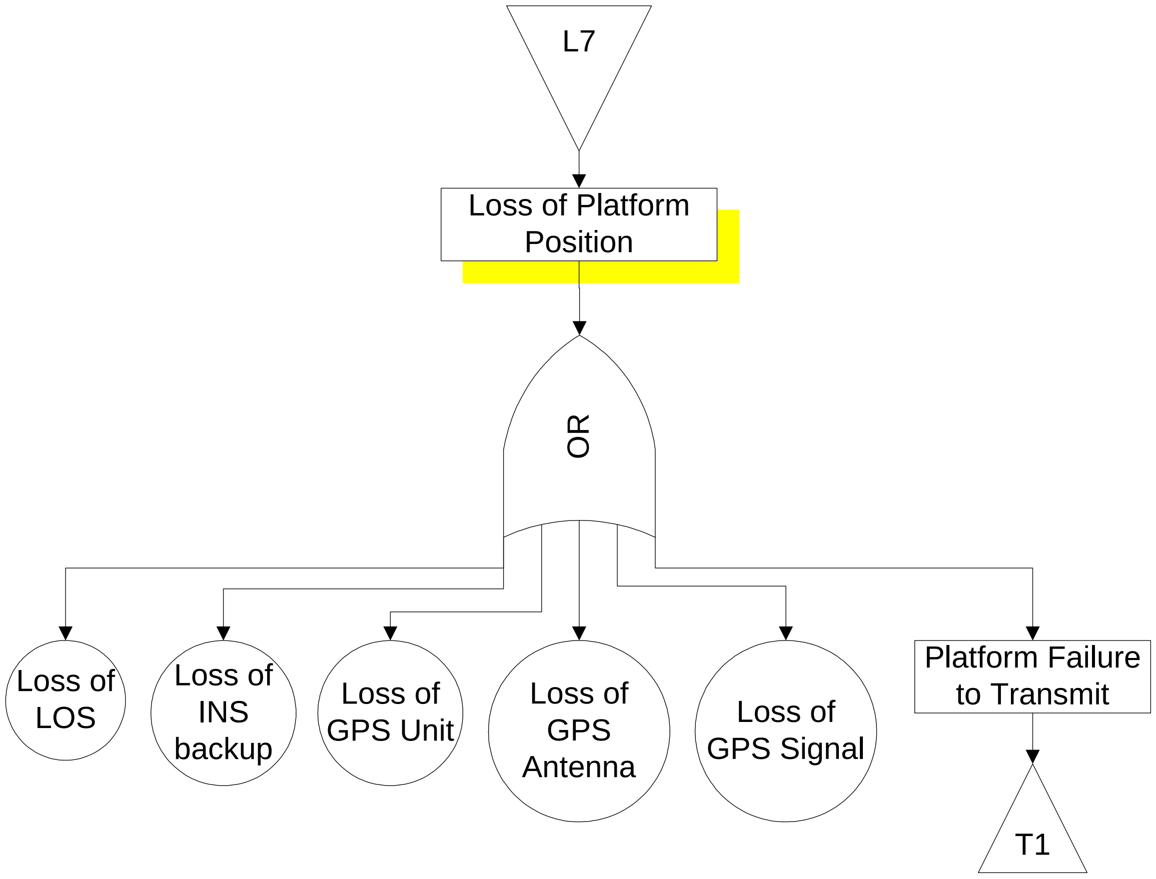

Figure 14. Loss of Platform's Position

15. Loss of Control Channel

The reasons for loss-of-control channel may be:

(1) Operator or pilot control panel failure

(2) Loss of LOS

(3) Failure of control receiver

(4) Failure of GCS control transmitter

(5) Loss of power, which could be due to:

  (a) Loss of platform’s power

  (b) Loss of GCS power

(6) Loss of platform control antenna, which could be due to:

  (a) Antenna disconnection

  (b) Short-circuit in antenna

  (c) Antenna failure

  (d) Structural damage

(7) Loss of GCS control antenna the same as reasons for loss of platform control antenna

Figure 15 illustrates the tree analysis for loss of control channel.

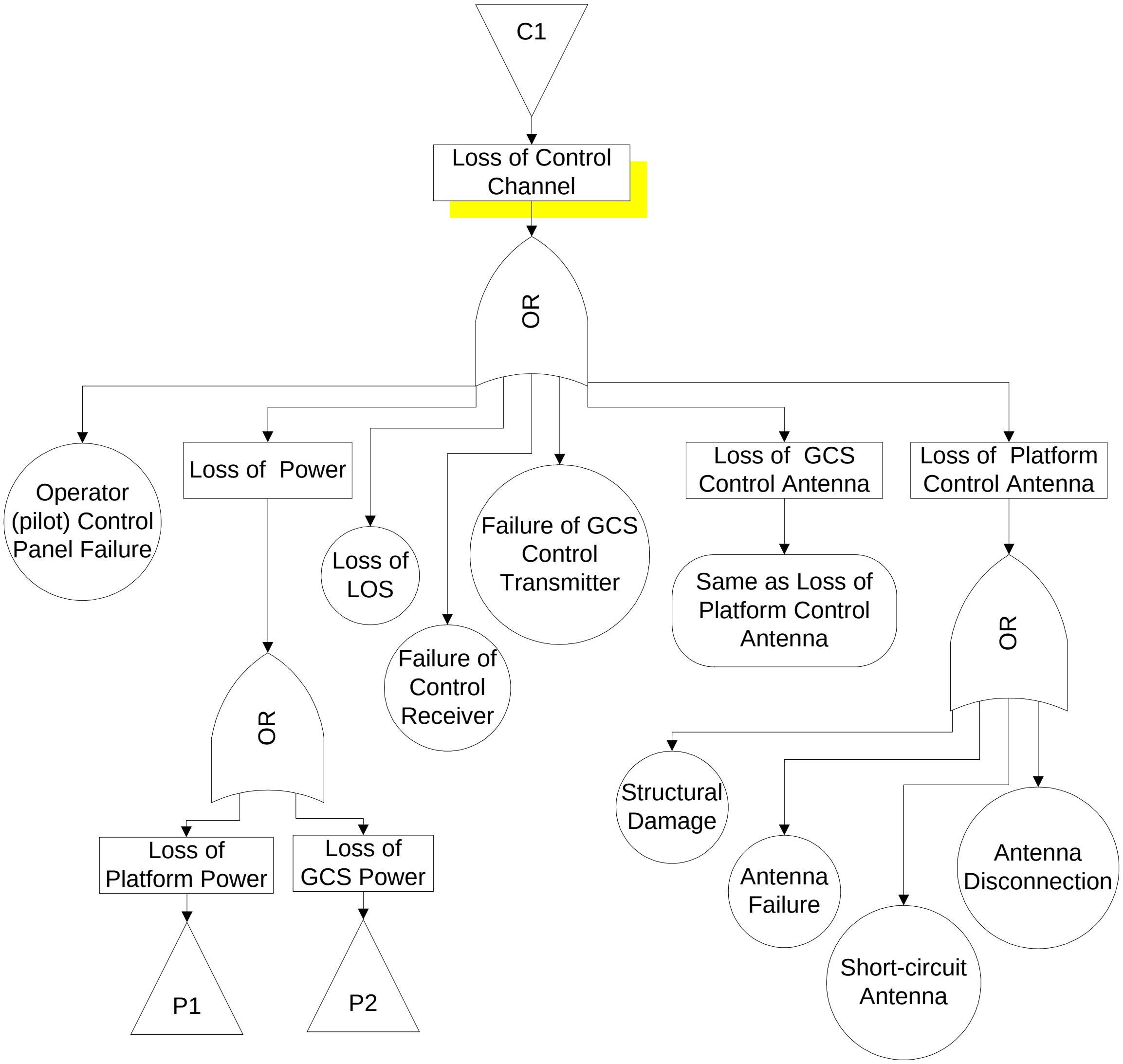

Figure 15. Loss of Control Channel

16. Engine Control Failure

Engine control failure may be caused by:

(1) Disruption of control cables

(2) Loss of OBC

(3) Loss of LOS

(4) Loss of servo unit

(5) Carburetor failure

(6) Engine failure

The fault-tree analysis for engine control failure can be seen in Figure 16.

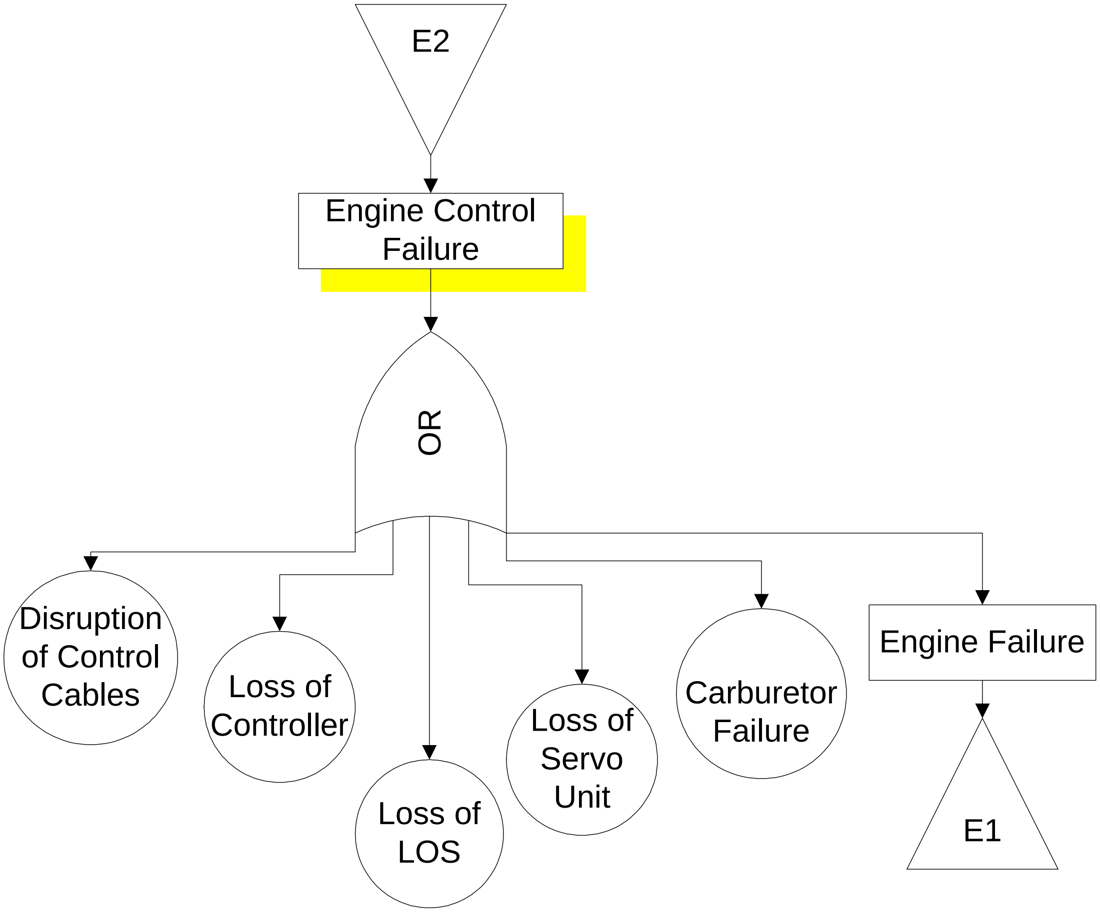

Figure 16. Engine Control Failure

17. Engine Failure

The reasons for engine failure may be:

- (1) Mechanical engine failure
- (2) Excessive engine vibration
- (3) Fuel/air improper mixture
- (4) Improper fuel
- (5) Engine fire
- (6) Loss of lubrication, which could be due to:
  - (a) Gas and lubricant improper mixture
  - (b) Excessive engine temperature rise
  - (c) Improper lubricant

The fault-tree analysis for engine failure can be seen in Figure 17.

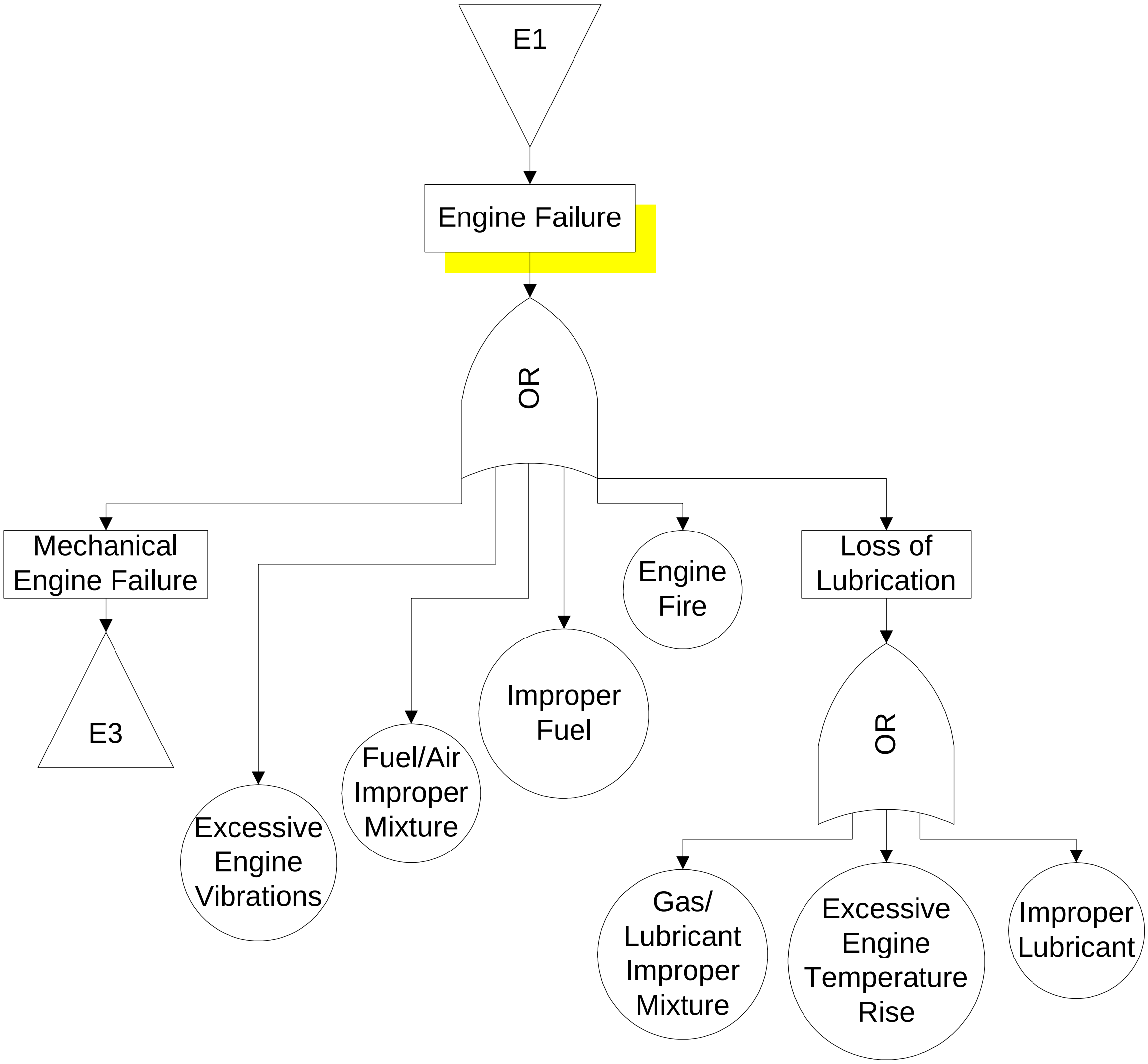

Figure 17. Engine Failure

18. Failure of Fuel System

The reasons for fuel system failure may be:

- (1) Failure of engine fuel system, which could be due to:
    - (a) Fuel pump line failure
    - (b) Fuel pump failure
    - (c) Fire
    - (d) Penetration of fuel lines
    - (e) Carburetor failure
- (2) Loss of fuel supply, which could be due to:
    - (a) Fuel tank lines failure
    - (b) Fire and/or explosion
    - (c) Fuel depletion
    - (d) Penetration of fuel lines
    - (e) Penetration of fuel tank
    - (f) Hydrodynamic ram

The fault-tree analysis for fuel system failure can be seen in Figure 18.

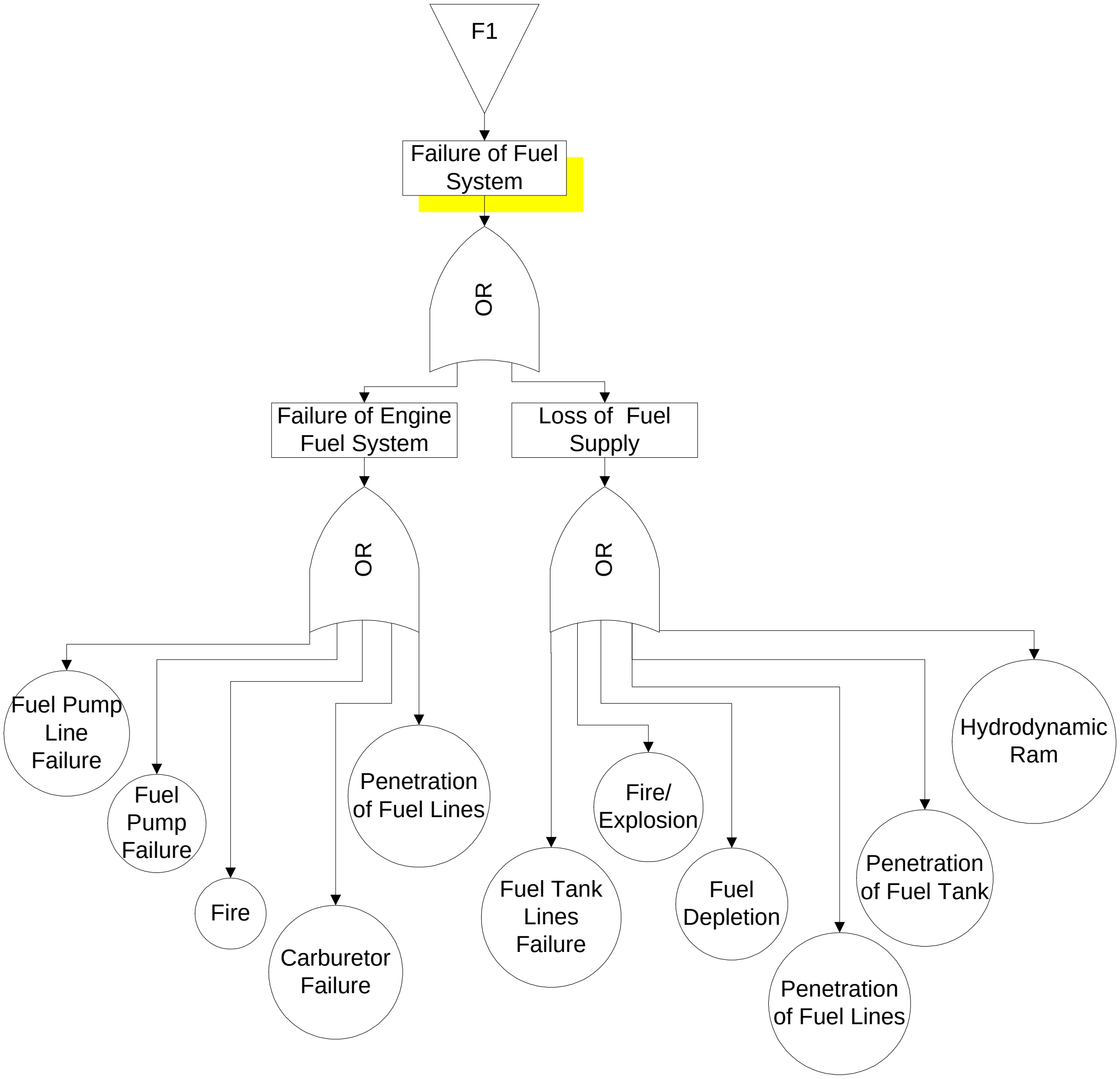

Figure 18. Fuel System Failure

19. Loss of Platform Power

The reasons for loss of platform power may be:

(1) Wiring short-circuit

(2) Fuse failure that could be due to:

    (a) Circuit problem

    (b) Improper fuse

(3) Battery failure that could be due to:

    (a) Battery discharge

    (b) Improper battery

    (c) Battery disconnection

    (d) Battery short-circuit

    (e) Battery exhaustion

    (f) Battery not fully charged

Figure 19 illustrates the fault-tree analysis for loss of platform power.

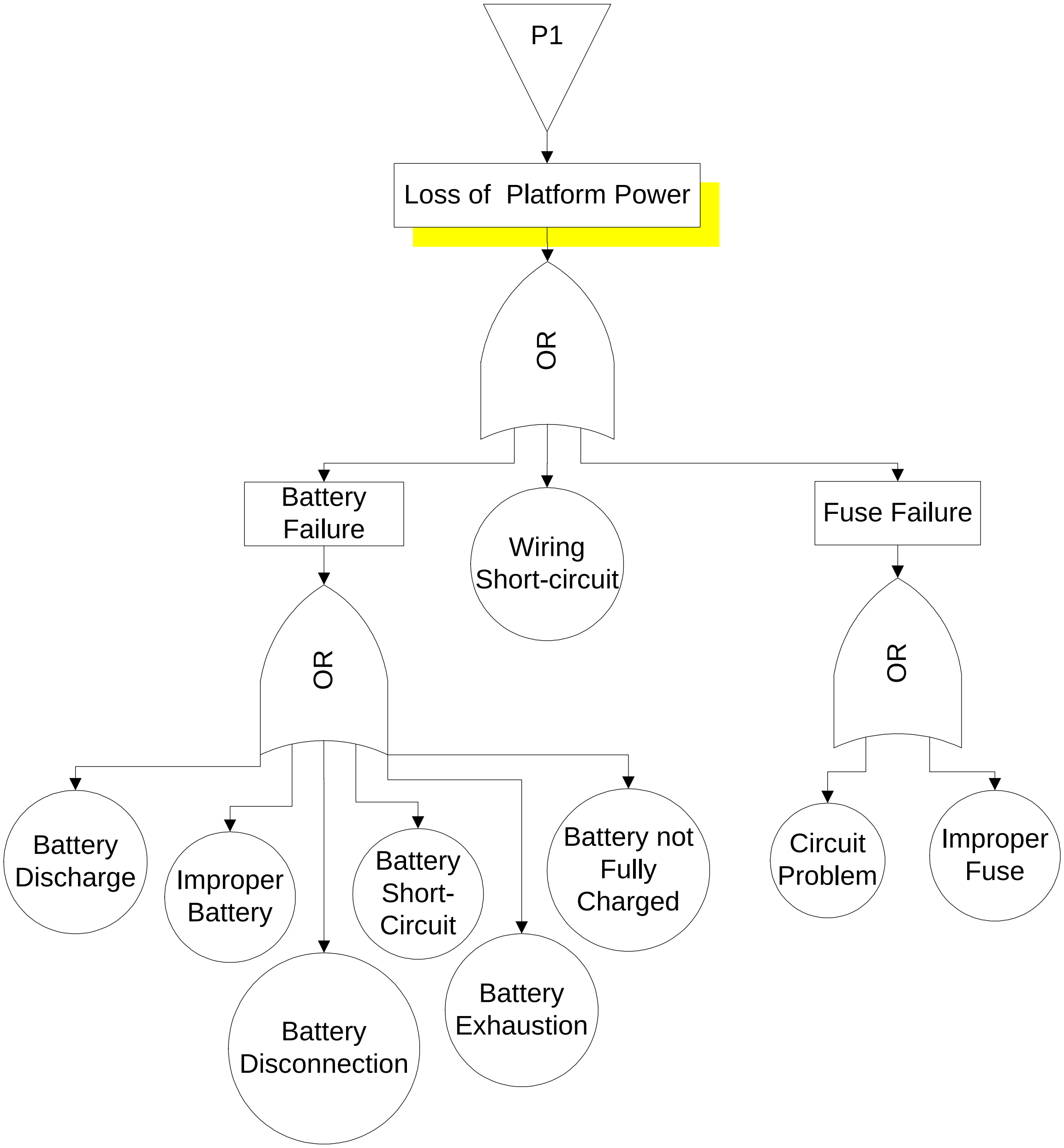

Figure 19. Loss of Platform Power

20. Loss of GCS Power

Reasons for loss of GCS power may be:

- (1) Wiring short-circuit
- (2) Fuse failure that could be due to:
  - (a) Circuit problem
  - (b) Improper fuse
- (3) Main and auxiliary power failure
- (4) Power disconnection
- (5) Loss of GCS generator

Figure 20 shows the fault-tree analysis for loss of GCS power.

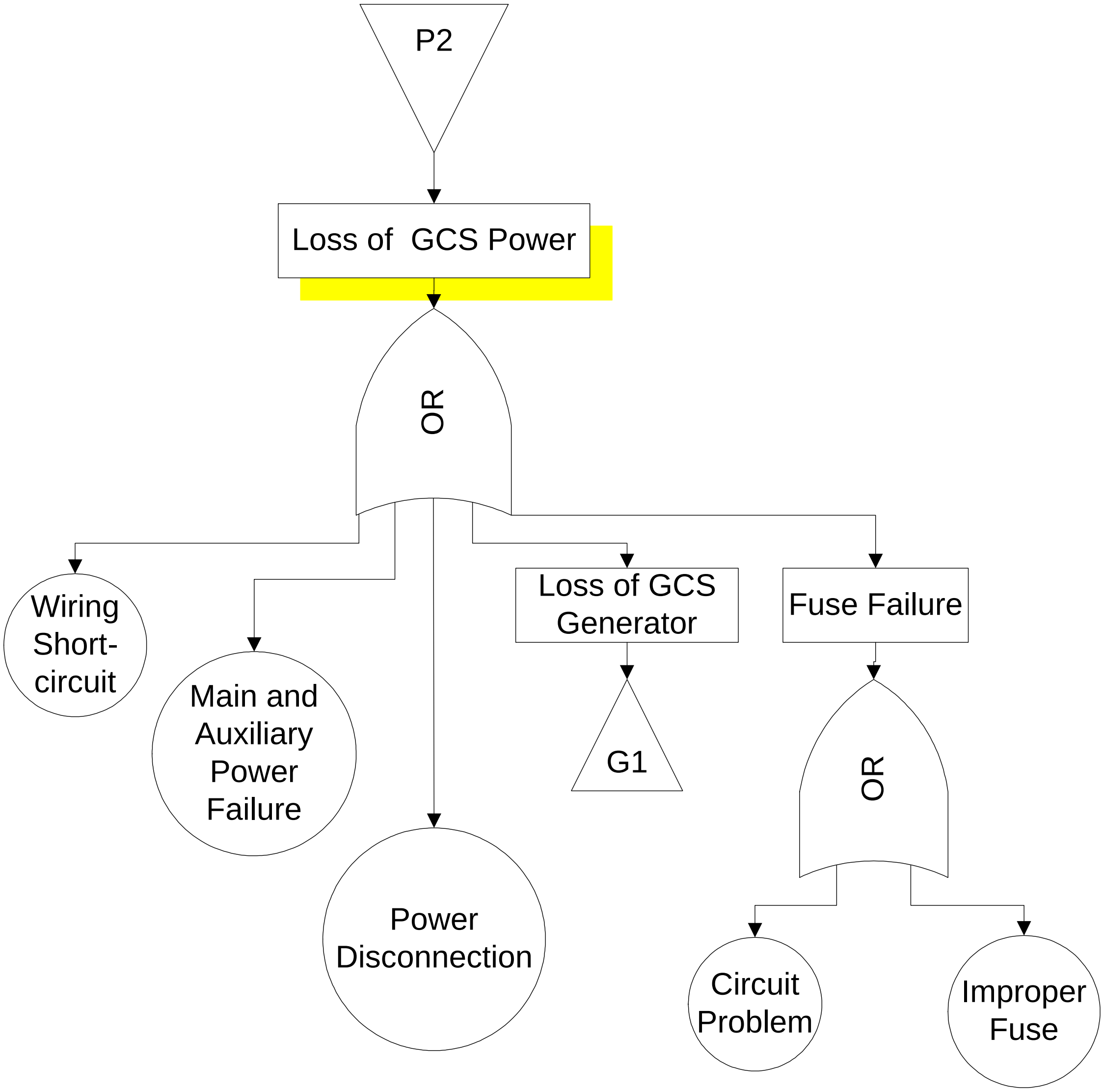

Figure 20. Loss of GCS Power

21. Operator Error

Reasons for operator error may be:

(1) Inadequate personnel training

(2) Personnel fatigue

(3) Personnel frustration and lack of experience

(4) Inadequate man machine interface

(5) Operator’s wrong reaction to failure

(6) Misjudgment due to environmental reasons (mainly weather)

(7) Poor documentation of procedures

(8) Poor workload balance resulting in task saturation with resulting loss of situational awareness

(9) Ergonomics (Human factors) of GCS

Figure 21 illustrates the fault-tree analysis for operator error.

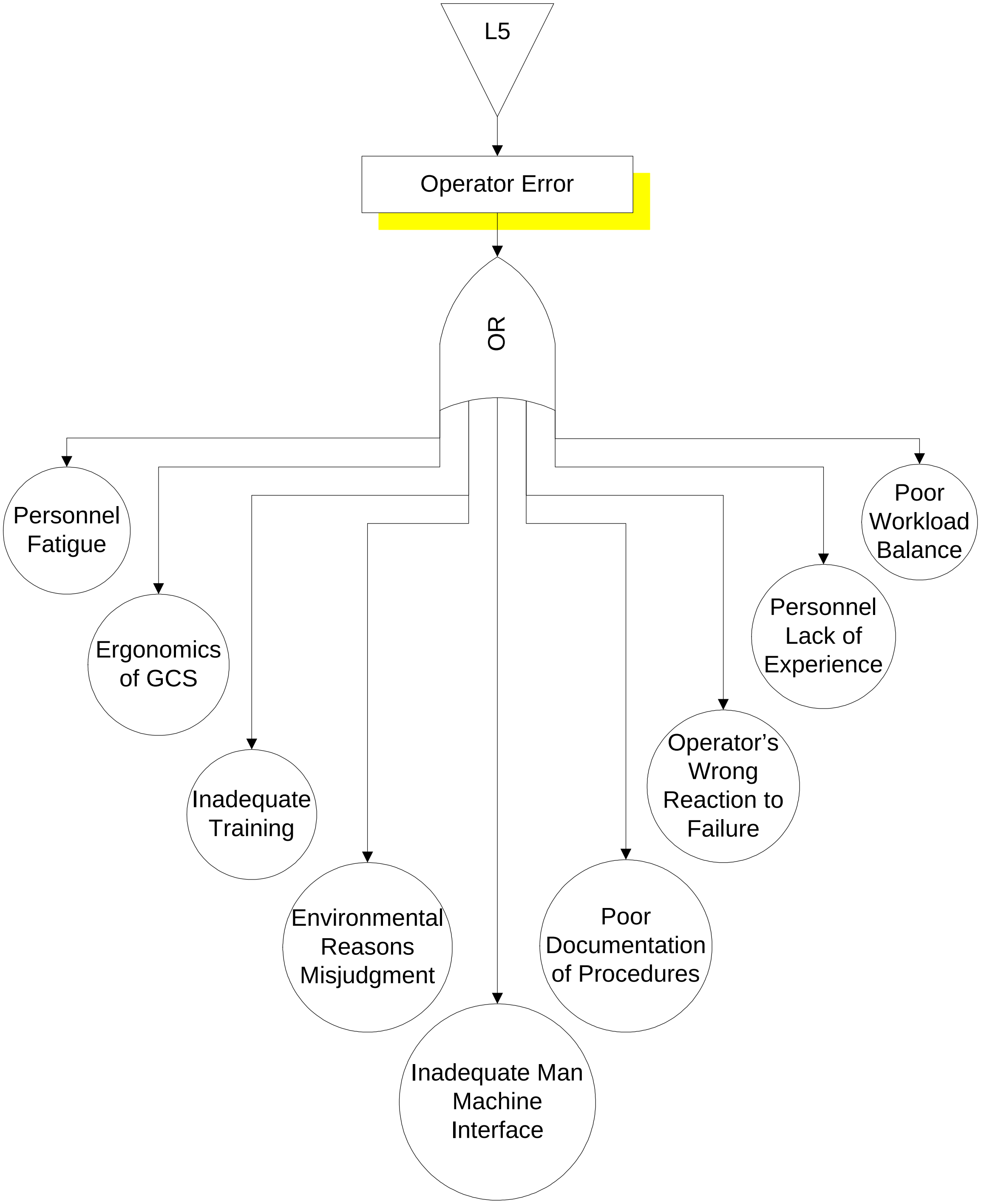

Figure 21. Operator Error

22. Mechanical Engine Failure

Reasons for mechanical engine failure may be:

(1) Bad material of engine parts:

  (a) Engine block

  (b) Cylinder head

  (c) Connecting rod(s)

  (d) Piston(s)

  (e) Piston rings

  (f) Bearings

  (g) Crankshaft

(2) Normal engine wear

(3) Bad manufacture of engine parts

(4) Bad design of the whole engine or engine parts

(5) Insufficient or bad maintenance

(6) Carburetor failure

(7) Inappropriate engine operation

(8) Overheating

(9) Crash damage, which is due to operator’s error

(10) Engine vibrations.

Figure 22 shows the fault-tree analysis for mechanical engine failure.

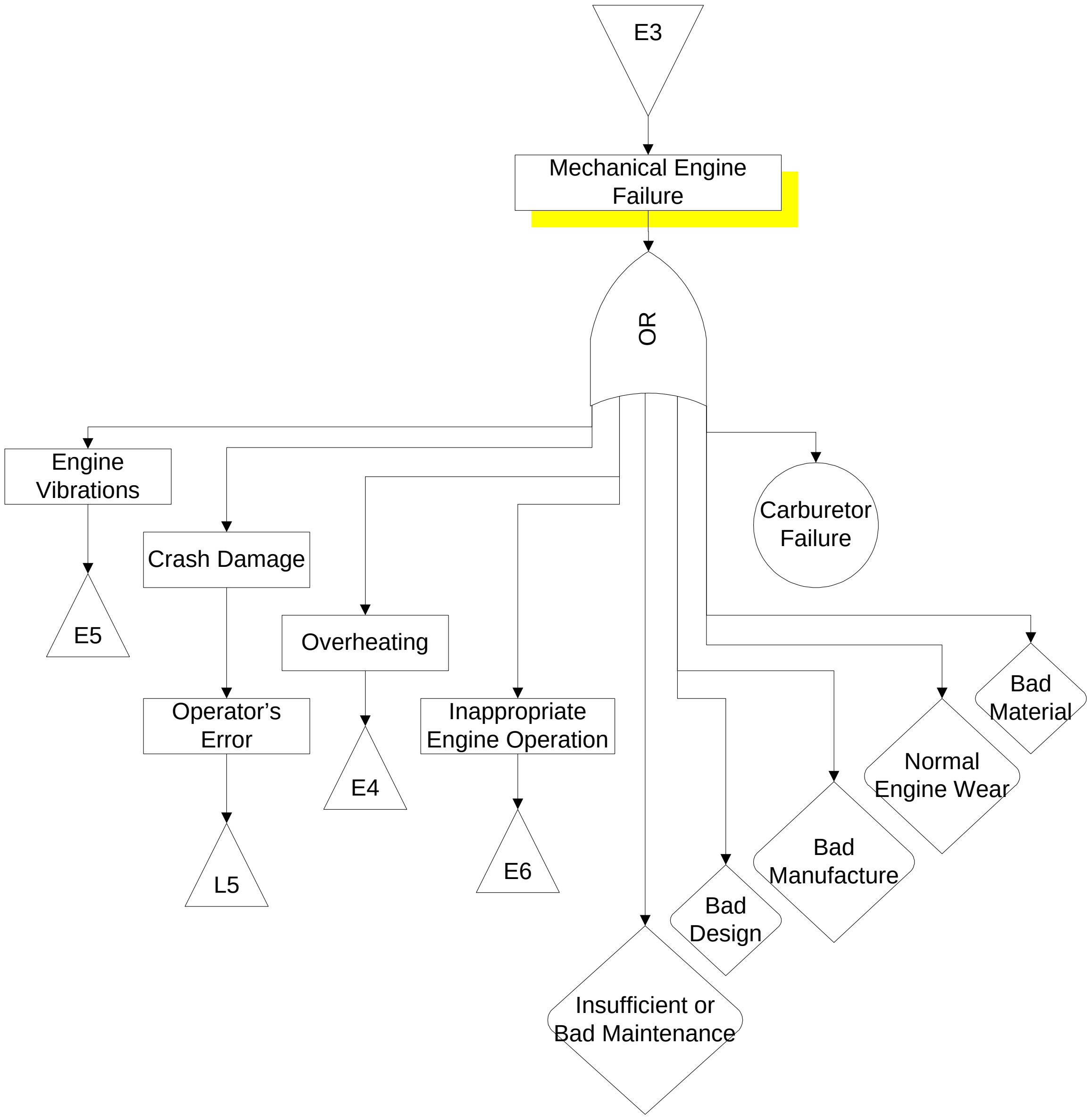

Figure 22. Mechanical Engine Failure

23. Engine Vibrations

Reasons for engine vibrations may be:

(1) Broken piston

(2) Bearing failure

(3) Broken piston rings

(4) Bad manufacture of engine parts like:

  (a) Cylinder head

  (b) Connecting rod(s)

  (c) Piston(s)

  (d) Piston rings

  (e) Bearings

  (f) Crankshaft

(5) Bad design of the whole engine or engine parts

(6) Improper engine mounting

(7) Lack of propeller balancing

Figure 23 shows the fault-tree analysis for engine vibrations.

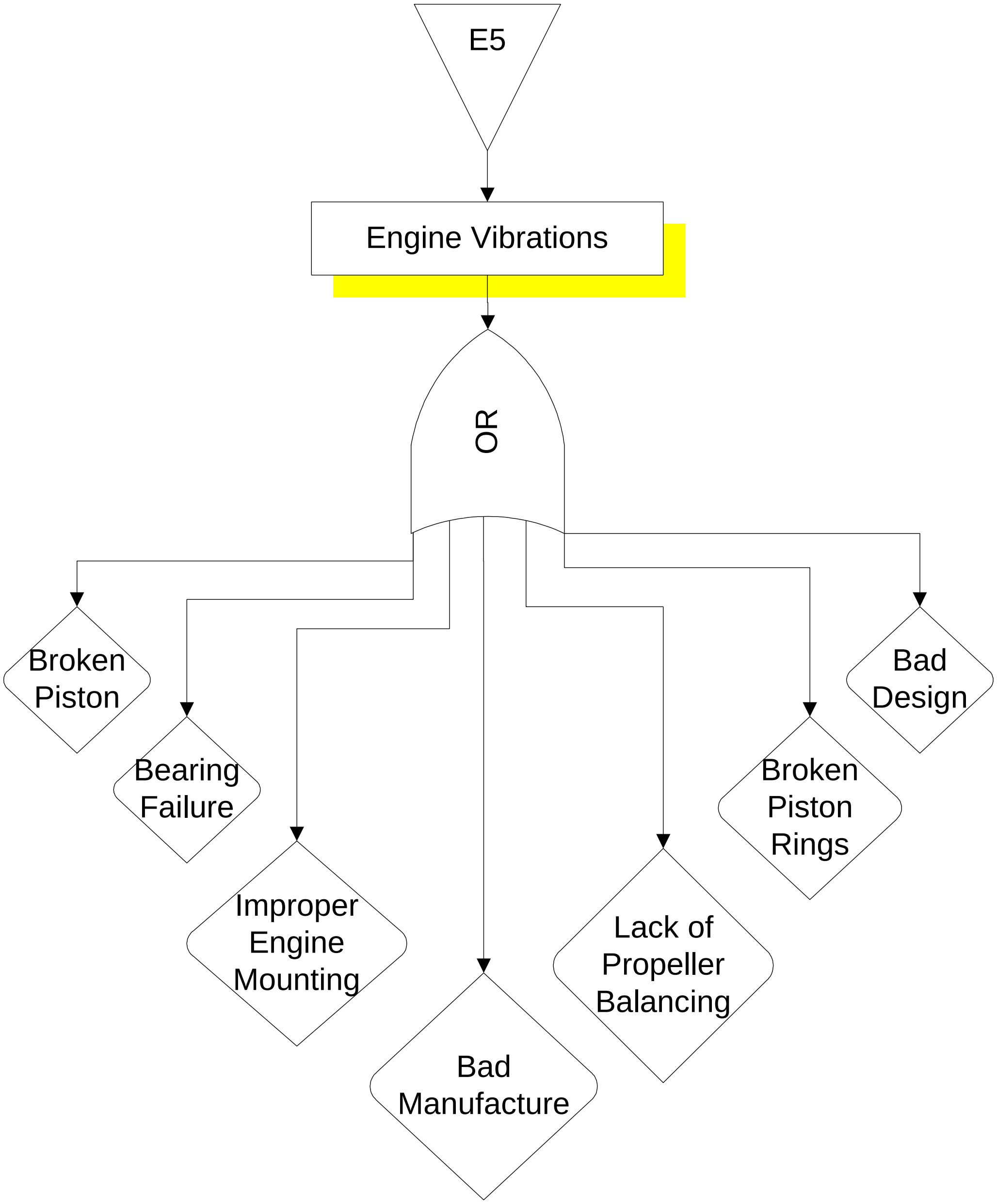

Figure 23. Engine Vibrations

24. Overheating

Reasons for engine overheating may be:

- (1) Broken piston rings
- (2) Bearing failure
- (3) Bad manufacture of engine parts like:
    - (a) Cylinder head
    - (b) Connecting rod(s)
    - (c) Piston(s)
    - (d) Piston rings
    - (e) Bearings
    - (f) Crankshaft
- (4) Bad design of the whole engine or engine parts
- (5) Dirty cooling surfaces
- (6) Bad lubricant
- (7) Engine operating too fast due to:
    - (a) Improper propeller size
    - (b) Improper engine adjustments
    - (c) Inappropriate fuel
- (8) Bad material of engine parts

Figure 24 illustrates the fault-tree analysis for engine overheating.

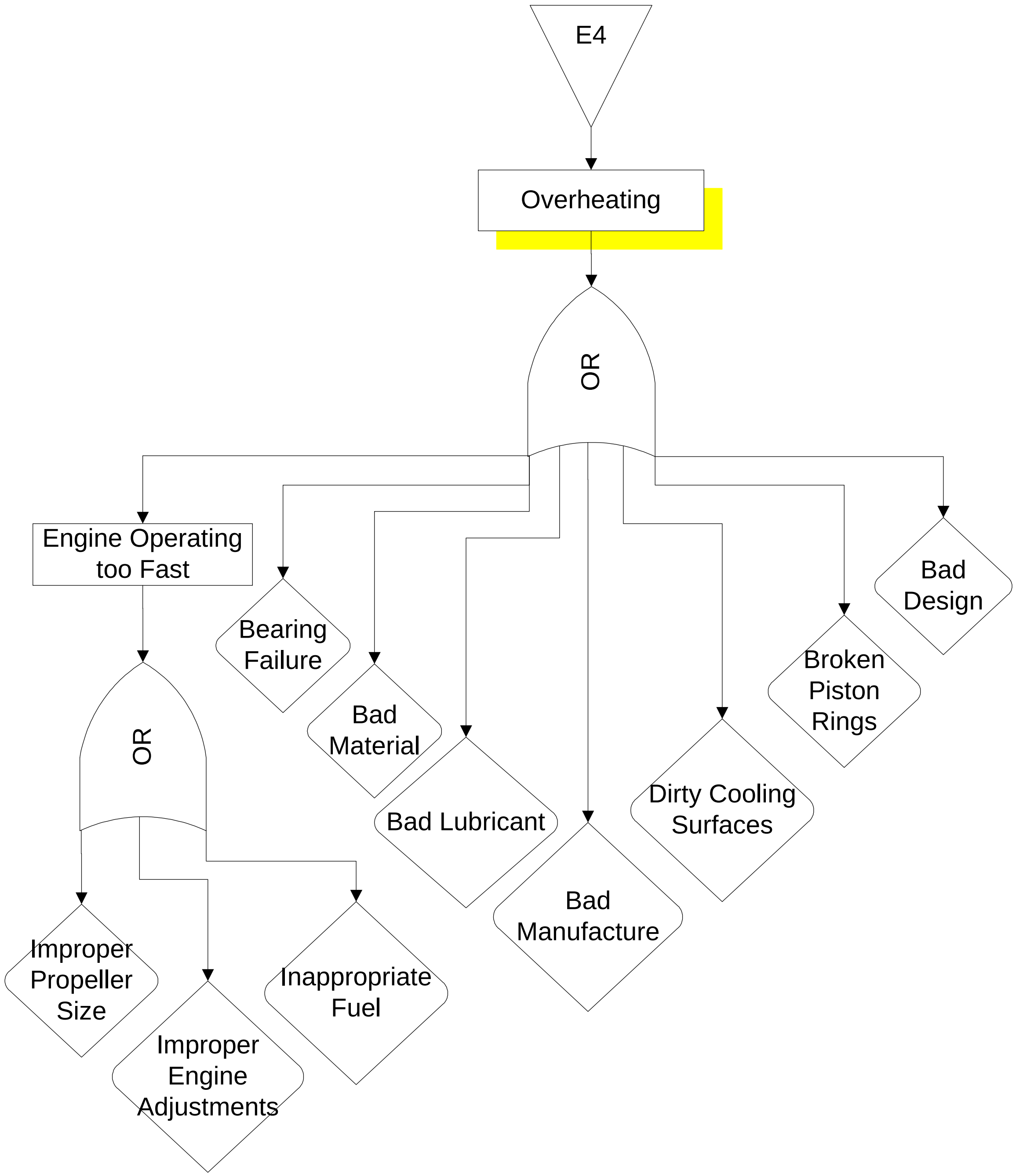

Figure 24. Overheating

25. Inappropriate Engine Operation

Reasons for inappropriate engine operation may be:

(1) Improper engine adjustment, mounting, disassembly

(2) Inappropriate fuel/lubricant mixture

(3) Improper propeller size

(4) Inappropriate fuel and/or lubricant

(5) Engine stall (during flight)

(6) Bad carburetor adjustments

(7) Inappropriate engine cleaning and/or storage after flights

(8) Inappropriate lean runs (starting after a long period of storage without any precautions) such as rusted bearings, seized connecting rod or piston, dry piston rings

(9) Propeller stops abruptly (due to external reason) while turning.

The fault-tree analysis for inappropriate engine operation can be seen in Figure 25.

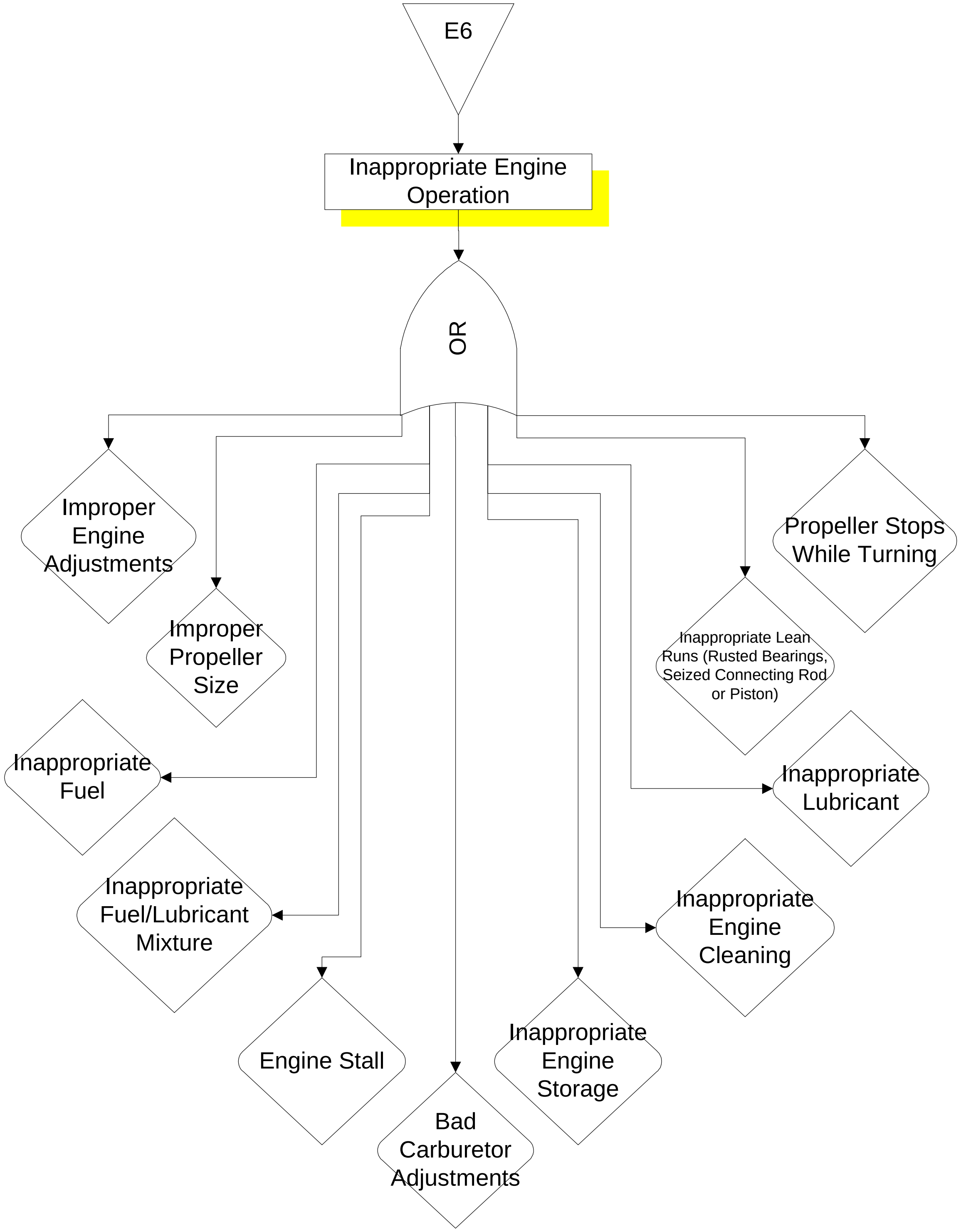

Figure 25. Inappropriate Engine Operation

26. Follow-on Analysis for the Model

The occurrence of the top event is due to different combinations of basic events. A fault tree provides useful information about these combinations. In this approach, we introduce the concept of the "cut set." A cut set is "a set of basic events" whose occurrences result in the top event. A cut set is said to be a "minimal cut set" if any basic event is removed from the set and the remaining events no longer form a cut set.[120]

For example, Figure 26 shows that the set {1, 2, 3, and 4} is a cut set because if all of the four basic events occur, then the top event occurs.

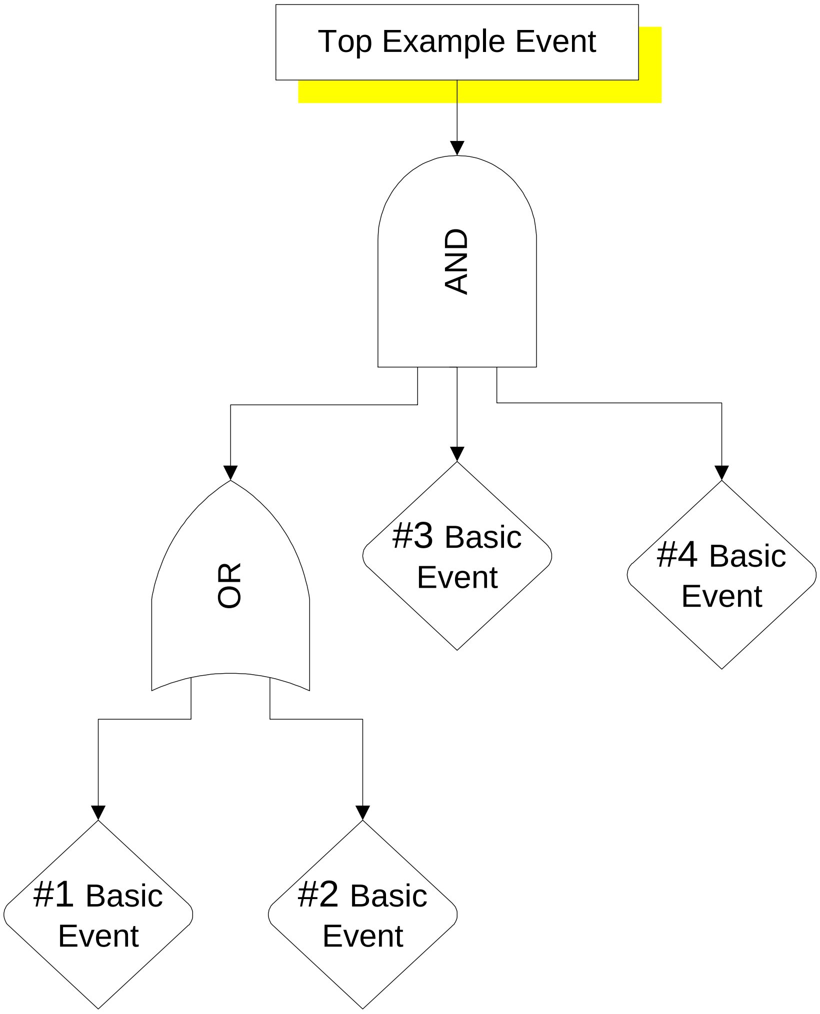

Figure 26. Example for Cut Set. (After Kececioglu, page 223)

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[120] Kececioglu, D., *Reliability Engineering Handbook* Volume 2, Prentice Hall Inc., 1991, page 222.

This is not the minimal cut set, however, because if the basic event 1 or basic event 2 is removed from this set, the remaining basic events {1, 3 and 4} and {2, 3 and 4} still form cut sets. These two sets are the minimal cut sets in that example.

In the SUAV case, there is an absence of AND gates. Only OR gates are present. For example, trying to find the minimal cuts for engine failure, gates in the following diagrams are involved:

(1) Engine failure diagram (E1)

(2) Mechanical engine failure (E3)

(3) Engine vibrations (E5)

(4) Operator error (L5)

(5) Overheating (E4)

(6) Inappropriate engine operation (E6)

Naming the gates G1, G2, up to G8,we number each basic event related to each of the gates. For example, in the engine failure diagram we have gate G1 with the following basic events:

(1) Mechanical engine failure that corresponds to gate G2 in Diagram E3.

(2) 1G1, engine fire

(3) 2G1, improper fuel

(4) 3G1, fuel/air improper mixture

(5) 4G1, excessive engine vibrations

(6) G3, the gate that corresponds to loss of lubrication

(a) 1G3, improper lubricant

(b) 2G3, excessive engine temperature raises

(c) 3G3, gas/lubricant improper mixture

Working in the same way we end up with the diagram in Figure 27.

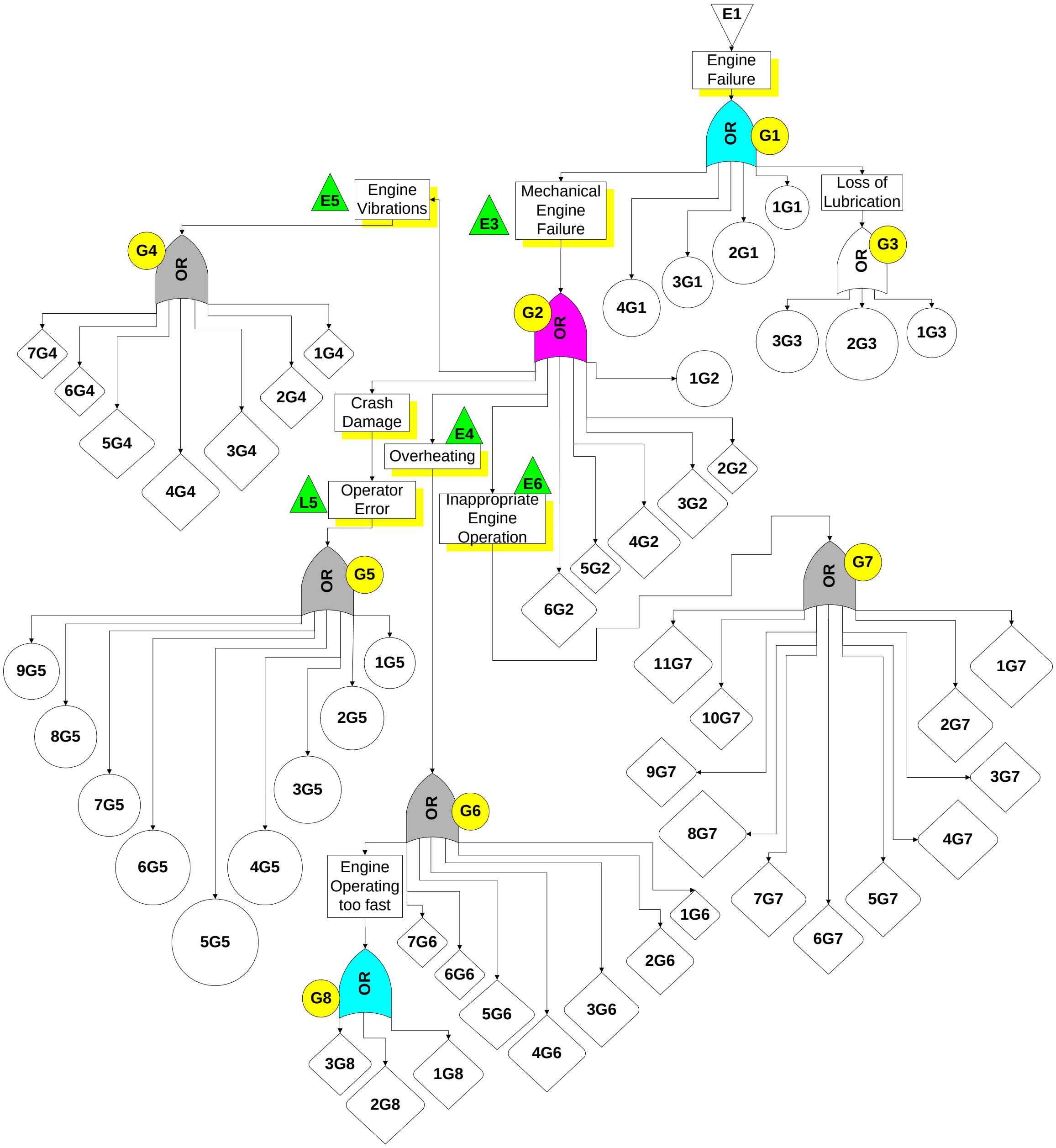

Figure 27. Engine Failure Combined Diagram

According to the MOCUS algorithm, which generates the minimal cut sets for a fault tree in which only AND and OR gates exist, an OR gate increases the number of cut sets while an AND gate increases the size of a cut set.[121] MOCUS “algorithm is best explained by an example.”[122] In the following paragraph, the steps of MOCUS algorithm were followed to determine the minimal cut sets.

Locating the uppermost gate, which is the OR gate G1, we replace the G1 gate with a vertical arrangement of the inputs to that gate. Were it an AND type, then we should have replaced it with a horizontal arrangement of the inputs to that gate. Continuing in the next level to locate the gates, and replacing them in the above-prescribed way yields Table 7.

---

[121] Kececioglu, page 222.

[122] Hoyland, page 88.

1	**2**	**3**	**4**	**5**	**……**	**……**	**Last**
G1	1G1	1G1	1G1				1G1
	2G1	2G1	2G1				……
	3G1	3G1	3G1				4G1
	4G1	4G1	4G1				1G2
	G2	1G2	1G2				……
	G3	2G2	2G2				6G2
		3G2	3G2				1G3
		4G2	4G2				……
		5G2	5G2				……
		6G2	6G2				……
		G4	1G4				……
		G5	…..				……
		G6	7G4				……
		G7	1G5				……
		1G3	……				
		2G3	9G5				
		3G3	1G6				
			……				
			7G6				
			G8				
			1G7				
			……				
			11G7				
			1G3				……
			2G3				……
			3G3				3G8

Table 7. Cut Set Analysis. (After Kececioglu, page 229)

In the last column of table 7, we have the set of minimal cuts for the engine failure, which is ({1G1},{2G1},{3G1},{4G1},{1G2},{2G2},…,{1G8},{2G8},{3G8}). The reason for the set of one element sets is the OR gates and the absence of AND gates.

An equivalent approach for the MOCUS algorithm starts from the lowermost gates. It replaces an OR gate with the union (+) sign and a AND gate with the intersection (*) sign, and after all the expressions are obtained, it continues the procedure to the gates one step above from the lowermost gates. It continues in this way until the expression for the top event is obtained.[123]

Following this algorithm, we have to end up with the same result as the MOCUS algorithm, given as an expression of intersections and unions. In our case, we end up with: E1= 1G1+2G1+3G1+4G1+1G2+2G2….+1G8+2G8+3G8. The equivalent to that expression diagram is given in Figure 28.

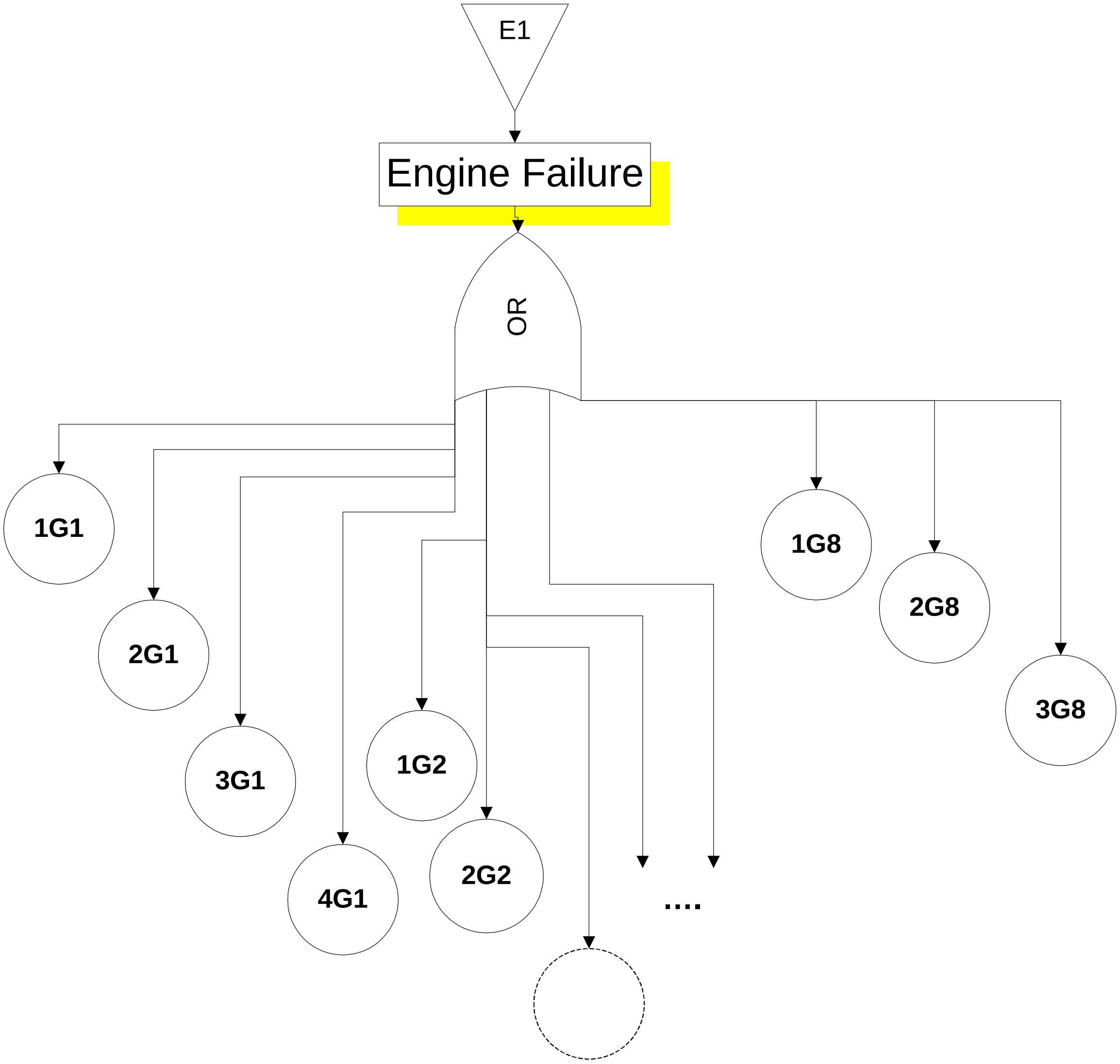

Figure 28. Equivalent Diagram

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[123] Kececioglu, page 230.

Trying to find the equivalent representation to a block diagram, we end up with a "chain like" representation that can be seen in Figure 29. A fault-tree representation of a system can be converted into a block-diagram representation by replacing the AND gates with parallel boxes and the OR gates with boxes in series. [124]

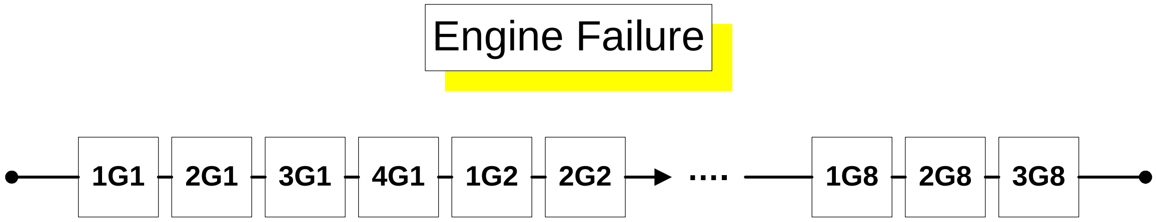

Figure 29. Equivalent Block Diagram

In a series structure, the component with the lowest reliability is the most important one. We can compare that with a chain. A chain is never stronger than its weakest link. So the most important element for reliability improvement is the one with the lowest reliability.[125] Reliability for a series system can be also explained by the use of Structural Functions, which is summarized in Appendix D.

27. Criticality Analysis

For the criticality matrix, we need a metric for the severity-of-failure effect, so we can use the designations in Table 8.

Description	**Classification**	**Mishap definition**
Catastrophic	I	System or platform loss
Critical	II	Major system damage
Marginal	III	Minor system damage
Minor	IV	Less than minor system damage.

Table 8. Classification of Failures According To Severity (After RAC *FMECA*, page 26)

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[124] Blischke, page 220.

[125] Hoyland, page 197.

Due to the absence of historic lack of data, it is appropriate to use a qualitative approach for the classification of failures according to their occurrence number which is the overall probability of failure during the item operating time internal, as illustrated in Table 9.[126]

Level	**Occurrence**	**Description**	**Occurrence number**
A	Frequent	High probability of occurrence	>0.20
B	Reasonably probable	Moderate probability of occurrence	>0.10 and <0.20
C	Occasional	Occasional probability of occurrence	>0.01 and <0.10
D	Remote	Unlikely probability of occurrence	>0.001 and <0.01
E	Extremely Unlikely	Essentially zero	<0.001

Table 9. Classification of Failures According To Occurrence

From our previous analysis for engine failure using FTA, we ended up with the following reasons:

a. Excessive engine vibrations

b. Fuel/air improper mixture

c. Improper fuel

d. Engine fire

e. Gas and lubricant improper mixture

f. Excessive engine temperature rise

g. Improper lubricant

h. Inadequate personnel training

---

[126] RAC *FMECA*, page 60.

i. Personnel fatigue

g. Operator’s frustration and lack of experience

k. Inadequate man machine interface

l. Operator’s wrong reaction to failure

m. Environmental reasons

n. Misjudgment due to environmental reasons (mainly weather)

o. Poor documentation of procedures

p. Poor workload balance resulting in task saturation with resulting loss of situational awareness

q. Ergonomics (Human factors) of GCS

r. Bad material

s. Normal engine wear

t. Bad manufacture

u. Bad design

v. Insufficient maintenance

w. Carburetor failure

x. Broken piston

y. Bearing failure

z. Improper engine mounting

aa. Lack of propeller balancing

bb. Broken piston rings

cc. Bearing failure

dd. Dirty cooling areas

ee. Improper propeller size

ff. Improper engine adjustments

gg. Broken piston rings

hh. Engine stalls (during flight)

ii. Bad carburetor adjustments

jj. Inappropriate engine cleaning and/or storage after flights

kk. Inappropriate lean runs such as rusted bearings, seized connecting rod or piston

ll. Propeller stops while turning.

From the above, we can derive the following issues about an engine failure criticality analysis, initially based on our own experience and judgment due to lack of tracking by current operators:

Number	**Issue**	**ID**	**Probability of occurrence**	**Severity of failure effect**
1	Excessive engine vibrations	L1	D	II
2	Engine fire	L2	D	I
3	Fuel type	L3	D	III
4	Lubricant type	L4	D	III
5	Fuel/air mixture adjustment	L5	C	III
6	Gas and lubricant mixture	L6	D	III
7	Personnel training	P1	C	II
8	Operator’s frustration	P2	C	II
9	Personnel experience	P3	B	III
10	Poor documentation of procedures	P4	C	II
11	Poor workload balance	P5	C	II
12	Ergonomics of GCS	P6	C	II
13	Misjudgment	P7	B	II
14	Environmental reasons	P8	C	II
15	Man machine interface	P9	D	III
16	Maintenance	P10	D	II
17	Engine adjustments	P11	C	III
18	Usage	P12	B	II
19	Manufacture	P13	D	III
20	Software failure	S	D	II
21	Material	M1	D	I
22	Hardware failure	M2	E	III
23	Design	M3	D	II
24	Engine wear	M4	D	II
25	Carburetor	M5	C	II
26	Piston	M6	E	II
27	Bearing	M7	C	I
28	Piston rings	M8	E	I
29	Propeller size	PR	E	II
30	Engine temperature	T1	D	II
31	Cooling areas	T2	D	II

Table 10. Qualitative Occurrence and Severity Table

Our next step is to construct the criticality matrix based on the previous qualitative analysis table:

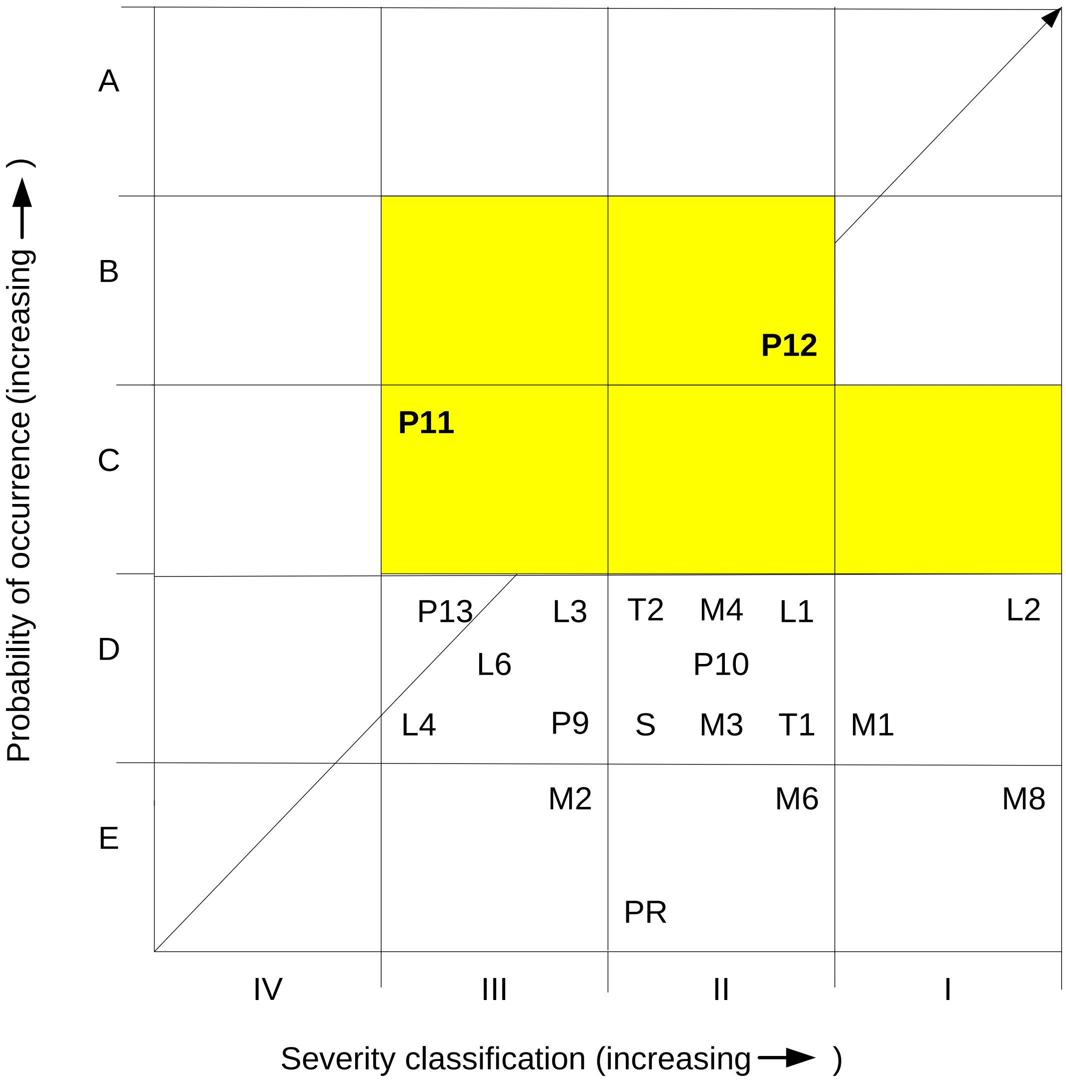

Figure 30. Engine Failure Criticality Matrix. (After RAC *FMECA*, page 33)

“The criticality matrix provides a visual representation of the critical areas” of our engine failure analysis.[127] Items in the upper most right corner of the matrix require the most immediate action and attention because they have a high probability of occurrence and a catastrophic or critical effect on severity. Diagonally toward the lower left corner of the matrix, criticality and severity decreases. In case the same severity and criticality,

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[127] RAC *FMECA*, pages 33-34.

exists for different terms, safety and cost are the driving factors of the analysis. For SUAVs, we do not take safety under great consideration because we are dealing with unmanned systems, but we do have to consider cost.

Table 11 shows the results from our analysis:

Number	Issue	ID	Probability of Occurrence	Severity of Failure Effect
1	Misjudgment	P7	B	II
2	Usage	P12	B	II
3	Bearing	M7	C	I
4	Personnel training	P1	C	II
5	Operator's frustration	P2	C	II
6	Personnel experience	P3	B	III
7	Poor documentation of procedures	P4	C	II
8	Poor workload balance	P5	C	II
9	Ergonomics of GCS	P6	C	II
10	Environmental reasons	P8	C	II
11	Carburetor	M5	C	II
12	Fuel/air mixture adjustment	L5	C	III
13	Engine adjustments	P11	C	III

Table 11. Results from Engine Failure Criticality Analysis. The most critical issues are highlighted.

28. Interpretation of Results

From the above, it is obvious how important the human factor is. The way the user operates the system: the ability to make the right decisions, frustration, training, experience, poor workload balance among the operators and poor documentation of procedures are among the most critical factors for our engine failure mode. The way the user maintains the system, also related to training and experience, the ability to adjust the engine and the fuel-air mixture properly are also among the critical contributors for engine failure mode.

The importance of the bearing and carburetor are clearly shown. Those two parts are the most critical among all the parts composing the engine, according to our analysis.

Finally, environmental reasons conclude the most critical of the issues that could result in an engine failure.

III. DATA COLLECTIONS SYSTEMS

A. RELIABILITY GROWTH AND CONTINUOUS IMPROVEMENT PROCESS

SUAVs do not have a FRACAS system. In this section of the thesis we construct one. The FRACAS system is addressed to the Program Manager of any SUAV type during the phase of design, development or operation.

1. Failure Reporting and Corrective Action System (FRACAS)[128]

"The basic measure of FRACAS effectiveness is its ability to function as a closed-loop coordinated system" in identifying and repairing product and/or process failure modes, and identifying, implementing and verifying a corrective action to prevent repetition of the failure. "As a result, early elimination of causes of failure or trends," greatly improves reliability.

At each stage of product development, the closed-loop FRACAS should collect and evaluate information for each failure incident, as shown in Figure 31.

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[128] The material for this section is taken (in some places verbatim) from: RAC *Toolkit*, pages 284-289, and: National Aeronautics and Space Administration (NASA), "Preferred Reliability Practices: Problem Reporting and Corrective Action System (PRACAS)," practice NO. PD-ED-1255, Internet, February 2004. Available at: http://klabs.org/DEI /References/design_guidelines/design_series/1255ksc .pdf

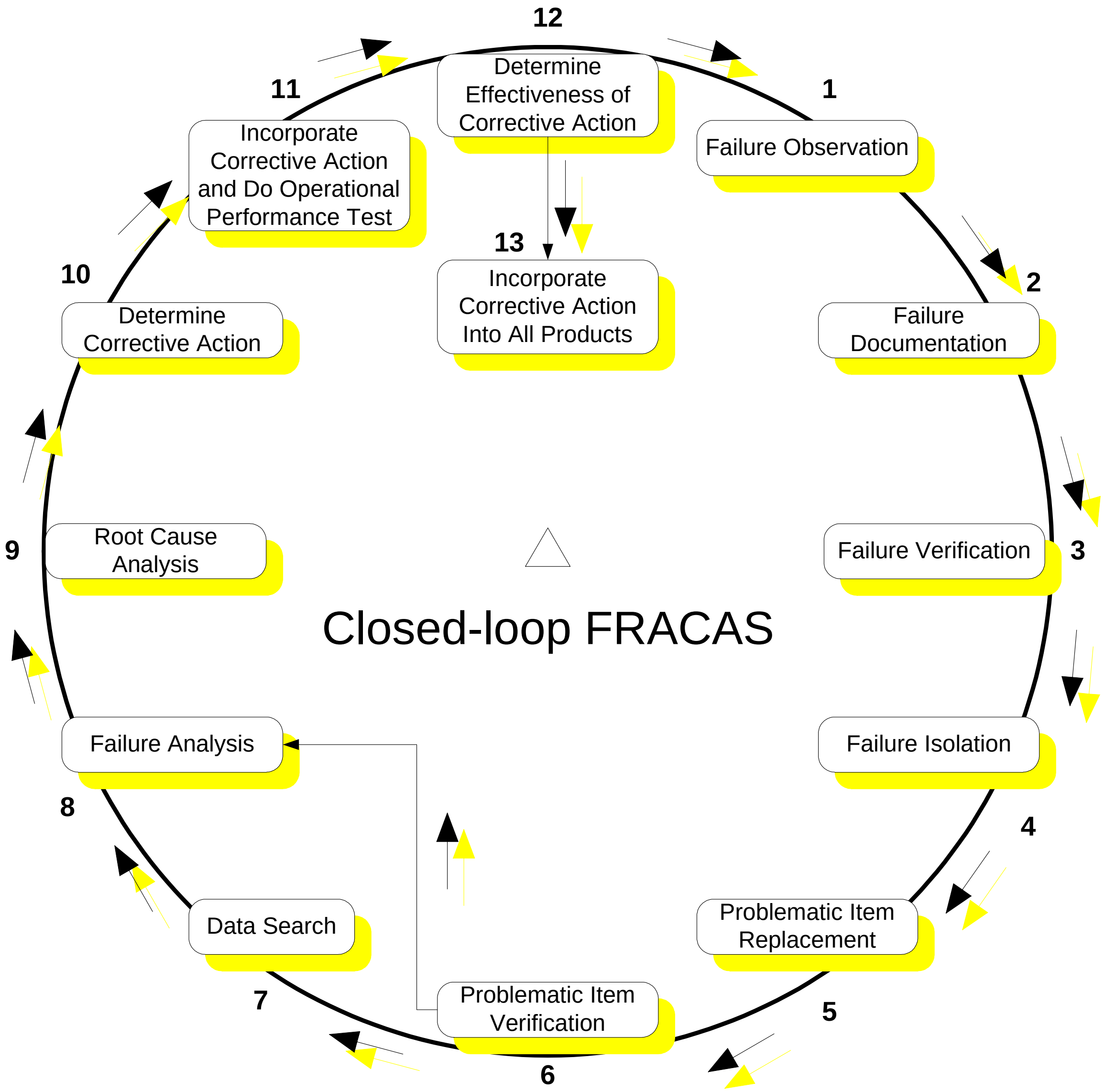

Figure 31. Closed-loop for FRACAS (After NASA, PRACAS, page 2)

In order to conduct FRACAS, we need to follow a FRACAS flow and evaluation checklist:

a. Failure Observation

In the first step, we identify that a failure incident has occurred and we notify all required personnel about the failure.

b. Failure Documentation

We record all relevant data describing the conditions in which the failure has occurred. A detailed description of the failure incident as well as supporting data and equipment operating hours is needed.

c. Failure Verification

If the failure is permanent, then we verify the incident by performing tests for failure identification. If the failure is not permanent, then we verify the incident by uncovering the conditions in which the failure has occurred. Finally, if the failure cannot be verified, we pay close attention to the reoccurrence of failure.

d. Failure Isolation

For failures that were verified, we perform testing and troubleshooting to isolate their causes. Isolating failure can identify a defective part or parts of the system, or it can relate the incident to other reasons, like operator's error, test equipment failure, improper procedures, lack of personnel training, etc.

e. Replacement of Problematic Part(s)

For the above failures, we replace the problematic part or parts with a known good one and replicate the conditions under which the failure has occurred. By testing, we confirm that the current part (or parts) has been replaced. If failure reappears we repeat failure isolation in order to determine the cause of failure correctly. We have to tag the replaced part or parts, including all relevant documentation and data.

f. Problematic Part(s) Verification

We have to verify the problematic part(s) independent of the system. If the failure cannot be confirmed then we have to review failure verification and isolation to determine the right failure part(s). The isolation of the failure to the lowest possible level of the system's decomposition is the key to reveal the root failure cause.

g. Data Search

In this step, it is necessary to look up historical databases and reports for similar or identical failure documentations. Databases could be from the implementation of FRACAS methodology itself or could be from a FMEA or other technical reports. Failure tendencies or patterns, if any, must be evaluated because they may reveal defective lots of parts, or bad design, or bad manufacturing, or even bad usage. This is obviously absent for SUAV systems.

h. Failure Analysis

A failure analysis to determine the root failure cause follows next. The depth and the extension of failure analysis depend on the criticality of the mission, the system's reliability impact and the related cost. The outcome of failure analysis should be specify failure causes and identify any external causes.

i. Root-Cause Analysis

This answers the question, "what could have been done to prevent failure?" It focuses more on the true nature of failure, which could be due to:

- Overstress conditions
- Design error
- Manufacturing defect
- Unfavorable environmental conditions
- Operator or procedural error, etc

j. Determine Corrective Action

In this phase, we have to develop a corrective action. We have to rely on the failure analysis and root-cause analysis results and our solution should prevent reappearance of the failure in the long term in order to be effective. Corrective actions could be:

- System redesign
- Part(s) redesign
- Selection of different parts or suppliers
- Improvements in processes
- Improvements in manufacturing etc

k. Incorporate Corrective Action and Operational Performance Test

Now, we can incorporate the identified corrective action in the failed system and perform initial baseline tests as a start in order to verify the desired performance. After the first successful results, our tests should become operational tests including conditions under which the failure had occurred. After the documentation of all test results, we can compare the pre-failure test results to identify alterations in baseline data. Testing should be sufficient enough to give us the confidence level that the original failure mode has been successfully eliminated from reoccurring. For large-scale incorporation of a corrective action, verifying the action is first needed to avoid unnecessary delays and expenses.

l. Determine Effectiveness of Corrective Action

We have to verify that our corrective action:

- Has successfully corrected the failure
- Has not created or induced other failures
- Has not degraded performance below acceptable levels

If the original failure reoccurs, we have to repeat the FRACAS process from the beginning to determine the correct root cause.

m. Incorporate Corrective Action into All Systems

After verifying our corrective action in one system, we can implement our solution to all similar systems. We have to keep the FRACAS procedure running in order to track, document, report, and determine the correct root cause and the corrective action necessary for all failure modes that appear. Corrective actions involve changes to procedures, alterations to processes and personnel training, so tracking is necessary to assure that the new versions were implemented correctly and not confused with old ones.

2. FRACAS Basics

Basically, the system must provide exact information on:

a. What was the failure?

b. How did the failure occur?

c. Why did the failure occur?
    (1) Was it an equipment or part design error?
    (2) Was it an equipment or part manufacturer workmanship error?
    (3) Was it a software error?
    (4) Was it a test operator error?
    (5) Was it a test procedure or equipment error?
    (6) Was it an induced failure?

d. How can we prevent such failures from reoccurring?

From all the above we can simplify the procedure to the next checklist shown in Figures 32 and 33.

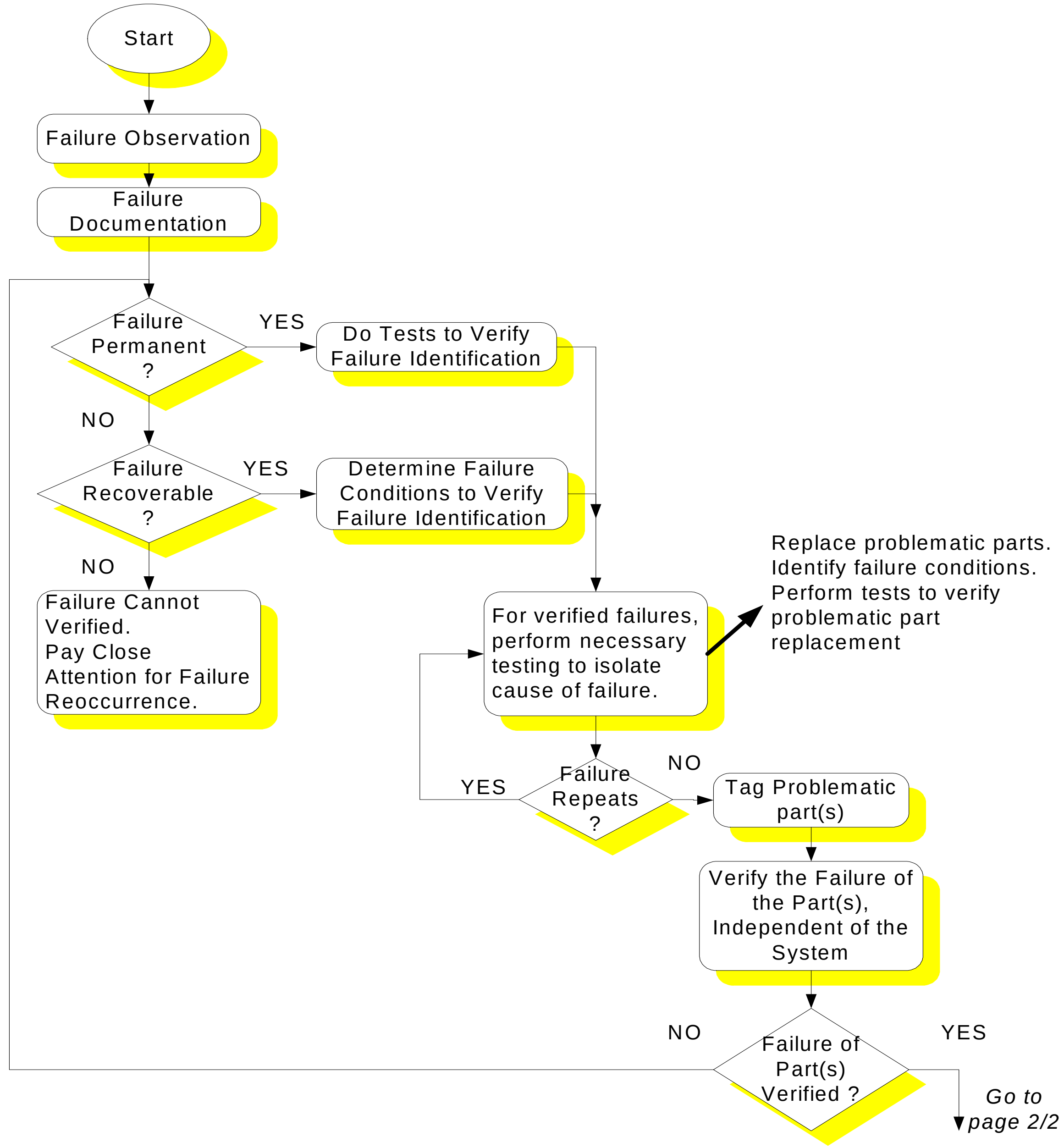

Figure 32. FRACAS Methodology Checklist page 1/2

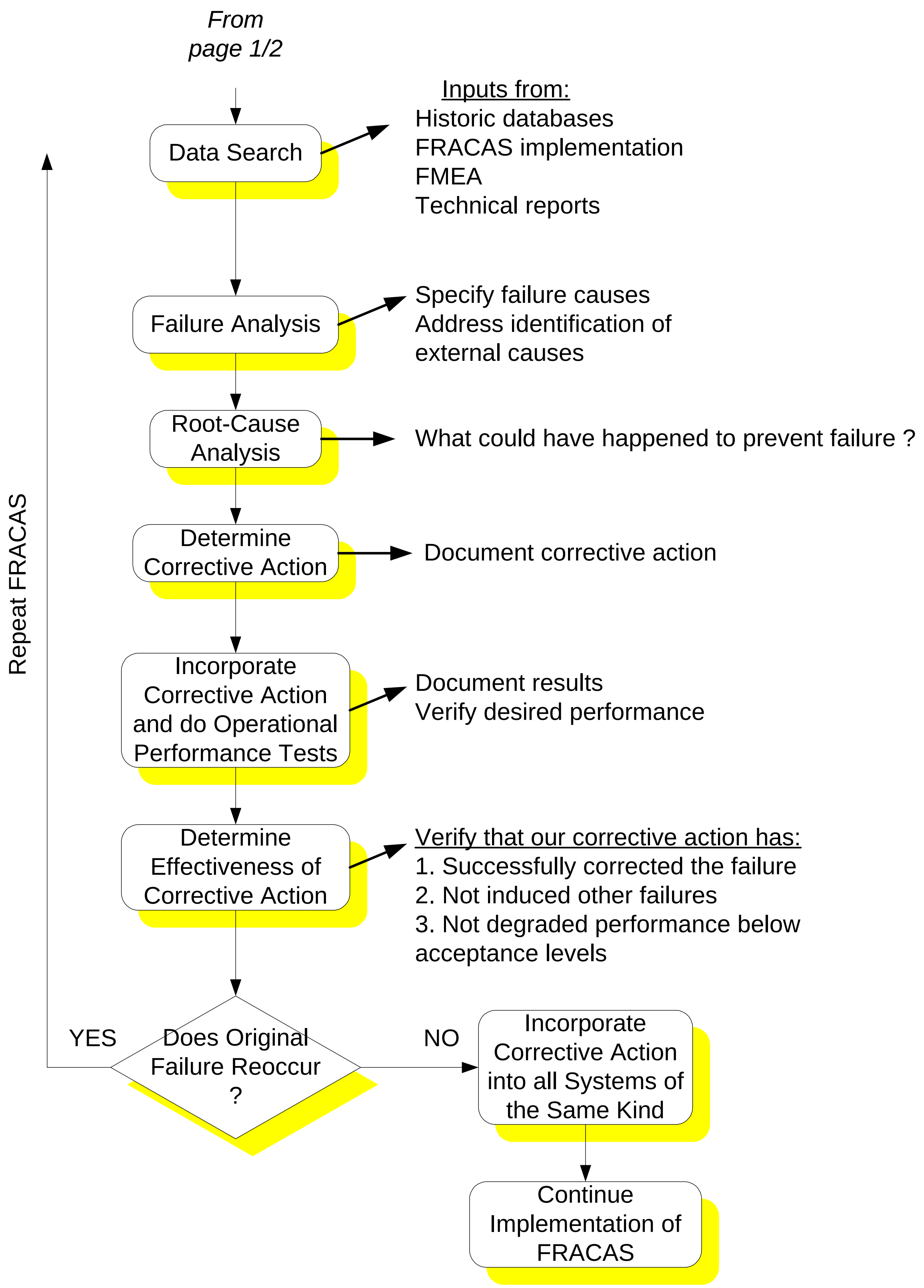

Figure 33. FRACAS Methodology Checklist page 2/2

3. FRACAS Forms

I have developed forms to implement the FRACAS methodology for SUAVs:

a. Failure report as shown in Table 12 and 13

b. Failure analysis report as shown in Table 14[129]

c. Corrective action verification report as shown in Table 15

d. Tag to problematic part as shown in Table 16.

e. Failure Log-Sheet as shown in Table 17.

During recent operations experimenting with the Surveillance and Tactical Acquisition Network (STAN) project at Camp Roberts, observers identified reliability and operational availability issues for SUAVs. As a result, I developed these forms for use during upcoming operations with the XPV 1-B TERN SUAV system.[130]

These forms were presented to a VC-6 team for use during the STAN experiment during May 2004. The effort to implement these forms was not successful. The primary reason was lack of personnel training related to the FRACAS system itself, the form filling, and the general concept of reliability. The secondary reason was lack of coordination and control to fill these forms. It was obvious that a member of the operating team, assigned with the extra task to coordinate and control the proper data entry for the forms, was needed.

"It is preferable to attempt to communicate the 'big picture,' so that each team member is sensitive to failure detection" and identification, and "the appropriate corrective action process." [131] Nevertheless, it is typical especially in military applications to have overall control, so a centralized FRACAS administration within a team or teams is needed.

The forms cover all aspects of SUAV design, development, production and operation with emphasis to experienced operation or test teams. All forms are addressed

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[129] RAC *Toolkit*, page 290.

[130] Gottfried.

[131] RAC *Toolkit*, page 284.

to the operating or test team. The Failure Analysis Report form is also addressed to the design and development team.

Using the forms we can collect information and data to the level of detail necessary to identify design and/or process deficiencies that should eliminated, preferably before the SUAV released to its users in the battlefield. For that reason the forms can be used for other systems as well as SUAVs.

The characteristics of the forms are:

a. Simple and easy to implement even by one or two persons

b. Brief in meanings and implementation time (time oriented)

c. Suitable for cheap systems like SUAV (cost oriented)

d. Focused on elimination of fault reoccurrence

e. Generates data collection that can be used as data-base source

There are no known forms of FRACAS or any other reliability tracking system that have been used for SUAV testing or operation in the past.

4. Discussion for the Forms Terms

Most of the terms in those forms are self-explanatory. Some discussion follows for some of them.

a. For the Initial Failure Report in Table 12:

(1) Total Operating Hours, in position (8), is the cumulative operation hours for the SUAV system

(2) Current Mission Hours, in position (9), is the operation hours from the beginning of the current mission that the fault was been detected

(3) Description of Failure, in position (15), is the full description of the observed failure.

(4) Supporting data, in position (16) all available telemetry data related to the failure time must be listed. In position (16a) Environmental Parameters/Conditions, is the list of environmental conditions and parameters available

like temperature, wind speed, humidity/precipitation, cloudiness, lightning, and fog, icing condition, proximity to sea or desert or inhabited area. In position (16b) System Parameters/Conditions, is a list of system conditions and parameters like, flight altitude, platform speed, engine RPM, fuel level, battery status, communication status, LOS availability.

(5) Actions for Failure Verification, in position (17), is a description of the operators' actions that verify the failure.

(6) Affected Subsystems, in positions (18) to (22) and (23) to (27) are references for the effected subsystems of the SUAV system, during the failure incidence.

(7) System Condition after Failure, in position (29) is a description of the system general condition after the failure. For example, "platform crashed due to loss of control."

b. For the Failure Report continued in Table 13:

(1) Problematic Parts Recognized, in position (16) is a list of the affected parts that have been recognized after the failure.

(2) Problematic Parts Replaced, in position (17) is a list of the parts that have been replaced after the failure in an effort to isolate the failure cause.

(3) Root Failure Cause, in position (18) is an estimate or the outcome of the previous efforts to isolate the failure cause.

(4) Previous Similar or Same Cases (if any), in position (29) is a reference to similar or same failure cases based on historical data or other accurate sources.

(5) Background, in position (30) is all background information related to the failure. For example it could be an explanation of a sensor subsystem, or a software function.

c. For the Failure Analysis Report in Table 14:

(1) History, in position (31) is a complete description of the observed failure and all the events that followed.

(2) Analysis, in position (32) is the failure analysis based on data, drawings and blueprints, manuals, and opinion from experts, designers, and operators.

(3) Conclusions, in position (33) are the analysis outcome.

(4) Corrective Action/Recommendation, in position (34) is the result of that form. This is the recommended solution to the problem.

d. For the Corrective Action Verification Report:

(1) Operating Hours after Previous Failure, in position (13), is the cumulative operation hours after the previous failure which resulted in corrective action taken for the SUAV system.

(2) Tests for Corrective Action Verification Made, in position (17), is a reference to all tests that have been made to verify that the recommended solution is correct.

(3) Alterations from Baseline Data, in position (22), is a list of all alteration from the initial data readings, after the implementation of the recommended solution.

(4) Corrective Action Taken, in position (21), is a statement about the corrective actions that have been taken in order to solve the problem.

e. For the Failure Log-Sheet:

All entries in the Log-Sheet, like Date, Time, Number, Initial Report Number and Failure Description, must be consistent to the relevant entries in the other forms. In that way we can easily track the failure cases when is needed.

In all forms, except the Log-Sheet form, there is a term for Comments. It covers any other detail that the operator or the tester estimates that is relevant to the failure and warrants mention.

1. No	Form type: **Initial Failure Report**	2. Page 1 of ____

3. Project ID	4. System	5. Serial No	6. Detected During	7. Failure Date, Time	8.Total Operating Hours	9. Current Mission Hours

10. Reported by	11. Verified by	12. System Operated by:	13. Type of System's Mission	14. Type of Failure (permanent/recoverable)

15. Description of Failure
16. Supporting Data: a. Environmental Parameters/Conditions b. System Parameters/Conditions
17. Actions for Failure Verification

AFFECTED SUBSYSTEMS	18. Name	19. Reference Drawings	20. Part No	21. Manufacturer	22.Serial No
	23. Name	24. Reference Drawings	25. Part No	26. Manufacturer	27.Serial No

28. Quick Failure Assessment (if any)
29. System Condition after Failure
30. Comments

31. Prepared by	32 Date	33 Checked (reliability)	34.Date	35. Problem No
36. Checked (engineering)	37. Date	38. Checked (program)	39. .Date	40. Distribution

Table 12. Initial Failure Report Form

1. No	Form type: **Failure Report (Continued)**	2. Page 1 of ———

3. Project ID	4. System	5. Serial No	6. Detected During	7. Failure Date, Time	8.Total Operating Hours	9. Current Mission Hours

10. Reported by	11. Verified by	12. System Operated by:	13. Type of System's Mission	14. Number of Failure

15. Description of Failure (brief)
16. Problematic Parts Recognized:
17. Problematic Parts Replaced:
18. Root Failure Cause

PROBLEMATIC PART(S)	19. Name	20. Reference Drawings	21. Part No	22. Manufacturer	23.Serial No
	24. Tagged by:	25. Failure Verified by(reliability) :	26. Failure Verified by (engineering) :	27. Failure Verified by (program) :	28. System Condition after Replacement:

29. Previous Similar or Same Cases (if any)
30. Background
31. Comments

321. Prepared by	33. Date	34. Checked (reliability)	35. Date	36. Problem No
37. Checked (engineering)	38. Date	39. Checked (program)	40. Date	41. Distribution

Table 13. Failure Report Continuation Form

<table>
<tr><td colspan="2">1. No</td><td colspan="9">Form type:
Failure Analysis Report</td><td>2. Page 1 of ____</td></tr>
<tr><td colspan="2">3. Project ID</td><td>4. System</td><td colspan="2">5. Serial No</td><td>6. Test Level</td><td colspan="2">7. Failure Date</td><td colspan="3">8. Operating Hours</td><td>9. Reported by</td></tr>
<tr><td colspan="2">*MAJOR COMPONENT OR UNIT*</td><td colspan="3">10. Name</td><td>11. Reference Drawings</td><td colspan="2">12. Part No</td><td colspan="3">13. Manufacturer</td><td>14.Serial No</td></tr>
<tr><td rowspan="2">*SUB ASSEMBLY*</td><td colspan="3">15. Name</td><td colspan="3">16. Reference Drawings</td><td>17. Part No</td><td colspan="3">18. Manufacturer</td><td>19.Serial No</td></tr>
<tr><td colspan="3">20. Name</td><td colspan="3">21. Reference Drawings</td><td>22. Part No</td><td colspan="3">23. Manufacturer</td><td>24.Serial No</td></tr>
<tr><td>*PART(S)*</td><td colspan="3">25. Name</td><td colspan="3">26. Reference Drawings</td><td>27. Part No</td><td colspan="3">28. Manufacturer</td><td>29.Serial No</td></tr>
<tr><td colspan="12">30. Related MRs and PINs</td></tr>
<tr><td colspan="12">31. History</td></tr>
<tr><td colspan="12">32. Analysis</td></tr>
<tr><td colspan="12">33. Conclusions</td></tr>
<tr><td colspan="12">34. Corrective Action/Recommendation</td></tr>
<tr><td colspan="6">35. Corrective Action by</td><td colspan="3">36. Document No</td><td colspan="3">37. Corrective Action Effectiveness</td></tr>
<tr><td colspan="3">38.Prepared by</td><td colspan="2">39. Date</td><td colspan="4">40. Approval (reliability)</td><td>41.Date</td><td colspan="2">42. Problem No</td></tr>
<tr><td colspan="3">43. Approval (engineering)</td><td colspan="2">44. Date</td><td colspan="4">45. Approval (program)</td><td>46. .Date</td><td colspan="2">47. Distribution</td></tr>
</table>

Table 14. Failure Analysis Report Form (From RAC *Toolkit*, page 290)

<table>
<tr><td>1. No</td><td colspan="7">Form type:
Corrective Action Verification Report</td><td>2. Page 1 of ____</td></tr>
<tr><td>3. Project ID</td><td>4. System</td><td>5. Serial No</td><td>6. Test Level</td><td>7. Failure Date</td><td colspan="3">8. Total Operating Hours</td><td>9. Reported by</td></tr>
<tr><td>10. Initial Failure Report form Number</td><td colspan="2">11. Failure Report Continue form Number</td><td>11. Failure Analysis Report</td><td>12. Current Mission Hours Before Failure</td><td colspan="3">13. Operation Hours after Previous Failure</td><td>14.Number of Corrective Action Taken</td></tr>
<tr><td colspan="9">16. Related Drawings, Documents, Other Data</td></tr>
<tr><td colspan="9">17. Tests for Corrective Action Verification Made</td></tr>
<tr><td colspan="9">18. Test Conditions
a. Environmental Conditions
b. System Condition</td></tr>
<tr><td colspan="9">19. Test Results</td></tr>
<tr><td colspan="9">20. Alterations from Baseline Data.</td></tr>
<tr><td colspan="9">21. Corrective Action Taken</td></tr>
<tr><td colspan="9">22. Comments</td></tr>
<tr><td colspan="3">23. Corrective Action Taken by</td><td>24. Date</td><td colspan="2">25. Document No</td><td colspan="3">26. Corrective Action Effectiveness</td></tr>
<tr><td colspan="2">27. Prepared by</td><td>28. Date</td><td colspan="3">29. Approval (reliability)</td><td>30. Date</td><td colspan="2">31. Problem No</td></tr>
<tr><td colspan="2">32. Approval (engineering)</td><td>33. Date</td><td colspan="3">34. Approval (program)</td><td>35. Date</td><td colspan="2">36. Distribution</td></tr>
</table>

Table 15. Correction Action Verification Report Form

1. No	Form type: **Tag to Problematic Part**	2. Page 1 of _____

3. Project ID	4. System	5. Serial No	6. Detected During	7. Failure Date	8. System's Total Operating Hours	9. Reported by

10. Initial Failure Report form Number	11. Failure Report Continue form Number	12. Failure Analysis Report	13. Corrective Action Verification Report	14. Operation Hours after Previous Failure	15. Total Number of Failures.

16. Failure Description
17. Failure Relevant Documentation
18. History

PROBLEMATIC PART	19. Name	20. Reference drawings	21. Part No	22. Manufacturer	23.Serial No
	24. Tagged by:	25. Failure Verified by(reliability) :	26. Failure Verified by (engineering) :	27. Failure Verified by (program):	28. System Condition after Replacement:

29. Comments

30. Verified by	31. Date	32. Document No	33. Corrective Action Effectiveness

34. Prepared by	35. Date	36. Approval (reliability)	37. Date	38. Problem No
39. Approval (engineering)	40. Date	41. Approval (program)	42. Date	43. Distribution

Table 16. Tag to Problematic Part Form

Form type:

Failure Log-Sheet

1. Number	2. Date	3. Time	4. Operator	5. Failure Description (brief)	6. Reported?	7. Initial Report Number	8. Initials
9. Checked by			10. Date	11. Mission Description			

Table 17. Failure Log-Sheet

Use of these forms will allow detailed analysis of the causes of failure and detailed modeling of reliability by subsequent analysts.

5. Reliability Growth Testing [132]

It is almost certain that prototypes or new designs will not initially meet their reliability goals. Implementation of a reliability enhancement methodology such as FRACAS is the only way to overcome the initial problems that may surface in the first prototype performance tests and later. Therefore, failures are identified, and actions taken to correct them. As the procedure continues, corrective actions become less frequent. After a reasonable amount of time, one must check whether reliability has improved, and estimate how much additional testing is needed.

Duane observed that there is a relationship between the total operation time (T) accumulated on a prototype or new design and the number of failures ($n(T)$) since the beginning of operation. [133] If we plot the cumulative failure rate (or cumulative mean time between failures MTBFc) $n(T)/T$ versus T in a log-log scaled graph, the observed data tends to be a linear regardless of the type of equipment under consideration.

Duane's plots provide a rough estimate of the increment of the time between failures. It is expected that time between failures at the early stages of development will be short. But soon after the first corrective actions they will gradually become longer. As a consequence Duane's plots will show a rapid reliability improvement in the early stages of development. After the first corrective actions the reliability improvement would be less rapid. After a corrective action we can see whether there is a reliability improvement or not. So we can have a measure of effectiveness of our corrective actions, which corresponds to the growth of reliability.

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[132] The material for this section is taken (in some places verbatim) from: Lewis, E. E., *Introduction to Reliability Engineering*, Second Edition, John Wiley & Sons, 1996, pages 211-212.

[133] Duane, J. J., "Learning Curve Approach to Reliability Modeling," Institute of Electrical and Electronic Engineers Transactions on Aerospace and Electronic Systems (IEEE. Trans. Aerospace) 2563, 1964.

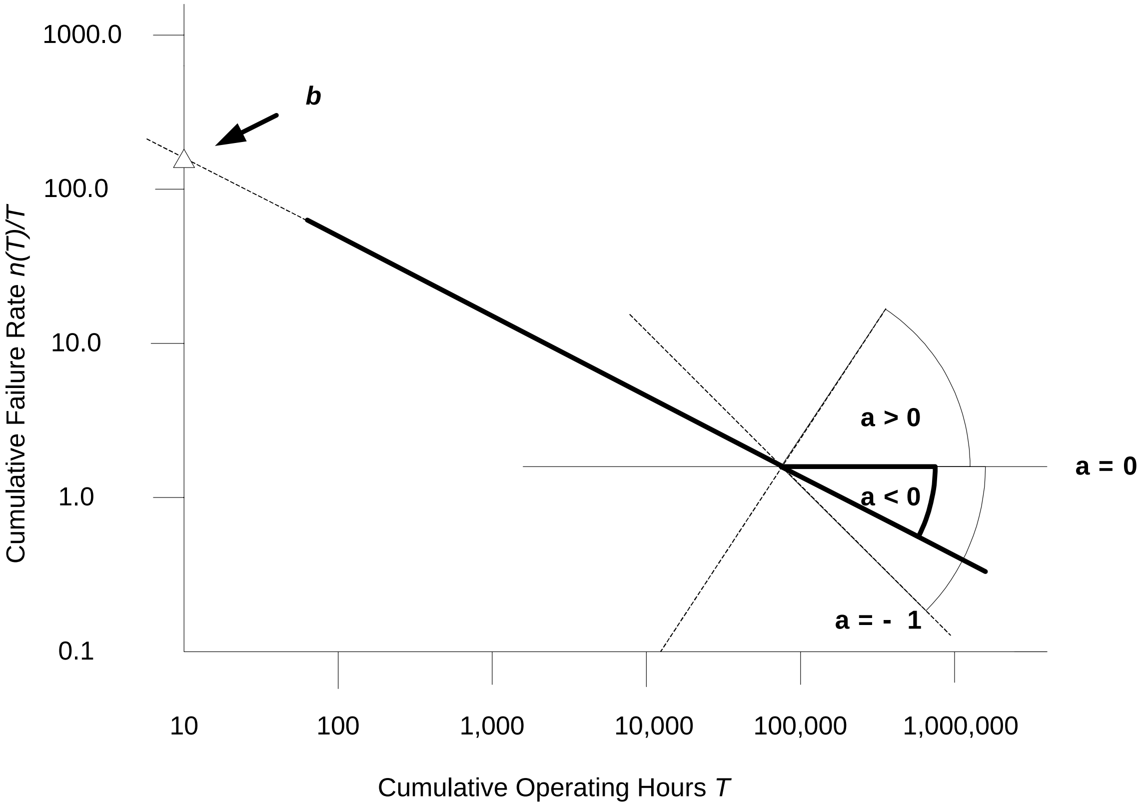

Figure 34. Duane's Data Plotted on a Log-log Scale.

Figure 33 illustrates a Duane's data plot for a hypothetical system. Because of the straight line we get: $\ln[n(T)/T] = \alpha \cdot \ln(T) + b$ and then: $e^{\ln[n(T)/T]} = e^{[\alpha \cdot \ln(T) + b]} \Leftrightarrow n(T)/T = e^b \cdot T^\alpha \Leftrightarrow n(T) = e^b \cdot T^{(1+\alpha)} = K \cdot T^{(1+\alpha)}$ if $K = e^b$, and so finally we have $n(T) = K \cdot T^{(1+\alpha)}$. Alpha (*α)* is the growth rate or the change in MTBF per time interval over which change occurred and *K* is a constant related with the initial MTBF.

a. If *α=0,* there is no improvement in reliability because the straight line is parallel to the cumulative operating hours axis, which means that there is no change in the cumulative failure rate.

b. If *α<0,* then the cumulative failure rate decreases, and the expected failures become less frequent as *T* increases. Therefore reliability increases.

c. If α=-1, $n(T) = K = e^b = \text{constant}$. Therefore the number of failures is independent of time *T*. We can assume that α=-1 is the theoretical upper limit for reliability growth.

d. If α>0, then the cumulative failure rate increases, and the expected failures become more frequent as *T* increases. Therefore reliability decreases.

From $n(T) = K \cdot T^{(1+\alpha)}$ we have: $n(T)/T = K \cdot T^{\alpha}$ which is the reciprocal of cumulative MTBF. And so the testing time required to achieve a given failure rate (MTBF), is $\left(K \cdot MTBF\right)^{\frac{-1}{\alpha}}$.

6. Reliability Growth Testing Implementation

In order to implement the above-mentioned methodology, we may consider the system as an entity and as a set of entities. In the first case, we just count all systems failures and the operational hours related to each failure. In the second case, we may consider that the system is the composition of:

a. Propulsion and power

b. Flight control and navigation

c. Communication and sensors

d. GCS (Human in the loop)

e. Miscellaneous.

Each failure can be assigned to one of the above categories and therefore we have to keep track of five different reliability tendencies.

B. RELIABILITY IMPROVEMENT PROCESS

1. UAVs Considerations

For a reliability improvement process application in SUAVs we can consider the following:

a. There is no officially accepted future system concept of operations for SUAVs.

b. There are many classified and unclassified reports published on many different types of SUAVs.

c. Many systems have been tested and there are plans for future tests in battlefield environments and in deployments with the fleet.

(1). The *EWASP* SUAV system.[134]

(2). The XPV-1B *TERN* UAV system[135]

(3). The *Sea ALL* (Sea Airborne Lead Line) SUAV system which is a variety of the USMC *Dragon Eye* UAV.[136]

d. There is a real operational need for SUAVs during deployments of the fleet. For example, due to an urgent requirement to maintain a continuous recognized maritime picture of the Carrier Strike Group vital area, small UAVs are needed to assist the limited existing maritime patrol aircrafts. For that reason, a request for the SUAV *Archangel* to be used onboard USS Enterprise CSG has been released.[137]

e. There is a real problem regarding the reliability of those systems. UAVs in general have roughly up to 100 times the failure rate of manned aircrafts, and SUAVs are even more failure prone than larger ones. The US Office of the Secretary of Defense's UAV Roadmap, which was released in May 2003, recommends that more research be made into low Reynolds-number flight regimes, investigations be carried out for enhancing UAV reliability and therefore availability. It also recommends the incorporation and development of all-weather practices into UAV designs.[138]

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[134] Morris Jefferson, *Aerospace Daily*, December 8, 2003, "Navy To Use Wasp Micro Air Vehicle To Conduct Littoral Surveillance."

[135] Message from COMMMNAVAIRSYSCOM to HQ USSOCOM MACDILL AFB FL, March 26, 2004, "UAV Interim Flight Clearance for XPV-1B TERN UAV System, Land Based Concept of Operation Flights."

[136] Sullivan Carol, Kellogg James, Peddicord Eric, Naval Research Lab, January 2002, Draft of "Initial Sea All Shipboard Experimentation."

[137] Undated message from Commander, Cruiser Destroyer Group 12 to Commander, Second Fleet, "Urgent Requirement for UAVs in Support of Enterprise Battle Group Recognized Maritime Picture."

[138] *UAV Rolling News*, "UAV Roadmap defines reliability objectives," March 18, 2003, Internet, February 2004. Available at: http://www.uavworld.com/_disc1/0000002

2. UAVs and Reliability

The U.S. military UAV fleet (consisting of Pioneers, Hunters, and Predators) reached 100,000 cumulative flight hours in 2002. This milestone is a good point at which to assess the reliability of these UAVs. Reliability is an important measure of effectiveness for achieving routine airspace access, reducing acquisition system cost, and improving UAVs mission effectiveness. UAV reliability is important because it supports their affordability, availability**,** and acceptance.[139]

UAV reliability is closely tied to their affordability primarily because UAVs are expected to be less expensive than manned aircraft with similar capabilities. Savings are based on the smaller size of the UAVs and the omission of pilot or aircrew systems.

a. Pilot Not on Board140

With the removal of the pilot and the tendency to produce a cheaper UAV, redundancy was minimized and component quality was degraded. Yet UAVs became more prone to in-flight loss and more dependent on maintenance. Therefore, their reliability and mission availability were decreased significantly. Being unmanned, they cannot provide flight cues to the user such as:

- Acceleration sensation,
- Vibration response,
- Buffet response,
- Control stick force feedback,
- Any higher longitudinal, directional and lateral control sensitivities.
- Direct feeling of the failure, in general.

Ground testing and instrumentation data analysis are the only source for such cues.

b. Weather Considerations[141]

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[139] OSD 2002, Appendix J, page 186.

[140] The material for this section is taken from: Williams Warren, Michael Harris, “The Challenges of Flight –Testing Unmanned Air Vehicles,” Systems Engineering, Test & Evaluation Conference, Sydney, Australia, October 2002.

Experience has shown that the most important operational consideration for flight is the weather, regardless of other technical characteristic, such as engine type, power or wingspan. Meteorological conditions affect both the platform and the GCS. Factors include winds, turbulence, cold temperatures at designated altitudes, icing, rain, fog, low cloudiness, humidity in general and lightning strikes. Meteorological conditions affect the GCS include extreme ambient temperatures, icing, rain, fog, low cloudiness, humidity and lightning strikes. These considerations can be mitigated because of the relaxed constraints of ground units compared to the restricted constraints for small aerial units.

For the platform the most important weather condition is wind speed and direction at surface (the lowest 100 meters of the atmosphere) and upper levels. Other weather conditions are important but do not affect the flight unless they are extreme. Surface winds affect air-platforms during takeoff and landings, but also during preflight and post flight ground handling. Light winds are most favorable for routine operation and testing. High winds during flight can cause significant platform drift, which results in poor platform position controllability. This can render a mission profile infeasible and result in flight cancellation.

Prior to deploying any UAV system, a study must be made of the prevailing meteorological conditions. If conditions are extreme (such as very high winds, extreme cold, or high altitude), then the UAV system may not be mission capable, and a different asset may be better suited. Alternate UAVs or manned systems should be considered in this case.

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[141] Teets, Edward H., Casey J. Donohue, Ken Underwood, and Jeffrey E. Bauer, National Aeronautics and Space Administration (NASA), NASA/TM-1998-206541, "Atmospheric Considerations for UAV Flight Test Planning," January 1998, Internet, February 2004. Available at: http://www.dfrc.nasa.gov/DTRS /1998/PDF/H-2220.pdf

c. *Gusts and Turbulence*

The high susceptibility of the platform to gusts and turbulence makes stabilizing flight operation points very difficult. The platform's low-wing loading can lead to high-power loading due to gusts, and turbulence and the low inertia are the main reasons for that behavior[142].

During the development test and evaluation period (DT&E), an SUAV can be tested in aerodynamic/wind tunnels to establish its general flight characteristics. A basic flight manual can be produced during DT&E that will be tested and refined during the operational test and evaluation period (OT&E). The advantage of SUAVs is that the actual airframe can be tested in the wind tunnel, without any analogy or other factor involved in the calculations because the original platform (and not any miniaturized model) is being tested.

d. *Non Developmental Items (NDI) or Commercial Off-the-shelf (COTS)*

> One of the factors in lack of reliability of inexpensive UAVs is the use of NDI/COTS components that were never meant for an aviation environment. In many cases, it would have been better to buy the more expensive aviation-grade components to begin with than to retrofit the system once constructed. Do not assume COTS components/systems will work for an application they were not designed for. In other words, they have to be COTS for that specific use.[143]

Using NDI/COTS items may save money but require testing in order to ensure compatibility and to reduce uncertainty in mission efficiency.[144]

e. *Cost Considerations*[145]

> By using COTS technology, distributed sensors, communications and navigation, it is also proposed that the total system reliability may be increased. It must be noted however that this approach does not currently account for issues of airworthiness certification.

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[142] NASA 1998.

[143] Clough.

[144] Hoivik, Thomas H., OA-4603 Test and Evaluation Lecture Notes, Version 5.5, "The Role of Test and Evaluation," presented at NPS, winter quarter 2004.

[145] The material for this section is taken (in some places verbatim) from: Munro Cameron, and Petter Krus, AIAA's 1st Technical Conference & Workshop on Unmanned Aerospace Vehicles, Systems, Technologies and Operations; a Collection of Technical Papers, AIAA 2002-3451,"A Design Approach for Low cost 'Expendable' UAV system," undated.

It is a fact that the primary cost item in UAVs is not the vehicles but the guidance, navigation, control and sensor packages that they carry. Typically all those technology “miracles” can represent 70% of the system’s cost. Although sensors continue to decrease in cost, size and power consumption, the demands for more capabilities and mission types are increasing. As a result, cost is increasing.

We can assume that acquisition cost is proportional to reliability, and wear out is not proportional to reliability. Then, a generic reliability trade-off can be seen as in Figure 35. We can conclude that a highly reliable UAV does not coincide with an overall low system cost.

Another point of interest related to cost and reliability is that reliability is low for SUAVs because SUAVs are designed to be inexpensive. This statement is true because reliability is expensive and one truly gets what one pays for.[146]

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[146] Clough.

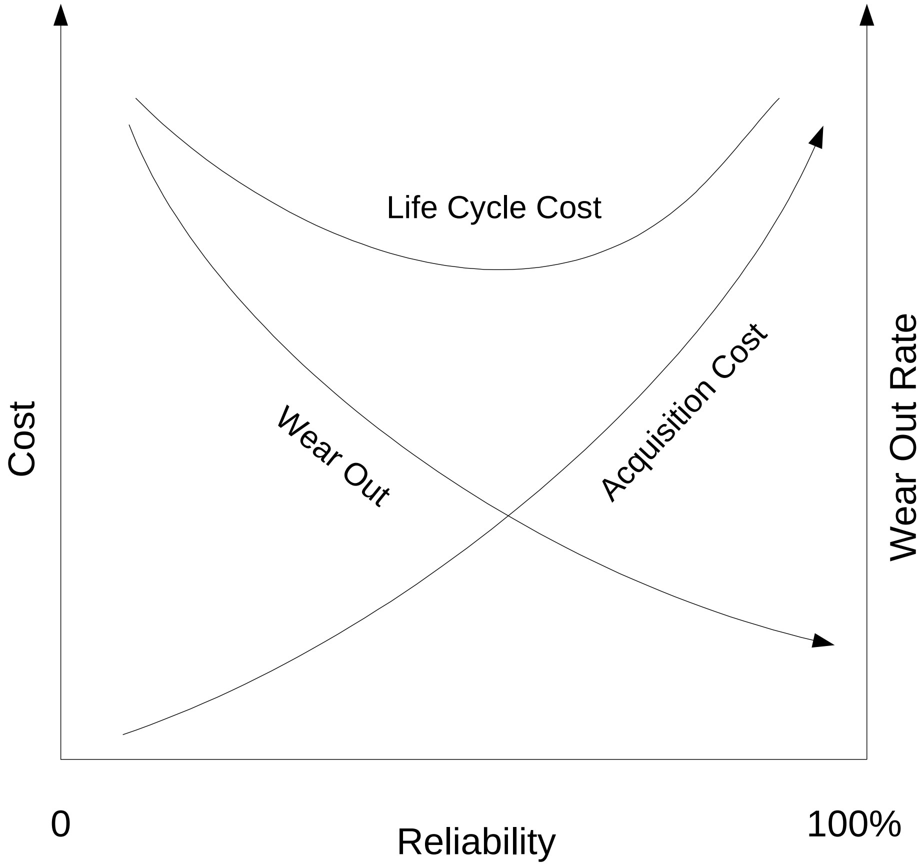

Figure 35. Generic Cost Relationship. (After Munro)

f. *Man in the Loop*

The man-in-the-loop can be accomplished "through nearly all of the potential controlling equipment available." UAV control equipment is the link between man and machine together with the data display mechanisms. Controlling equipment can be remotely piloted, semi-autonomous with a combination of programmed and remote piloted, and fully autonomous (full-auto) with pre-flight and/or in-flight programmed.[147]

Another point of interface between man and machine is maintenance and pre-flight and after-flight servicing. Piloting a UAV resembles an instrumented manned flight. For that reason there are four main considerations:

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[147] Carmichael, Bruce W., and others, "Strikestar 2025," Chapter 4, "Developmental Considerations, Man-in-the-Loop," August 1996, Department of Defense , Internet, February 2004. Available at: http://www.au.af.mil/au/2025/volume3/chap13/v3c13-4.htm

(1) Collision avoidance

(2) Multiple platforms control

(3) Landing (recovery)

(4) Loss of flight control and regain of it.

g. Collision Avoidance

For UAVs, a system is needed that can weigh tasks and put priorities only on the flight requirements or mission requirements. It is essential to have the capability, like the pilot does, to sense and to avoid obstacles that most of the time the remote pilot cannot see.[148]

If an accurate collision avoidance system were developed, UAVs could become more responsive to the demanding needs of the battle commander.[149] "NASA, the U.S military, and the aerospace community have joined forces to develop detect, see, and avoid (DSA) technologies for UAVs."[150] These technologies will also increase safety operations above residential areas and allow UAVs to join the piloted aerial vehicles in national airspace.

h. Landing

A lot of UAV mishaps are related to landing. The usual ways for UAVs to land are:

- Using landing gear on runways or airstrips
- Using landing gear and arresting gear on ship flight-decks
- Making a calculated crash landing without using landing gear
- Recovering in an arresting net

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[148] Finley, Barfield, Automated Air Collision Avoidance Program, Air Force Research Laboratory, AFRL/VACC, WPAFB,"Autonomous Collision Avoidance: the Technical Requirements," 0-7803-6262-4/00/$10.00(c)2000 IEEE.

[149] Coker, David, Kuhlmann, Geoffrey, "Tactical-Unmanned Aerial Vehicle 'Shadow 200' (T_UAV)," Internet, February 2004. Available at: http://www.isye.gatech.edu/~tg/cources/6219/assign /fall2002 /TUAVRedesign/

[150] Lopez, Ramon, American Institute of Aeronautics and Astronautics (AIAA), "Avoiding Collisions in the Age of UAVs," Aerospace America, June 2002, Internet, February 2004. Available at: http://www.aiaa.org /aerospace/Article.cfm?issuetocid=223&ArchiveIssueID=27

- Landing in sea water
- Using a parachute
- Vertical take-off-and-landing (VTOL)

The most common problems with recovery are lack of experience by the remote pilot and low altitude winds, even for the VTOL UAVs. To resolve or mitigate this problem, automated recovery systems can be used. Those systems have been developed to improve precision, ease and safety of UAV recoveries, on land and sea, and in a variety of weather conditions.[151]

i. Losing and Regaining Flight Control

The need for uninterrupted communication between the operator in the GCS and the platform is a critical capability.[152] An interruption of that link is always possible due to loss of Line-of-Sight (LOS), communication failure related to platform or GCS, and electromagnetic interference (EMI). The only way to overcome this problem is autonomy with dependable autopilot and mission control software.[153]

Autonomy for a UAV platform is based on an onboard computer, which is responsible for most of the platform's performance and "behavior". Subprograms for time-related loss of communications, regaining communications, points of regaining communication efforts, and other functions related with mission effectiveness are very common among UAV software. Additionally, emission control applications help allocate bandwidth for different uses and may decrease the EMI hazard. For UAVs, which use different sensor configurations in the same type of platform, there is also a need for reconfigurable multi-mission processing.[154]

j. Multiple Platforms Control

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[151] UAV Annual Report FY 1997: Subsystems, Key subsystem program, "UAV common recovery system (UCARS)," Internet, February 2004. Available at: http://www.fas.org/irp/agency/daro/uav97/page36.html

[152] Coker.

[153] Puscov, Johan, "Flight System Implementation," Sommaren-Hosten 2002, Royal Institute of Technology (KTH), Internet, February 2004. Available at: http://www.particle.kth.se/group_docs/admin/2002/Johan_2t.pdf

[154] Robinson, John, Technical Specialist Mercury Computers, *COTS Journal*, "UAV Multi-Mission Payloads Demand a Flexible Common Processor," June 2003, Internet, February 2004. Available at: http://www.mc.com/literature/literature_files/COTSJ_UAVs_6-03.pdf

Demands for piloting a UAV require two operators in general. The aviator operator (AVO) is responsible for aviating and navigating, and the mission payload operator (MPO), or Sensor Operator (SENSO), is responsible for target search and system parameters monitoring. In smaller UAVs there may be only one operator who does both tasks. Requiring two operators limits the number of operators available for other missions. Is it possible for those two operators to control two or more platforms simultaneously?[155] Is it also possible for the single operator for the smaller UAV to do the same?

The SUAV operators are part of a battle team and their primary skill and training is to fight and then to operate the SUAVs. They operate SUAVs from a distance yet in the proximity of the battlefield. So, care must be taken in making excessive workload demands on the SUAV operators. Instead, by making the platform control and operation more user-friendly, we can optimize the benefits of SUAVs capabilities. When the operators can stand far enough from the battlefield, user-friendly control of SUAVs is advantageous, and multiple platform control can become a more realistic capability if SUAV autonomy is high.

k. Reliability, Availability, Maintainability of UAVs

Reliability is the probability that a UAV system or component will operate without failures for a specified time (the mission duration) as well as the preflight tests duration. This probability is related to the mean time between failures (MTBF) and availability.

Availability is defined as the ability of a system to be ready for use when needed at an unknown (random) time. It is the natural interpretation of reliability of our everyday life. Availability is a function of reliability and maintainability.

As discussed earlier, redundancy plays an important role to keep reliability high. Keeping redundancy at a high level increases system complexity and cost, however.

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[155] Dixon, Stephen R., and Christopher D. Wickens, "Control of multiple UAVs: A Workload Analysis," University of Illinois, Aviation Human Factors Division, Presented to 12th International Symposium on Aviation Psychology, Dayton, Ohio 2003.

Volume, weight, and cost are also important for UAVs system's operational usage and real system needs. There is a trade off as indicated in Figure 36.[156]

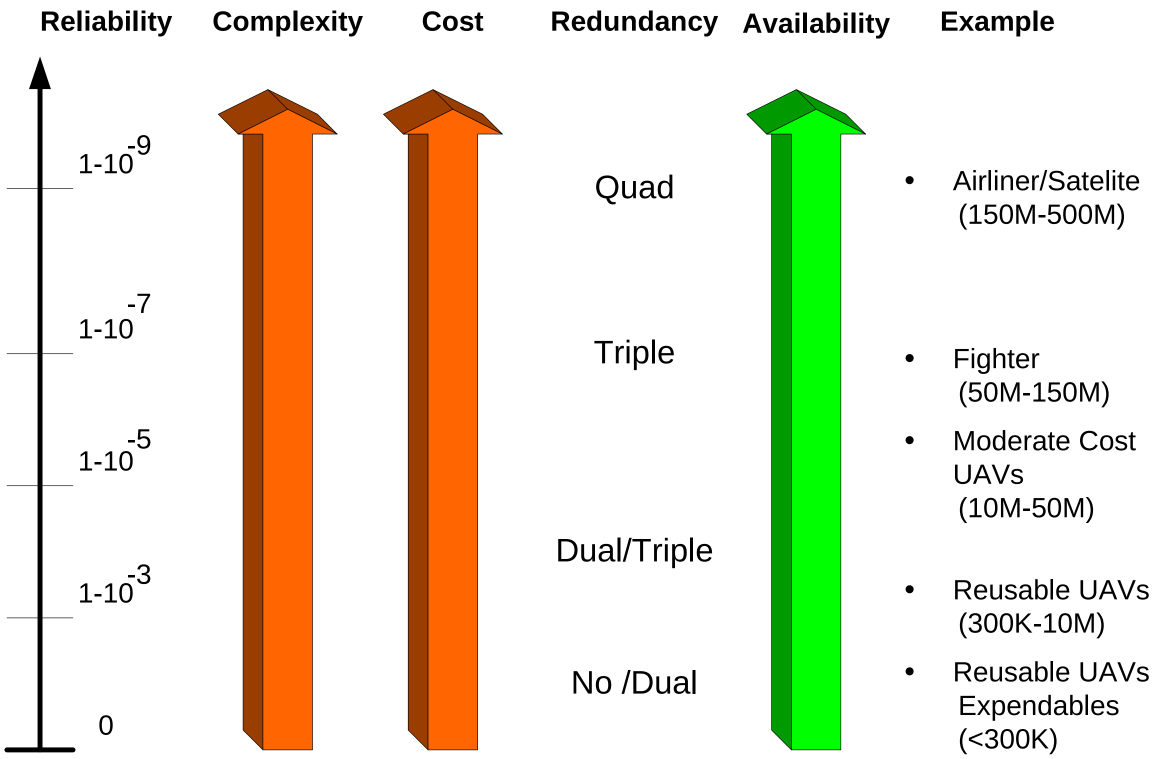

Figure 36. Reliability Trade-Offs. (After Sakamoto, slide 8)

Where redundancy is difficult to implement, fault avoidance or parts quality is the solution to improve reliability. In some cases adding redundancy in critical subsystems, like navigation aids, is unavoidable. Thus, cost and complexity increases.[157] Maintainability is a system effectiveness concept that measures the ease and rapidity with which a system or equipment is restored to its operational state after failing. Reliability, availability, and maintainability are discussed in Appendix D.

3. Reliability Improvement for *Hunter*

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[156] Sakamoto, Norm, presentation: "UAVs, Past Present and Future," Naval Postgraduate School, February 26, 2004.

[157] Clough.

The Army's acquisition of the *Hunter* RQ-5 system is an example of reliability improvement after the implementation of a reliability improvement program. In 1995, during acceptance testing, three *Hunter* platforms crashed within a three week period. As a result, full rate production was canceled. The Program Management Office and the prime contractor Thompson Ramo Wooldridge (TRW) performed a Failure Mode Effect and Criticality Analysis (FMECA) for the whole system. Failures were identified and design changes were made after failure analyses and corrective actions were implemented. As a result, *Hunter's* Mean Time Between Failures (MTBF) for its servo actuators, which were the main cause for many crashes, increased from 7,800 hours to 57,300 hours.

Hunter returned to flight status three months after its last crash. Over the next two years, the system's MTBF doubled from four to eight hours and today stands close to 20 hours. Prior to the 1995, Hunters mishap rate was 255 per 100,000 hours; afterwards (1996-2001) the rate was 16 per 100,000 hours. Initially canceled because of its reliability problems, Hunter has become the standard to which other UAVs are compared in reliability.[158]

4. Measures of Performance (MOP) for SUAVs

In manned aviation, the usual Measures Of Performance (MOPs) used for reliability tracking are

- Accidents per 100,000 hours of flight
- Accidents per 1,000,000 miles flown
- Accidents per 100,000 departures[159]

In the Vietnam War, the MOPs used for the *Lightning Bug* were

- The percent of platforms returned from a mission, calculated as the number of platforms recovered from similar successful missions divided

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[158] OSD 2002, Appendix J.

[159] National Transportation Safety Board (NTSB), Aviation Accident Statistics,"Table 6. Accidents, Fatalities, and Rates, 1984 through 2003, for U.S. Air Carriers Operating Under 14 CFR 121, Scheduled Service (Airline), Internet, April 2004. Available at: http://www.ntsb.gov/aviation/Table6.htm

by the number of platforms launched for that mission in a certain time period.

- Missions accomplished per platform per mission type in a certain time period.[160]

The frequency of mishaps is the primary factor for choosing a MOP. In the SUAV case, we can use the following MOPs for reliability tracking:

a. Crash Rate (CR): The total number of crashes divided by the total number of flight hours. A crash results in loss of platform.

b. Operational CR: The total number of crashes divided by the total number of operating flight hours.

c. Mishap Rate (MR): The total number of mishaps divided by the total number of flight hours. This thesis defines a mishap for a SUAV as significant platform damage or a total platform loss. A mishap requires repair less than or equal to a crash depending on the condition of the platform after the mishap.

d. Operational MR: The total number of mishaps divided by the total number of operating flight hours.

e. Current Crash Rate (CCR): The total number of crashes from the last system modification divided by the total number of flight hours from the last system modification.

f. Operational CCR: The total number of crashes from the last system modification divided by the total number of operating flight hours since the last modification.

g. Current Mishap Rate (CMR): The total number of mishaps from the last system modification divided by the total number of flight hours from the last modification.

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[160] Carmichael, Bruce W., Col (Sel), and others, “Strikestar 2025,” Appendix A,B & C, “Unmanned Aerial Vehicle Reliability,” Appendix A, Table 4August 1996, Department of Defense, Internet, February 2004. Available at: http://www.au.af.mil/au/2025/volume3/chap13/v3c13-8.htm

h. Operational CMR: The total number of mishaps from the last system modification divided by the total number of operating flight hours from the last modification.

i. Crash Rate "X" (CRX): The crash rate for the last "X" hours of operational flight hours, as in "CR50" which is the CR for the last 50 flight hours.

j. Mishap rate "X": The MR for the last "X" hours of operational flight hours, as in "MR50" which is the MR for the last 50 flight hours.

k. Achieved Availability (AA): The total operating time (OT) divided by the sum of OT, plus the total corrective maintenance time, plus the total preventive maintenance time.

l. Percent Sorties Loss: The total number of sorties lost (for any reason) divided by the total number of sorties assigned.

m. Percent Sorties Mishap: The total number of sorties with a mishap divided by the total number of sorties assigned.

SUAVs are generally low cost systems with prices from $15K to $300K. For that reason there is no official data collecting system in effect detailed enough to provide reliability data. Usually, only the number of flight hours and the number of crashes is known. For that reason, the most suitable reliability MOPs currently are CR, CCR and CRX.

5. Reliability Improvement Program on SUAVs

A reliability improvement program seeks to achieve reliability goals by improving product design. The objective of an improvement program is to identify, locate and correct, faulty and weak aspects of the design, manufacturing process, and operating procedures. For the SUAV, we first applied existing techniques for improving system reliability.

Starting with the FMEA, which is the basis for the most common methodologies for improving reliability; we also discussed FMECA and FTA. After that, reliability centered maintenance, specifically MSG-3, was presented as the prevailing methodology for enhancing civil aviation reliability and maintenance preservation methodology. We showed that MSG-3 is not suitable for UAVs applications because of its dependence on an in-board operator. We highlighted the need for a data collection system and presented FRACAS. FRACAS is best suited for SUAVs especially during their initial phases of development or operational test development. Finally, a method or technique is needed to keep track of reliability growth. Duane's plots presented and recommended for their simplicity.

6. Steps for Improving Reliability on SUAVs

We can consider a FRACAS system as a part of a generic reliability improvement program. The first step of such a program is an environmental stress screening (ESS). ESS is a process that uses random vibration within certain operational limits, and temperature cycling to accelerate part and workmanship imperfections. Identification of infant mortality failures can be identified in a short time and relatively easily.

In addition to ESS, the next actions should be taken:

a. Verify/calibrate the instruments for the field tests or field operations. With calibrated instruments we can substantially reduce instrumentation errors. A rule of thumb is to use another instrument that is at least 10 times more accurate than the instrument we want to calibrate.[161]

b. Set the initial weather restrictions for UAVs flights.

c. Conduct a FMEA of the system and/or perform an FTA if it is necessary when we want to focus on a certain failure. For that purpose, we have tailored a form as in Table 18.[162]

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[161] Hoivik.

[162] Department of Defense, MIL-STD-1629A, "Procedures For Performing a Failure Mode Effects and Criticality Analysis," Task 101 FMEA sheet, November 24, 1980.

UAVs FMEA Form	FMEA Date
System Name	Page of Pages
Part Name	Prepared by
Reference Drawing	Approved by
Mission	Revisited by/Revision Date

ID Number	Item/ functional ID	Design Function	Failure Modes and Causes	Operational Phase	Failure Effects			Failure Detection Method	Fault Acceptance	Severity Classification	Remarks
					Local	Next Higher Level	End Effects				

Table 18. UAVs FMEA Form (After MIL-STD-1629A, Figure 101.3)

The cell definitions are: [163]

(1). ID Number, given to each entry on the FMEA form for record-keeping purposes.

(2). Item/Functional Identification, for the item or the functional block or subsystem, such as the carburetor or the fuel tank, for example.

(3). Design Function, a brief statement about the item's design function. State that the carburetor mixes fuel and air in order to feed the engine with the proper fuel-air density, for example.

(4). Failure Modes and Causes, a brief statement about the way(s) in which the item may fail. In the case of the carburetor, the failure modes are improper adjustment, plugged needle valve, jammed leverage, servo failure, excess vibrations, throttle failure, insufficient fastening to the frame, etc.

(5). Operational Phase, a brief statement about the item's objective or task must be written; in the case of the carburetor, it controls engine running speed.

(6). Local Failure Effects, explaining the immediate consequences of the item's identified failure mode. In the case of the carburetor, we can state "Engine cannot be controlled."

(7). Next Higher Level, about the effect of the local failure on the next higher functional system level; in the case of the carburetor, we can state "Loss of engine."

(8). End Effects, explaining the effects of the indicated failure mode on the whole system. In the case of the carburetor, we can state "Loss of thrust."

(9). Failure detection method, explaining the way(s) by which a failure can be detected. In the case of the carburetor, it could be detected by the operator or by the control system itself.

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[163] The material from the following part of section is taken (in some places verbatim) from: RAC *FMECA*, pages 60-66.

(10). Fault Acceptance, statement of the ways that the system can overcome or bypass the effects of failure. In the case of the carburetor the system design does not provide any alternatives so the word “None” can be placed under fault acceptance.

(11). Severity Classification, representing the degree of damage that will be caused by the occurrence of the failure mode. It could be any of the following categories:

(a) Classification I, for complete loss of system

(b) Classification II, for degraded operation of the system

(c) Classification III, for a failure status that still needs to be investigated

(d) Classification IV, for no effect on systems functions.

The failure effect for the carburetor can be classified as a Category I severity.

(12). Remarks, relating details about the evaluation of the given failure mode.

d. Establish a FRACAS. Implementation of FRACAS through the system’s life cycle, even for the ESS tests, should continue for all failures occurring during developmental and operational testing.

For a reliability improvement program, FRACAS is the most critical facet.[164] Failures must be identified and isolated to the root failure mode. After the failure analysis is complete, corrective actions are identified, documentation is completed and data is entered into FRACAS. The system’s manufacturer can use the information in FRACAS to incorporate the corrective actions into the product. We can use the same FRACAS forms we presented in the previous subsection.

e. Track of reliability improvement by using Duane’s theory, MTBFs and/or achieved availability of the system.

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[164] Pecht, page 323.

f. Complete a reliability improvement plan. This plan must be completed, approved and coordinated by the manufacturer's engineers and reliability manager in cooperation with the military personnel who operate the systems. The following need to be addressed in the plan:

- Resources,
- Test schedule and test equipment,
- Personnel,
- Test environment,
- Procedures,
- Data base establishment, and
- Corrective action implementation program.

Figure 37 outlines the reliability improving process for SUAVs.

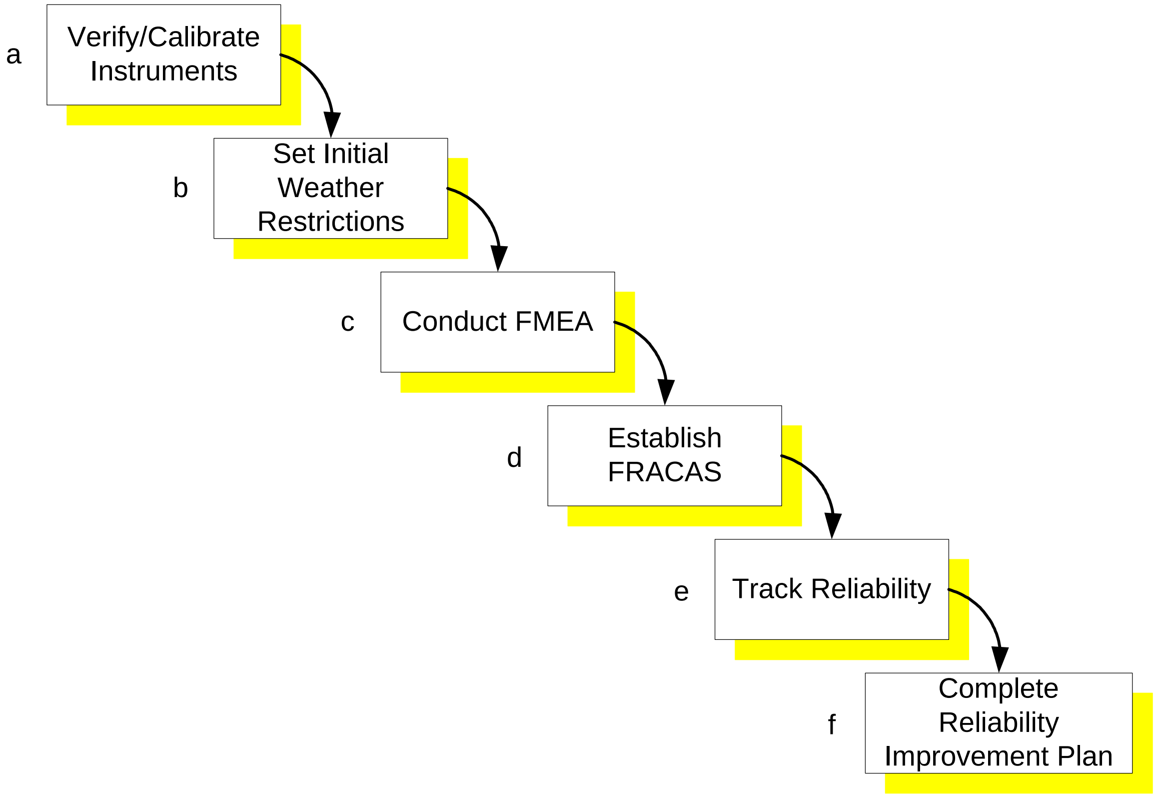

Figure 37. Reliability Improving Process on SUAVs

IV. EXAMPLE

A. RQ-2 PIONEER 86 THROUGH 95

From the US Navy’s Airborne Reconnaissance Office, 15 March 1996, come the following data regarding the RQ-2 Pioneer battlefield UAV mishaps from 1986 until 1995.[165]

Year	Mishaps	Flight hours
86	5	96.3
87	9	447.1
88	24	1050.9
89	21	1310.5
90	21	1407.9
91	28	2156.6
92	20	1179.3
93	8	1275.6
94	16	1568
95	16	1752

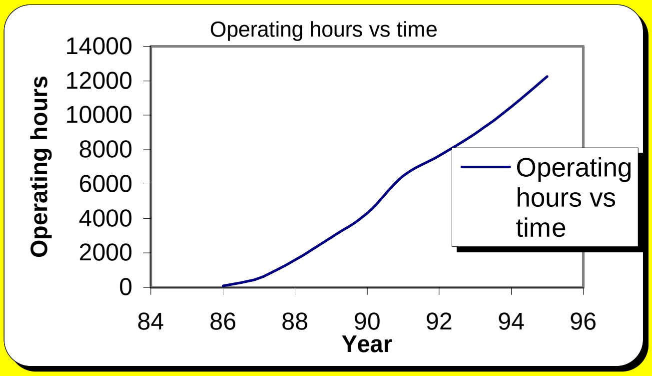

Table 19. RQ-2 Pioneer data

As discussed in Chapter 3, we can calculate only the Mishap Rate (MR) and the Current Mishap Rate (CMR) because we have data only for mishaps and total flight hours. Assuming that each year we have modifications in the system, we calculate the following:

Year	Mishap Rate (MR)	Current Mishap Rate (CMR)
86	0.051921	0.05192108
87	0.025764	0.020129725
88	0.023835	0.022837568
89	0.020311	0.016024418
90	0.01855	0.014915832
91	0.016694	0.0129834
92	0.016735	0.016959213
93	0.015239	0.006271558
94	0.014487	0.010204082
95	0.013721	0.00913242

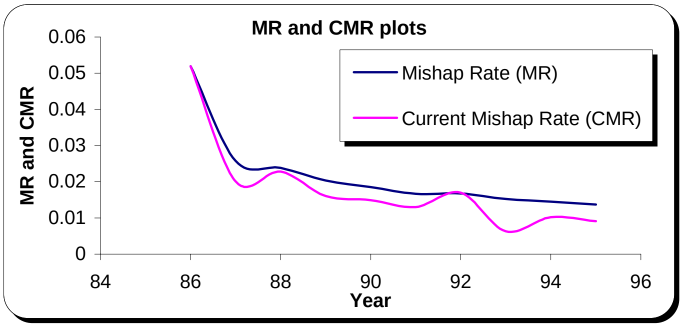

Table 20. MR and CMR

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[165] Carmichael, Bruce W., Col (Sel), and others, “Strikestar 2025,” Appendix A, B & C, “Unmanned Aerial Vehicle Reliability,” August 1996, Department of Defense school, Internet, February 2004. Available at: http://www.au.af.mil/au/2025/volume3/chap13/v3c13-8.htm

It is obvious that both MOPs provide the notion of rapid improvement during the first two years followed by a much slower rate of improvement.

1. We follow Duane’s theory and analyze the data as seen in Table 21. We assume that reliability improvement efforts have been implemented every year on all similar systems.

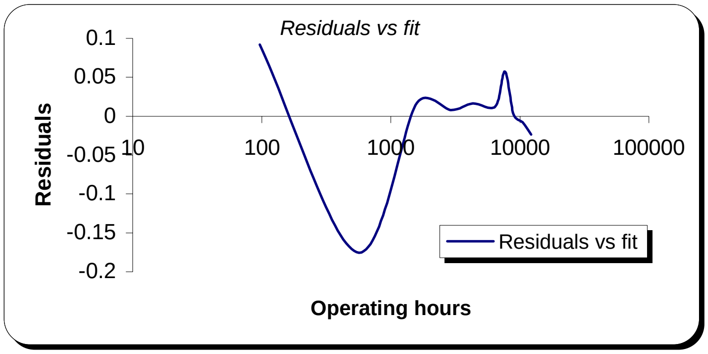
N **Cum Mish**	T **Cum flight hours**	**N/T**	**ln(T)**	**ln(N/T)**	**Regression**	**exp(regression)**
5	96.3	0.051921	4.567468	-2.95803	-3.0499928	0.047359265
14	543.4	0.025764	6.297846	-3.658788	-3.4840591	0.030682613
38	1594.3	0.023835	7.37419	-3.736604	-3.7540609	0.023422437
59	2904.8	0.020311	7.97412	-3.896582	-3.9045536	0.020149947
80	4312.7	0.01855	8.369319	-3.987293	-4.0036897	0.018248183
108	6469.3	0.016694	8.774823	-4.092692	-4.1054106	0.016483249
128	7648.6	0.016735	8.942278	-4.090248	-4.1474168	0.015805192
136	8924.2	0.015239	9.096522	-4.183867	-4.186109	0.015205334
152	10492.2	0.014487	9.258387	-4.234507	-4.226713	0.014600302
168	12244.2	0.013721	9.412808	-4.288844	-4.2654495	0.014045553

Table 21. Duane’s Theory Data Analysis

The results from the regression analysis are the following:

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.984226284
R Square	0.968701379
Adjusted R Square	0.964789051
Standard Error	0.073881376
Observations	10



ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.351526748	1.351526748	247.6023	2.65748E-07
Residual	8	0.043667661	0.005458458		
Total	9	1.39519441			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-1.90424026	0.129763159	-14.6747372	4.57E-07
ln(T)	-0.25085068	0.015941821	-15.7353841	2.66E-07

Table 22. Regression Results

In that case α is -0.25 for the total 12,244.2 hours of operations. In the next figure, we can see Duane’s regression and failure rate versus time plots.

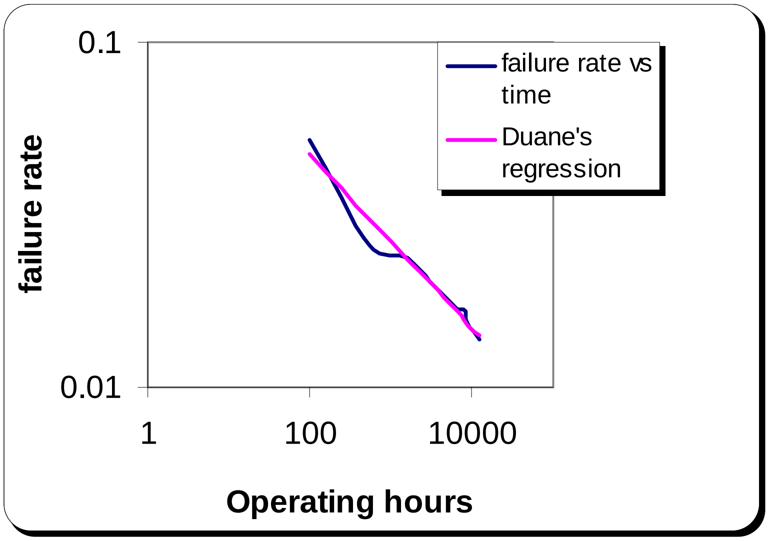


Figure 38. Duane’s Regression and Failure Rate versus Time

From the residual and the Duane’s plots we see a steeper descent for the failure rate in the first years followed by a short period of constant failure rate. The last year’s failure rate is not as steep as the first year’s.

2. Using the same data set, we concentrate on the last six years, from 1990 to 1995.

Year	Mishaps	Fllight hours
90	21	1407.9
91	28	2156.6
92	20	1179.3
93	8	1275.6
94	16	1568
95	16	1752

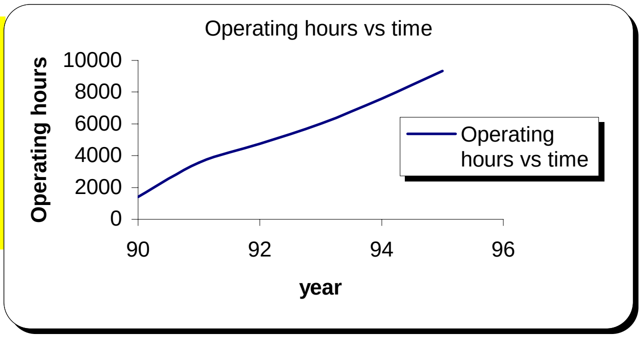


Table 23. RQ-2 Pioneer Data, 1990 to 1995

We follow Duane’s theory and analyze the data as seen in the next table.

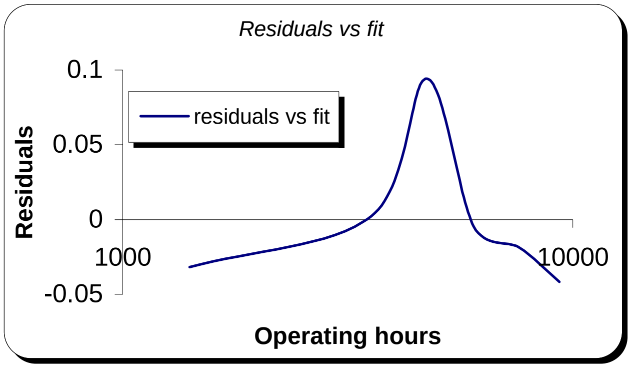
N	T					
Cum Mish	**Cum flight hours**	**N/T**	**ln(T)**	**ln(N/T)**	**Regression**	**exp(regression)**
21	1407.9	0.014916	7.249855	-4.205332	-4.173563	0.015397302
49	3564.5	0.013747	8.178779	-4.286959	-4.2891601	0.013716442
69	4743.8	0.014545	8.464594	-4.230487	-4.3247274	0.013237158
77	6019.4	0.012792	8.702743	-4.358937	-4.3543631	0.012850622
93	7587.4	0.012257	8.934244	-4.401645	-4.3831715	0.012485697
109	9339.4	0.011671	9.141997	-4.450649	-4.4090247	0.012167039

Table 24. Duane’s Theory Data Analysis for 1990 to 1995

Now the results from the regression analysis follow:

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.864537515
R Square	0.747425115
Adjusted R Square	0.684281394
Standard Error	0.054749695
Observations	6



ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.035481414	0.035481	11.83689	0.026282253
Residual	4	0.011990116	0.002998		
Total	5	0.047471531			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-3.271377559	0.306285094	-10.68083	0.000435
ln(T)	-0.124441862	0.036169936	-3.440478	0.026282

Table 25. Regression Results for 1990 to 1995

Now the parameter α is -0.12 for the last 9,339.4 hours of operations. That means we have less rapid reliability growth the last six years. Figure 39 depicts Duane’s regression and failure rate versus time plot:

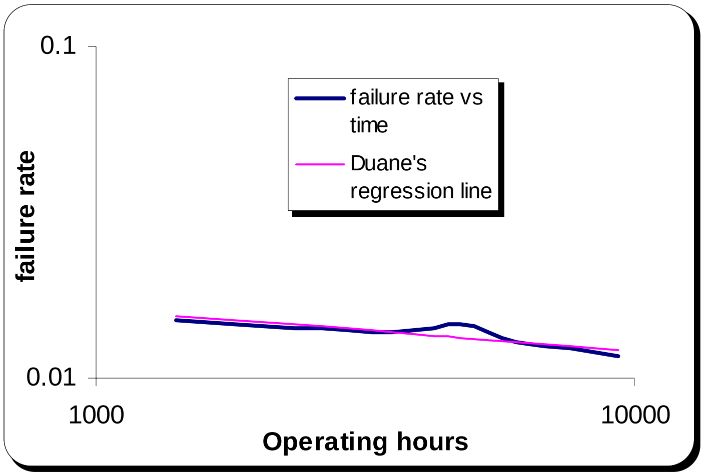


Figure 39. Duane’s Regression and Failure Rate versus Time for 1990 to 1995

Comparing the two time periods, we can say that rate of reliability growth for the last six years (factor of -0.12) from 1990 to 1995 decreased compared to the overall factor -0.25 for the whole ten-year period from 1986 to 1995.

3. Using the same data set, we concentrate in the first six years from 1986 to 1991.

Year	Mishaps	Fllight hours
86	5	96.3
87	9	447.1
88	24	1050.9
89	21	1310.5
90	21	1407.9
91	28	2156.6

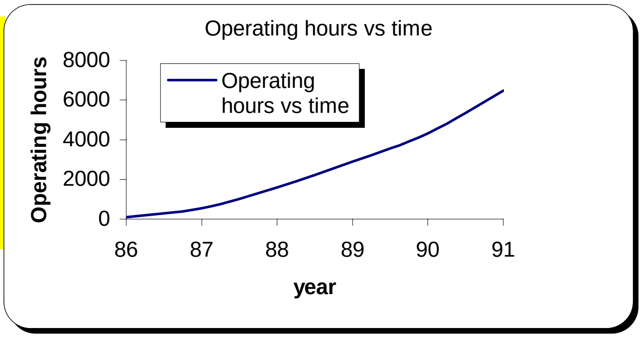


Table 26. RQ-2 Pioneer Data, 1986 to 1991

We follow Duane’s theory and analyze the data as seen in the next table:

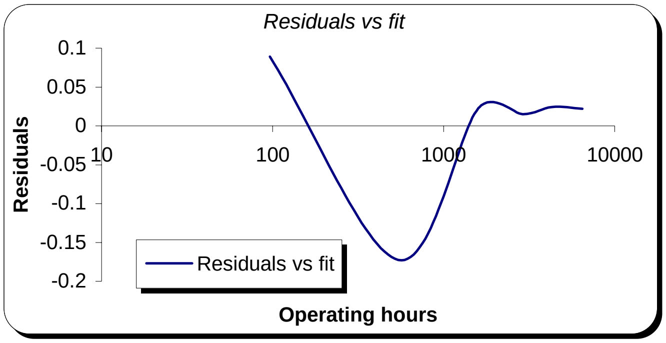
N Cum Mish	T Cum flight hours	N/T	ln(T)	ln(N/T)	Regression	exp(regression)
5	96.3	0.051921	4.567468	-2.95803	-3.0470131	0.047500591
14	543.4	0.025764	6.297846	-3.658788	-3.4860799	0.030620672
38	1594.3	0.023835	7.37419	-3.736604	-3.7591921	0.023302559
59	2904.8	0.020311	7.97412	-3.896582	-3.9114186	0.020012093
80	4312.7	0.01855	8.369319	-3.987293	-4.0116967	0.018102654
108	6469.3	0.016694	8.774823	-4.092692	-4.1145894	0.016332645

Table 27. Duane's Theory Data Analysis for 1986 to 1991

Now the results from the regression analysis follow:

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.975768582
R Square	0.952124325
Adjusted R Square	0.940155406
Standard Error	0.099437813
Observations	6



ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.786578144	0.786578144	79.54973601	0.000873629
Residual	4	0.039551515	0.009887879		
Total	5	0.826129659			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-1.888061479	0.209552206	-9.009981407	0.000840246
ln(T)	-0.25374049	0.028449223	-8.919065871	0.000873629

Table 28. Regression Results for 1986 to 1991

Now α is -0.25 for the first 6469.3 hours of operations. In the next figure, we see Duane's regression and failure rate versus time plots:

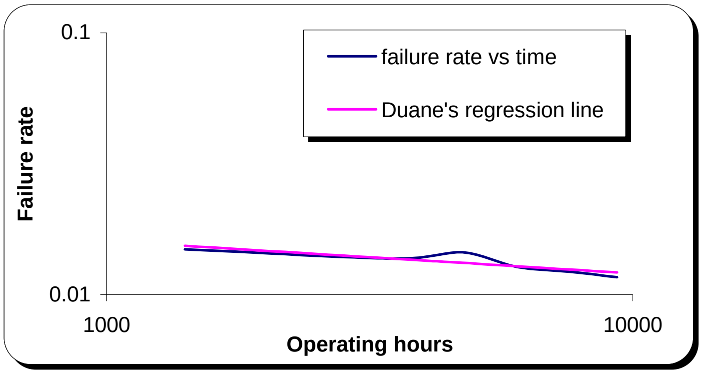


Figure 40. Duane’s Regression and Failure Rate versus Time for 1986 to 1991

If we compare the first six years with the last six years, we can say that reliability growth for the last six years has increased according to the factor of -0.12, instead of the factor -0.25, which related to the first six years. We do not know why the reliability growth rate has decreased, but it has.

4. We can use the Duane curve to predict the MTBF for the future. From the previous discussion on Duane’s plots on IIIB4, MTBF is $K \cdot T^{\alpha}$ where $K = e^{b}$. Using the results for the last six years we have a is -0.1244 and b is -3.2714. So the equation for the curve is $MTBF = e^{-3.2714} \cdot T^{-0.1244}$. This curve can be used as the prediction curve for the MTBF. For example, in 12,000 hours of operation after 1990, the MTBF will be 0.011793 failures per hour of operation or 12 failures per 1,000 hours of operation.

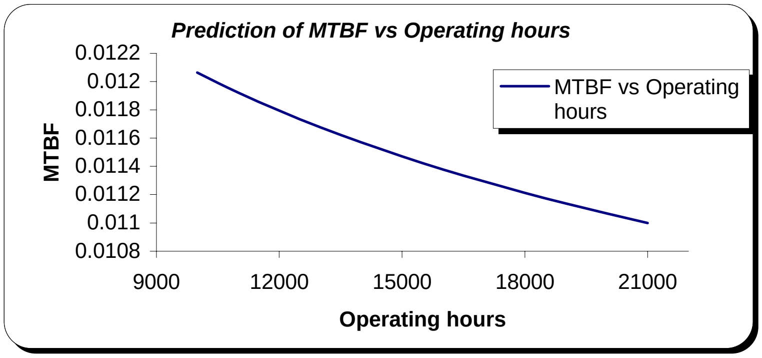


Figure 41. Prediction Plot Curve

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V. CONCLUSION

A. SUMMARY

From the material presented in this thesis, we can conclude the following:

1. There is a real need for reliability improvement in Small UAV systems.

2. RCM (or MSG-3) is a system suitable for civil and military manned aviation and other industry fields in which experience is prevalent, hidden failures can be easily identified by personnel, and safety considerations are the primary factor. For small UAV systems in military applications, safety is not the primary factor. Experience has not reached the manned aviation levels and hidden failures for unmanned systems are very difficult to be observed. Therefore MSG-3 is not a suitable standard for SUAVs.

3. FMEA may be used for almost any kind of reliability analysis that focuses on finding the causes of failure. A good and complete knowledge of the system is necessary prior to proceeding with the FMEA. FMEA is an appropriate method for SUAVs. This thesis has developed FMEA forms for the SUAV.

4. FTA is another useful method of analysis based on the top-down approach and can be used to focus only on the weak points that need enhancing. It is appropriate for SUAVs, and can be used to focus on engine, control, and navigation subsystems that are among the most critical elements. We developed FTA diagrams for the SUAV in this thesis.

5. Functional flow diagrams or block diagrams are used to give a quick and comprehensive view of the system design requirements illustrating series and parallel relationships, hierarchy and other relationships among system’s functions. Since a SUAV is essentially a series system it is less useful.

6. FRACAS, a failure reporting analysis and corrective action system, should be implemented for a program during production, integration, test, and field deployment phases to allow for the collection and analyses of reliability and maintainability data for the hardware and software items. For a successful reliability improvement program, all failures should be considered. SUAVs need FRACAS system.

This research effort developed the framework of one aircraft, including the necessary forms.

7. For SUAVs we have to use fault avoidance due to size and weight limitations. Redundancy cannot be easily implemented, especially due to platform cost and size constrains.

8. In a series structure, like SUAVs, the component with the lowest reliability is the most important one for reliability improvement. Currently, there is no bans for estimating the reliability of a system for operational planners.

9. We can track the overall reliability of a system for SUAVs under experimental development by implementing a method that records failure data. By analyzing the data we can calculate and predict reliability growth.

10. Similarly we can track the reliability of subsystems of a SUAV system. We divide the system into:

- Propulsion and power
- Flight control and navigation
- Communication
- GCS (Human in the loop)
- Miscellaneous

and keep track of the reliability for each subsystem separately. The forms that we have developed can be used as data source for subsystem reliability separation.

12. For a reliability improvement program, we need to:

- Conduct an Environmental Stress Screening (ESS),
- Calibrate and verify the instruments for the field tests or field operations,
- Set the initial weather restrictions for UAVs flights,
- Execute a FMEA of the system and/or perform an FTA,
- Establish a FRACAS,

- Track of reliability improvement,
- Complete a reliability improvement plan.

13. Reliability costs, and benefits, are like an investment. One truly gets what one pays for.

This thesis is a qualitative approach to the issue of reliability and UAVs. In order to obtain further benefit and value from that research effort, we must have data. For a specific type of UAV, we can start implementing FRACAS and collecting data. A database can be created easily after the implementation of FRACAS, and we can start analyzing and interpreting reliability improvement, if any, quite soon.

B. RECOMMENDATIONS FOR FUTURE RESEARCHERS

This thesis outlines methods of improving SUAV reliability. Methods must be defined for better data collections. Real data from SUAV systems must be collected in order to formulate reliability databases. The quantitative reliability analysis follows and detailed information about reliability improvement results.

Researching many issues would be worthwhile.

1. SUAVs are considered expendables since no pilot is onboard. As we increase their reliability, their cost, and their importance in the battlefield operations, we have to start considering their survivability. Being small in size may be is not enough to cope with enemy-fires. Researching survivability issues for SUAVs is another field of interest with many extensions and relations to design philosophy and cost.

2. Some experts believe that difficult problems can be solved with better software, but software is not free. In the near network-centric future, software will probably be one of the most expensive parts of a UAV system. Additionally, software is a dynamic part of the system. It must be constantly upgraded to meet new expectations, or to integrate new equipment technologies. For that reason software reliability is another critical issue that will become more intense in the near future. The emerging question is how we can find the best means to maintain software reliability at acceptable levels.

3. Similar to the above issue, micro-technologies are quickly evolving. New ones are rapidly being inserted into UAV systems. In what way can our reliability tracking methodology cope with new subsystems?

4. If there is a need to achieve a certain level of reliability, what would the economic consequences be?

5. Generally, it would be of great interest to research the potential mechanisms for incorporating new equipment into a reliability improvement program.

6. What is the best number of maintenance personnel to keep the system at a given level of availability?

7. What should the spares policy be for SUAVs?

8. What fraction of failures are due to software instead of hardware failures?

Data collected using the methods developed in this thesis will provide the material with which to answer these essential questions.

APPENDIX A: DEFINITION OF FMEA FORM TERMS

1. First Part of the Analysis of Design FMEA[166]

(1) Subsystem Identification: Name the subsystem or identification title of the FMEA.

(2) Design Responsibility: Name the system design team and for (2A) name the head of the system design team.

(3) Involvement of Others: Name other people or activities within the company that affect the design of the system.

(4) Supplier Involvement: Name other people, suppliers and/or outside organizations that affect the design of the system.

(5) Model/product: Name the model and/or the product using the system.

(6) Engineering Release Date: This is the product release date.

(7) Prepared by: The name of the FMEA design engineer.

(8) FMEA Date: Record the date of the FMEA initiation.

(9) FMEA Date, revision: Record the date of the latest revision.

(10) Part Name: Identify the part name or number.

2. The Second Part of the Analysis of Design FMEA[167]

(11) Design Function: This is the objective function of the design. The function should be described in specific terms. Active verbs defining functions and appropriate nouns should be used.

(12) Potential Failure Mode: The defect refers to the loss of a design function or a specific failure. “For each design function identified in Item 11 the corresponding failure of the function must be listed. There can be more than one failure from one function. ” To identify the failure mode ask the question: “How could this

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[166] The material from this section is taken (in some places verbatim) from: Stamatis, pages 130-132.

[167] Ibid, pages 132-149.

design fail?” or “Can the design break, wear, bind and so on?” Another way to identify a failure mode is through a FTA. In a FTA the top level is the loss of the part function and the lower levels are the corresponding failure modes.

(13) Potential Effect(s) of failure: This is the ramification of the failure on the design. The questions usually asked are “What does the user experience as a result of that failure?” or “What are the consequences for the design?” To identify the potential effects, documents like historical data, warranty documents, field-service data, reliability data and others may be reviewed. If safety is an issue, then an appropriate notation should be made.

(14) Critical Characteristics: Examples of critical items may be dimensions, specifications, tests, processes etc. These characteristics affect safety and/or compliance with rules and regulations and are necessary for special actions or controls. An item is indicated critical when its severity is rated 9 to 10 with occurrence and detection is higher than 3.

(15) Severity of Effect: Indicates the seriousness of a potential failure. For critical effects severity is high while for minor effects severity is very low. Usually there is a rating table, which is used for evaluation purposes. This table is made in such a way that all designing issues have been taken into consideration. The severity rating should be based on the worst effect of the failure mode. An example of the severity guideline table for design FMEA is in Table 29.

Effect	Rank	Criteria
None	1	No effect
Very slight	2	User not annoyed. Very slight effect on the product performance. Non-essential fault noticed occasionally
Slight	3	User slightly annoyed. Slight effect on the product performance. Non-essential fault noticed frequently.
Minor	4	User's annoyance is minor. Minor effect on the product performance. Non-essential faults almost always noticed. Fault does not require repair.
Moderate	5	User has some dissatisfaction. Moderate effect on the product performance. Fault requires repair.
Significant	6	User is inconvenienced. Degradation on product's performance but safe and operable. Non-essential parts inoperable.
Major	7	User is dissatisfied. Major degradation on product's performance but safe and operable. Some subsystems are inoperable.
Extreme	8	User is severely dissatisfied. Product is safe but inoperable. System is inoperable.
Serious	9	Safe operation and compliance with regulations are in jeopardy.
Hazardous	10	Unsafe for operation, non-compliance with regulations, completely unsatisfactory.

Table 29. Example of Severity Guideline Table for Design FMEA (After Stamatis, page 138)

(16) Potential Cause of Failure: This identifies the cause of a failure mode. For a failure mode there may be a single cause or numerous causes, which in that case are symptoms, with one root cause. A good understanding of the system's functional analysis is needed at that stage. Trying to find the real cause can identify the root cause. Asking "Why?" five times is the rule of thumb for finding the cause of a failure mode. It is essential to identify all potential failures while performing the FMEA. There is not always a linear or "one-to-one relationship" between the cause and failure mode. Listing as many causes as possible makes FMEA easier and less error prone. If the severity of a failure is rated 8 to 10, then an effort should be made to identify as many root causes as possible.

(17) Occurrence: This is the value that corresponds to the estimated frequency of failures for a given cause over the life of the design. To identify the frequency for each cause, we need reliability mathematics, expected frequencies or the

cumulative number of component failures per 100 or 1000 components (CF/100 or CF/1000). If expected frequencies and/or the cumulative number of failures cannot be estimated, then alternative systems or components could be examined for similar data that could be used as a surrogate. Usually, the assumption of a single-point-failure is used in design FMEA. It is a component failure, which could cause the system to fail and is not balanced by an alternative method. So occurrence referred to a single-cause-failure. A guideline for occurrence is shown in Table 30.

Occurrence	**Rank**	**Criteria**	**CF/1000**
Almost impossible	1	Failure unlikely. Historical data indicate no failures	<0.00058
Indifferent	2	Rare number of failures likely	0.0068
Very slight	3	Very few failures likely	0.0063
Slight	4	Few failures likely	0.46
Low	5	Occasional number of failures likely	2.7
Medium	6	Medium number of failures likely	12.4
Moderately high	7	Moderately high number of failures likely	46
High	8	High number of failures likely	134
Very high	9	Very high number of failures likely	316
Almost certain	10	Failure almost certain	>316

Table 30. Example of Occurrence Guideline Table for Design FMEA (After Stamatis, page 142)

(18) Detection Method: This is a procedure, test, design or analysis used to detect a failure in a design or part. It can be very simple or very difficult, to identify problems before they reach the end user. If there is no method, then “None identified at this time” is the answer. Two of the leading questions are “How can this failure be discovered?” and “In what way can this failure be recognized?” A checklist may be helpful. Nevertheless, some of the most effective ways to detect a failure are simulation techniques, mathematical modeling, prototype testing, specific design tolerance studies and design and material review. The design review is an important way to revisit the suitability of the system or design. A design review can be quantitative or qualitative, using a systematic methodology of questioning and design.

(19) Detection: Is the "likelihood that the proposed design controls will detect" the root cause of a failure mode before it reaches the end user. The detection rating estimates the ability of each of the controls in (18) to detect failures before it reaches the customer. A typical detection guideline is shown in Table 31.

Effect	**Rank**	**Criteria**
Almost certain	1	Has the highest effectiveness
Very high	2	Has very high effectiveness
High	3	Has high effectiveness
Moderately high	4	Has moderately high effectiveness.
Medium	5	Has medium effectiveness
Low	6	Has low effectiveness
Slight	7	Has very low effectiveness.
Very slight	8	Has the lowest effectiveness
Indifferent	9	It is unproven, or unreliable, effectiveness unknown
Almost impossible	10	There is no design technique available or known

Table 31. Example of Detection Guideline Table for Design FMEA (After Stamatis, page 147)

(20) Risk Priority Number (RPN): This is the product of severity, occurrence, and detection. RPN is just a number that represents the priority of the failure. Reducing RPN is the FMEA's goal, and this is the result after the reduction in severity and/or occurrence and/or detection. So, changing the design, one can reduce the severity rating. By improving the requirements and engineering specifications while focusing on "preventing causes or reducing their frequencies," one can reduce the occurrence rating. Adding detection equipment and tools or "improving the design evaluation technique" can reduce the detection rating.

(21) Recommended Actions: These may be specific actions or suggestions for further study. Recommended actions intend to reduce the RPN for the different failure modes. Prioritization of failure modes according to their RPN, severity and occurrence, is needed while conducting a FMEA.

(22) Responsible Area or Person and Completion Date: Name the responsible person/area and the completion date for the recommended action.

(23) Action Taken: This is about the follow-up actions.

(24) Revised RPN: This is the reevaluation of RPN after the corrective actions have been implemented. If the revised RPN is less than the original then that indicates an improvement.

3. Third Part of the Analysis of Design FMEA[168]

(25) Approval signatures: Name the authority to conduct the FMEA.

(26) Concurrence signatures: Names there responsible for carrying out the FMEA.

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[168] Stamatis, page 149.

APPENDIX B: THE MRB PROCESS

The Maintenance Review Process (MRB process) "is broadly defined as all of the activities necessary to produce and maintain a Maintenance Review Board Report (MRBR)." The process involves three major objectives, which are to ensure that:

1. Scheduled maintenance instructions (tasks and intervals) which are developed for a specific aircraft, contribute to the continuing airworthiness and environmental requirements of the Regulatory Authorities and the Standards and Recommended Practices (SARPs) as published by the International Civil Aviation Organization (ICAO).

2. The tasks are realistic and capable of being performed.

3. The developed scheduled maintenance instructions may be performed with a minimum of maintenance expense.[169]

"MRBRs are developed as a joint exercise involving the air operators, the type of certificate applicant," ATA and other Regulatory Authorities. The MRB process

> consists of a number of specialist working groups who use an analytical logic plan to develop and propose maintenance/inspection tasks for a specific aircraft type. The proposed tasks are presented to an Industry Steering Committee (ISC) who, after considering the working group proposals, prepares a proposal for the MRBR.

The MRB chairperson reviews the proposed MRBR, which is then published as the MRBR.[170]

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[169] Transport Canada Civil Aviation (TCCA), Maintenance Instruction Development Process, TP 13850, Part B, "The Maintenance Review Board (MRB) Process(TP 13850), Chapter 1. General," last updated: April 19, 2003, Internet, February 2004. Available at: http://www.tc.gc.ca/civilaviation /maintenance/aarpd/tp13850/partB.htm

[170] TCCA, Chapter 2.

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APPENDIX C: FAILURES

1. Functions[171]

A function statement should consist of a verb, an object and a desired standard of performance. For example: A SUAV platform flies up to 4,000 feet at a speed of at least on 55 knots sustained. The verb is "fly" while the object is "a SUAV platform" and the standard is "up to 4,000 feet at a sustained speed of at least 55 knots."

2. Performance Standards[172]

In our example: One process that degrades the SUAV platform, in other words one failure mode for the SUAV, is engine failure. Engine failure happens due to many reasons. The question is how much an engine failure can impair the ability of the UAV to fly at the desired altitude on the designated sustained speed.

In order to avoid degradation, the SUAV must be able to perform better than the minimum standard of performance desired by the user. What the asset is able to deliver is known as its "initial capability," say 4,500 feet on 60 knots sustained speed. This leads one to define performance as:

- Desired performance, which is what the user wants the asset to do (4,000 feet on 55 knots sustained speed in our case).
- Built-in capacity, which is what the asset really is (4,500 feet on 60 knots sustained speed in our case).

3. Different Types of Functions[173]

Every physical asset usually has more than one function. If the objective of maintenance is to ensure that the asset can continue to fulfill these functions, then they must all be identified together with their current standards of performance.

Functions are divided in two main categories: primary and secondary functions.

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[171] Moubray, John, an excerpt of the first chapter of the book "Reliability-centered Maintenance," Plant Maintenance Resource Center, "Introduction to Reliability-centered Maintenance," Revised December 3, 2002, Internet, May 2004, Available at: http://www.plant-maintenance.com/RCM-intro.shtml

[172] Moubray, "Introduction."

[173] The material from this section is taken (in some places verbatim) from: Moubray, "Introduction."

a. Primary functions are fairly easy to recognize and most industrial assets are based on their primary functions. For example, the primary function of a “printer” is to print documents, and of a “crusher” is to crush something, etc. In the SUAV example the primary function is to provide lift and thrust so as the platform flies up to 4,000 feet at a sustained speed of at least 55 knots.

b. In addition to their primary functions, most assets are expected to fulfill one or more additional functions, which are the secondary functions. For example, the primary function of the SUAV platform in the example, is to provide thrust and lift so as to fly up to 4,000 feet on 55 knots sustained speed at least. A secondary function could be to use an auto-recovery system. Secondary functions could include environmental expectations, safety, control, containment, and comforts aspects, appearance, protection, economy, efficiency and other extra functions.

4. Functional Failure[174]

If, for any reason, the asset is unable to do what the user wants, the user will consider it to have failed. “Failure is defined as the inability of any asset to do what its users want it to do.” This definition treats the concept of failure as if it applies to an asset as a whole.

However, each asset has more than one function, and each function often has more than one desired standard of performance. It is possible for the asset to fail for each function, so the asset can fail in different states. Therefore, it is required that failure can be defined more accurately in terms of loss of specific functions rather than the failure of an asset as a whole.

According to British Standard (BS) 4778 failure is defined as “The termination of an item’s ability to perform a required function.”

5. Performance Standards and Failures[175]

The limit between satisfactory performance and failure is specified by a performance standard. Failure can be defined by defining a functional failure as follows:

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[174] The material from this section is taken (in some places verbatim) from: Moubray, “Introduction.”

[175] The material from this section is taken (in some places verbatim) from: Hoyland, pages 11-12.

A functional failure is defined as the inability of any "asset to fulfill a function to a standard of performance, which is acceptable to the user." [176]

A failure could have different aspects of functional failure:

- Partial and total failure
- Upper and lower limits
- Gauges and indicators
- The operating context

Failures may be classified in many different ways:

a. Sudden versus gradual failures

b. Hidden versus evident failures

c. According to effects of severity

(1). Critical failure: A failure that is sudden and causes termination of one or more primary functions.

(2). Degraded failure: A failure that is gradual and/or partial.

(3). Incipient failure: A deficiency in the condition of an item so that a critical or degraded failure can be expected unless corrective action is not taken.

d. Another classification according to the effects of severity by US Mil-Std 882, "System Safety Program Requirements":

(1) Catastrophic, which results in loss of life and/or loss of system.

(2) Critical, which results in severe injury and/or illness and/or severe system damage.

(3) Marginal, which results in minor injury and/or illness and/or minor system damage.

(4) Negligible with less than minor results.

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[176] The material from this part of section is taken (in some places verbatim) from: Aladon Ltd, "Introduction."

e Another classification according to the effects of severity:

(1) Primary failure due to aging.

(2) Secondary failure due to excessive stresses.

(3) Command fault or transient failures due to improper control signal or noise.

6. Failure Modes[177]

"Once each functional failure has been identified, the next step is to try to identify all the events that are reasonably likely to cause each failed state. These events are known as failure modes." Failure modes are those that have occurred on the same or similar equipment operating with the same parameters and conditions, failures that can be prevented by existing maintenance policies, and failures that have not yet happened but they can be considered as likely to happen.[178]

Failure mode is "the effect by which a failure is observed on the failed item." Technical items are designed to perform one or more functions. So a failure mode can be defined as nonperformance of one of these functions. Failure modes may generally be subdivided as "demanded change of state is not achieved" and "change of conditions."

For example, an automatic valve may show one of the following failure modes:

a. Fail to open on command

b. Fail to close on command

c. Leakage in closed position

The first two failure modes are "demanded change of state is not achieved" while the third one is "change of condition."

7. Failure Effects[179]

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[177] The material from this section is taken (in some places verbatim) from: Hoyland, page 10.

[178] The material from this part of section is taken (in some places verbatim) from: Aladon Ltd, "Introduction," page 5.

[179] The material from this section is taken (in some places verbatim) from: Aladon Ltd, "Introduction," page 5.

The fourth of the seven questions in the RCM process, as previously mentioned in IIA2b of this thesis, is listing “What happens when each failure occurs?” These are known as “failure effects.”

Failure effects describe what happens when a failure occurs. While describing the effects of a failure, the following should be recorded:

a. What is the evidence that the failure has happened?

b. In what way does it pose a threat to safety or the environment?

c. In what way does it affect production or operation?

d. What physical damage is caused by the failure?

e. What must be done to repair the failure?

8. Failure Consequences[180]

Failures affect output, but other factors such as product quality, customer service, safety or environment also influence output. The nature and severity of these effects govern the consequences of the failure. The failure effects tell us what happens, and when a failure occurs. The consequences describe how and how much it matters. For example, if we can reduce the occurrence (frequency) and/or severity of failure effects, then we can reduce the consequences.

Therefore, if a failure matters very much, efforts will be made to mitigate or eliminate the consequences. On the contrary, if the failure is of minor consequence, no proactive action may be needed.

A proactive task is worth doing if it reduces the consequences of the failure mode and justifies the direct and indirect costs of doing the task.

Failure consequences could be classified as:

a. Environmental and safety consequences, when it is not able to fulfill the local and/or national and/or international environmental standards, or if the failure causes injury and/or death.

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[180] The material from this section is taken (in some places verbatim) from: Aladon Ltd, “Introduction,” page 5.

b. Operational, if the failure affects the operation, production output, quality, cost or customer satisfaction.

c. Non-operational, when only maintenance and/or repair is involved, without affecting the environmental, safety or production.

d. Hidden, when failures have no direct impact, but they expose the organization to multiple failures with serious and often catastrophic consequences.

APPENDIX D: RELIABILITY

1. Introduction to Reliability[181]

Reliability is a concept that has dominated systems design, performance and operation for the last 60 years. It appeared after WWI, when it was used to compare operational safety of one, two, three, and four-engine airplanes. At that time reliability was measured as the number of accidents per flight hour.

During WWII, a group of scientists, under Wernher von Braun in Germany, developed the V-I missile. After the war it was reported that the first ten V-I missiles were all ridiculous failures. All of the first missiles either exploded on the launching rail, or landed earlier than planned, in the English Channel. It was the mathematician Robert Lusser who analyzed the missile system and derived the “product probability law of series components.” The theorem states that “a system is functioning only if all the components are functioning and is valid under special assumptions.” It simply says that the reliability of the system is equal to the product of the system’s individual components reliabilities. If the system has many components, then its reliability is rather low, even though the individual components have high reliabilities.

In order to avoid low system reliability, engineers in the USA, at that time tried to improve the individual system’s components. They used “better” materials and “better” designs for the products. The result was higher system reliability but broad and further analysis of the problem was not performed.

By the end of 1950s and early 1960s, interest in the USA focused on production of the intercontinental ballistic missile and space research like the Mercury and Gemini programs. In the race to put a man on the moon, a reliable program was very important. The first association for engineers working with reliability issues was established. *IEEE-Transactions on Reliability* was the first journal published on the subject in 1963. After that, a number of textbooks were published and in the 1970s many countries from Europe

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[181] The material from this section is taken (in some places verbatim) from: Hoyland, pages 1-2.

and Asia began dealing with the same issues. Soon it became clear that a low reliability level cannot be compensated by extensive maintenance.

2. What is Reliability?

"Until the 1960s, reliability was defined as the probability that an item will perform a required function under stated conditions for a stated period of time." According to the International Standard Organization (ISO) 8402 and British Standard (BS) 4778, "reliability is the ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time." The term "item" is used to denote any component, subsystem or an entity system. A "required function" may be a single function or a combination of functions necessary to provide a certain service.[182]

For a defense acquisition system, reliability is a measure of effectiveness.[183] It is one of the "ilities" that a system needs to comply with, in order to be operationally suitable.

We can keep track of reliability by measuring or calculating some measures of performance such as:

a. The probability of completing a mission

b. The number of hours without a critical failure under specified mission conditions or mean time between critical failures (MTBCF)

c. The probability of success as the number of successes divided by the total number of attempts

d. The mean time to failure (MTTF)

e. The failure rate (failures per unit time)

f. The probability that the item does not fail in a time interval.

3. System Approach

A system is a group of elements, parts, or components that work together for a specified purpose. A failure of the system is related at least to one of its parts or elements

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[182] Hoyland, page 3.

[183] Hoivik, slide 6.

or components failure. A part starts at its working state and for various reasons changes to a failed state after a certain time. The time to failure is considered a random variable that we can model by a failure-distribution function.[184]

Failure occurs due to a complex set of interactions between the material properties and/or physical properties of the part and/or stresses that act on the part. The failure process is complex and is different for different types of parts or elements or components.[185]

The strength or endurance of a part may be significantly and unpredictably varied because of manufacturing variability. So that strength, say "X", must be modeled as a random variable. When the system is being used it is subjected to a stress, say "Y". If "X" is less than "Y", then the part fails immediately because its strength is not enough to withstand the magnitude of stress "Y". If "Y" is less than "X", then the strength of that part is enough to withstand the stress and the part is functional.

Even though the failure mechanisms vary, they are basically divided into two categories, the overstress and the wear-out. The overstress failures are those due to fracture, yielding, buckling, large elastic deformation, electrical overstress, and thermal breakdown. Wear-out failures are those due to wear, corrosion, metal migration, inter-diffusion, fatigue-crack propagation, diffusion, radiation, fatigue-crack initiation and creep.[186]

For multi-component systems like a SUAV the number of parts may be very large and a multilevel decomposition of such a system is necessary.

4. Reliability Modeling

a. System Failures[187]

System failures for a multi-component system can be modeled in several ways. A system failure is due to the failure of at least one of its components. So analysis

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[184] Hoyland, page 18.

[185] Pecht, page 93.

[186] Ibid, page 96.

[187] The material from this section is taken (in some places verbatim) from: Blischke, pages 204-205.

of failures at the component level is the initial point of a failure system analysis. “Henley and Kumamoto (1981) propose the following classification of failures:

(1) Primary failure

(2) Secondary failure

(3) Command fault”

Primary or “natural” is when the component fails due to natural causes like aging. In that case, replacement of the aging component is the remedy.

Secondary or “induced” is the failure of a component due to excessive stress resulting from the primary failure of some other component(s) and/or environmental factors and/or user actions.

“Command fault occurs when a component is in not working state because of improper control signals or noise.” This can be due to a user’s faulty operation or a logic controller’s faulty operation signal.

b. Independent vs Dependent Failures[188]

The failure times of components are often influenced by environmental conditions. As the environment becomes “harsher, the time it takes to reach a failure decreases.” Thus if the system’s components share the same environment their failure times are statistically dependent. If the dependence is weak, it can be ignored and failure times can be treated as statistically independent. In that way failure times can be modeled separately using univariate failure-distribution functions. But in case of significant dependence, multivariate failure distributions must be used and modeling becomes much more complicated.

c. Black-Box Modeling189

A system failure is due to the failure of one or more of its components. “The number of failed components that must be restored to their working state is usually small relative to the total number” of the system’s components. Replacing or repairing the defective component(s) restores the system to its operational state. If the restoration

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[188] The material from this section is taken (in some places verbatim) from: Blischke, page 205.

[189] Ibid.

time is very small relative to the mean time between failures, then it can be ignored, and we can model the failure system as a function reflecting the effect of age. In other words, the model function can be viewed as the failure rate of the system through time.

After overhauls or major repairs or design alterations the failure rate of the system can be significantly reduced. Usually, it becomes smaller than the failure rate before.

Therefore, in black-box modeling we can collect data through the life cycle time of a system and find a function that is the failure rate through time. A lot of data is needed in order for the function to be precisely estimated, so black-box modeling is not recommended for the design and development phase of a system because of the changes that continuously alter the failure rate.

d. White-Box Modeling[190]

"In a white-box modeling, system failure is modeled in terms of the failures of the components of the system." We can reach system failures from component failures using the bottom-up (or forward) approach or the top-down (or backwards) approach. In the forward approach, we start with part-level failures, and then we proceed to the system level to evaluate the consequences of such failures on the system's performance. FMEA uses this approach. In the backward approach, we start at the system level failures, and then we proceed downward to the part level to relate pure-system performance to part-level failures. FTA uses this approach.

"The linking of the system performance to failures at the part level can be done either qualitatively or quantitatively." In the qualitative case, we are interested in the causal relations between failures and system performance. In the quantitative case, we can use many measures of system effectiveness, like reliability, in terms of component reliabilities.

For an example assuming independent failures, if a machine has a failure rate of 1 failure every 100 days then the probability of having a failure on any day is 1/100. If a second redundant machine has the same failure rate, then a system that

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[190] Blischke, pages 206-207.

consists of both those machines has a probability that both machines fail on the same day as 1/100 squared or 1/10,000.

e. Reliability Measures[191]

In order to understand the reliability measures, we must determine the "time-to-failure" as a basic step. Time-to-failure of a system or component or part or unit or element (system) is the time elapsing from when the system is put into operation until the first failure. Let *t=0,* the operation starting time. The time to failure is subject to many variables. Consequently, we can represent time-to-failure as a random variable *T*. We can describe the condition or state of the system at time *t* by the condition random variable *X(t)* where $X(t) = \begin{Bmatrix} 1 \text{ if the system is functioning at } t \\ 0 \text{ if the system is in failed condition at } t \end{Bmatrix}$

The graphical representation of *X(t)* versus time *t* is shown in Figure 43.

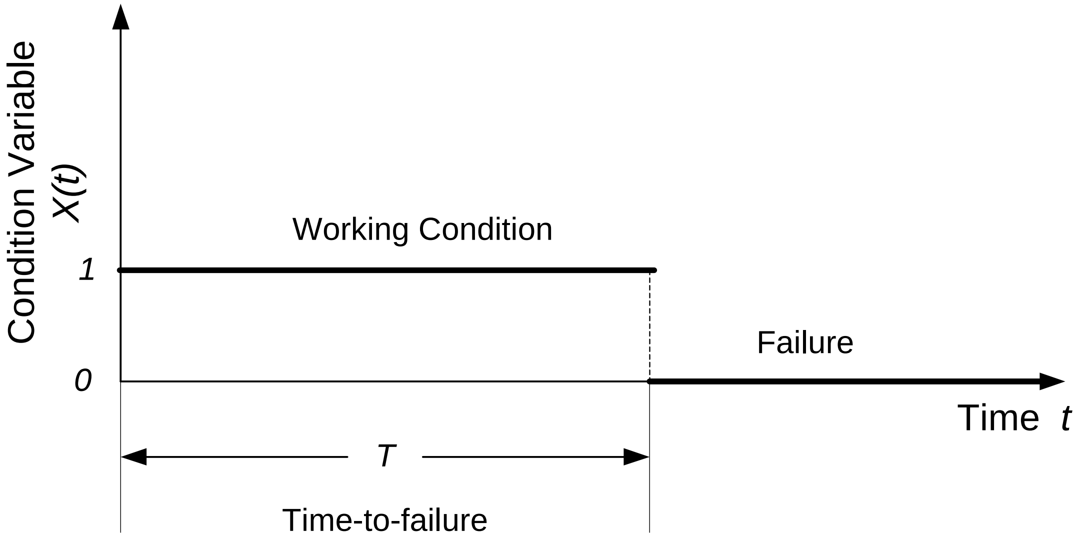

Figure 42. Condition Variable Versus Time.(From Hoyland, page 18)

The time-to-failure may not always be measured in time but can also be measured in numbers of repetitions of operation, or distance of operation, or number of rotations of a bearing, etc. We can assume that the time-to-failure *T* is continuously distributed with a probability density *f(t)* and distribution function :

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[191] The material from this section is taken (in some places verbatim) from: Hoyland, pages 18-25.

$$F(t) = P(T \le t) = \int_0^1 f(u)du \quad \text{for } t > 0 \,.$$

The probability density *f(t)* is defined as :

$$f(t) = \frac{d}{dt}F(t) = \lim_{\Delta t \to 0} \frac{F(t+\Delta t) - F(t)}{\Delta t} = \lim_{\Delta t \to 0} \frac{P(t < T \le t + \Delta t)}{\Delta t} \,.$$

If *Δt* is small then:

$$f(t) \cdot \Delta t = P(t < T \le t + \Delta t) \,.$$

A typical distribution function F(t) and the corresponding density function f(t) are shown in Figure 44.

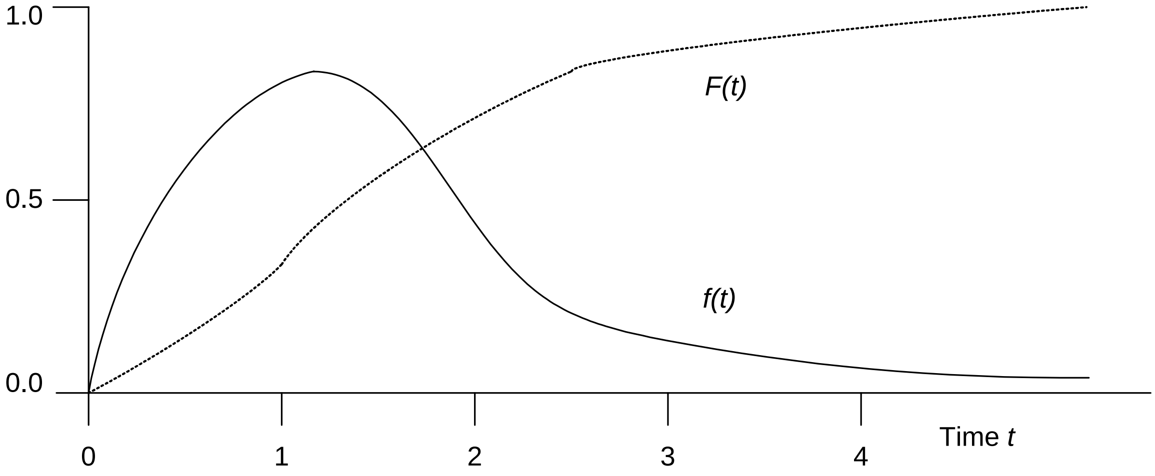

Figure 43. Distribution and Probability Density Functions (From Hoyland, page 18)

There are three important measures of reliability:

(1) The reliability or survivor function *R(t)*

(2) The failure rate *z(t)*

(3) The mean time to failure *(MTTF)*

(1). Reliability or Survivor Function R(t). The reliability function of a system is defined as:

$$R(t) = 1 - F(t) = P(T > t) \text{ for } t > 0. \qquad \text{(A)}$$

So R(t) is the probability that the system has operated without failure in the time interval (0,t]. Equivalently we can say that R(t) is the probability that the unit survives in the time interval (0,t]. The reliability function R(t) is also called the "survivor function". A typical reliability function that corresponds to the distribution function of Figure 43 can be seen in Figure 44.

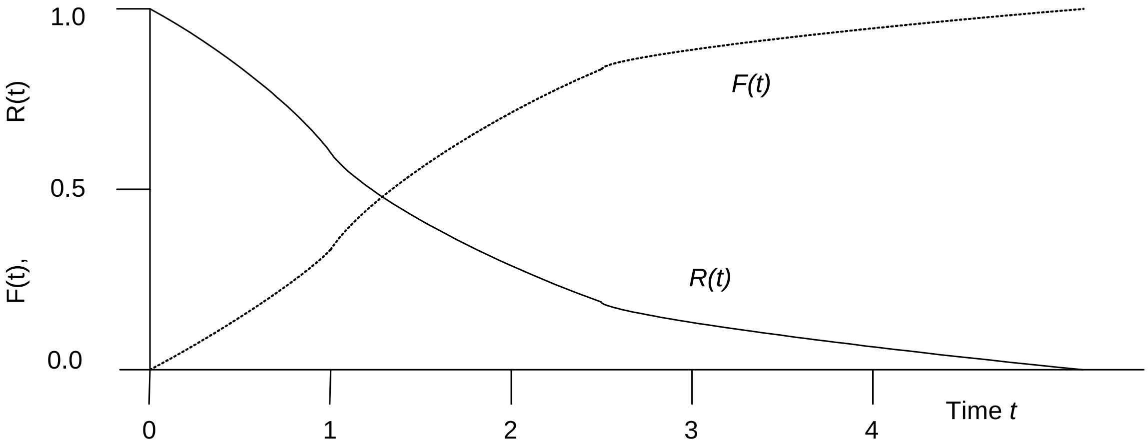

Figure 44. Typical Distribution and Reliability Function

(2). Failure-rate or Hazard Function. The probability that a system will fail in the time interval (*t, t+Δt*], given that it is in operating condition at time *t*, is

$$P(t < T \le t + \Delta t \mid T > t) = \frac{P(t < T \le t + \Delta t)}{P(T > t)} = \frac{F(t + \Delta t) - F(t)}{R(t)}.$$

Failure-rate *z(t)* is the limit as $\Delta t \to 0$ of probability that a system will fail in the interval (*t, t+Δt*], given that it is in operating condition at time *t*, per unit length of time. If this unit length of time approaches 0, then we have the following expression for the failure rate: $z(t) = \lim_{\Delta t \to 0} \frac{P(t < T \le t + \Delta t \mid T > t)}{\Delta t} = \lim_{\Delta t \to 0} \frac{F(t + \Delta t) - F(t)}{\Delta t} \frac{1}{R(t)} \Rightarrow z(t) = \frac{f(t)}{R(t)}$ (B)

because it is known that $f(t) = \lim_{\Delta t \to 0} \frac{F(t + \Delta t) - F(t)}{\Delta t}$ or equivalently

$$f(t) = \frac{d}{dt} F(t) \,. \qquad \text{(C)}$$

From the above it is implied that when *Δt* is small: $P(t < T \leq t + \Delta t \mid T > t) \approx z(t) \cdot \Delta t$. So the conditional probability is approximately equal to the failure rate *z(t)* at time *t,* times the length of the interval *Δt*.

From (A) and (C) we get: $f(t) = \frac{d}{dt}(1 - R(t)) = -R'(t)$.

So (B) becomes:

$z(t) = \frac{-R'(t)}{R(t)} = -\frac{d}{dt} \ln R(t) \Rightarrow$ since R(0)=1, $\int_0^1 z(t)dt = -\ln R(t)$, so $R(t) = e^{-\int_0^t z(u)du}$. Finally we have:

$$f(t) = -R'(t) = -\frac{d}{dt}\left(e^{-\int_0^t z(u)du}\right) \Leftrightarrow f(t) = z(t) e^{-\int_0^t z(u)du}, \; t>0.$$

So the failure-rate or hazard function is very useful for modeling, because everything else can be derived from that.

In the following table the relationships between the distribution function *F(t)*, the density function *f(t)*, the reliability or survivor function *R(t)*, and the failure-rate or hazard function *z(t)* are presented.[192]

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[192] Hoyland, page 22.

	F(t)	**f(t)**	**R(t)**	**z(t)**
F(t)=		$\int_0^t f(u)du$	$1-R(t)$	$1-e^{-\int_0^t z(u)du}$
f(t)=	$\frac{d}{dt}F(t)$		$-\frac{d}{dt}R(t)$	$z(t)e^{-\int_0^t z(u)du}$
R(t)=	$1-F(t)$	$\int_t^\infty f(u)du$		$e^{-\int_0^t z(u)du}$
z(t)=	$\frac{dF(t)/dt}{1-F(t)}$	$\frac{f(t)}{\int_t^\infty f(u)du}$	$-\frac{d}{dt}\ln R(t)$	

Table 32. Relationships Between Functions F(t), R(t), f(t), z(t) (From Hoyland, page 22)

For the most mechanical and electronic systems the failure rate over the life of the system has three discrete periods, characterized by the well known “Bathtub Curve,” shown in Figure 45.[193]

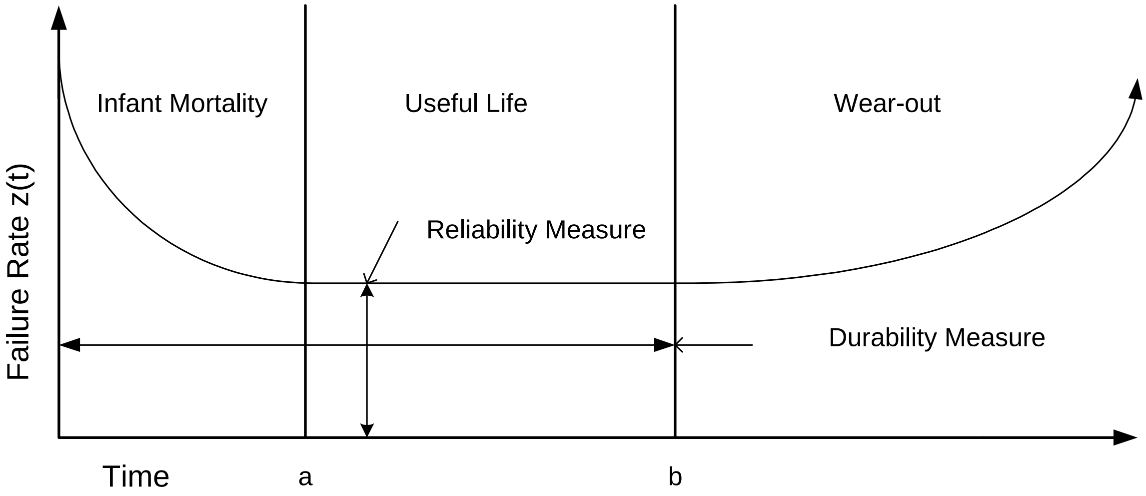

Figure 45. The Bathtub Curve

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[193] RAC *Toolkit*, page 38.

Infant mortality is the first phase of the bathtub curve where the failure rate is high because of early manufacturing tolerances and inadequate manufacturing skills. The failure rate is decreasing through time because of the maturity of the design and the manufacturing process. Useful life is the second phase, which is characterized as a relative constant failure rate. Wear-out is the last phase where components start to deteriorate to such a degree that they have reached the end of their useful life. This can be modeled either piece-wise or as the sum of three failure-rate or hazard functions, one for each phase. Then $R(t) = e^{-\int_0^t z(u)du}$ and

$$z(t) = \begin{cases} z_1(t), \ t < a \\ z_2(t), \ a < t < b \\ z_3(t), \ t > b \end{cases} \text{,or } z(t) = \sum_{i=1}^{3} z_i(t) .$$

These concepts are illustrated in Figure 45.

(3). Mean-Time-to-Failure (MTTF). The MTTF of a system is the expected value of *T,* which is given by the density function *f(t)* and is defined as:

$$MTTF = E(T) = \int_0^\infty tf(t)dt . \qquad \text{(D)}$$

If the time needed to repair or replace a failed system is very short relative to MTTF, then the mean time between failures (MTBF) is represented by MTTF. If the repair time is comparable to MTTF, then the MTBF also includes the mean time to repair (MTTR). These concepts are illustrated in Figure 46.

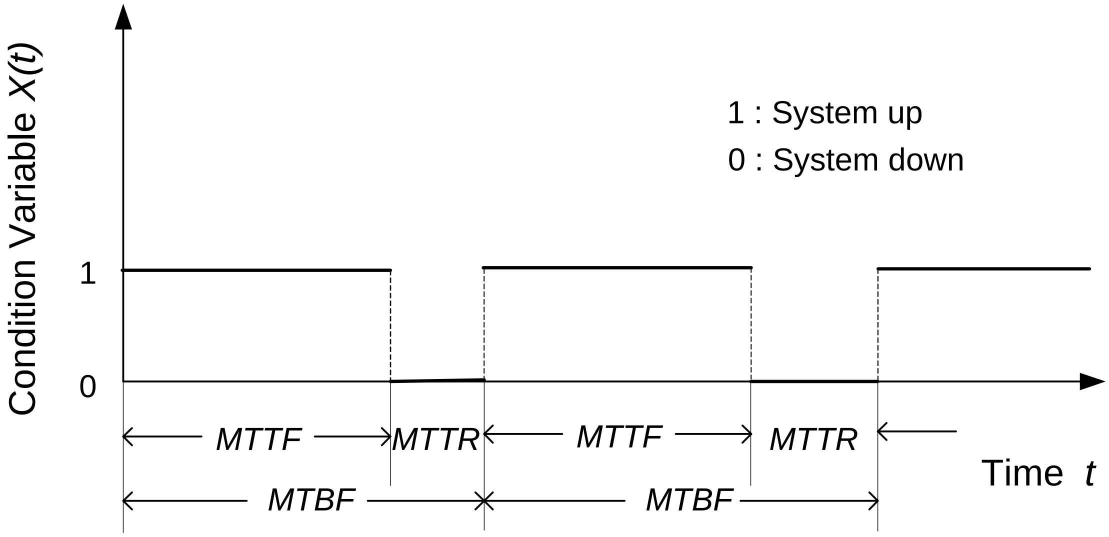

Figure 46. MTTF, MTTR, MTBF. (From Hoyland, page 25)

Because $f(t)=-R'(t)$ (D) becomes :

$MTTF = -\int_0^{\infty} tR'(t)dt = -\int_0^{\infty} t\frac{dR(t)}{dt}dt = -[tR(t)]_0^{\infty} + \int_0^{\infty} R(t)dt,$ by partial integration, and if $MTTF < \infty$ which is what is happening in reality, then $-[tR(t)]_0^{\infty} = 0$ and so $MTTF = \int_0^{\infty} R(t)dt$ also. (E)

f. Structure Functions

The system and each component may only be in one of two states, operable or failed. Let x_i indicate the state of component i, for $1 \le i \le n$, and $x_i = \begin{cases} 1 \text{ if component } i \text{ works} \\ 0 \text{ if component } i \text{ failed} \end{cases}$ where $\mathbf{x} = (x_1, x_2, \ldots x_n)$ is the component state vector.

The state of the system is also a binary random variable, which is determined by the states of its components.

$$\Phi = \Phi(\mathbf{x}) = \text{system state} = \begin{cases} 1 \text{ if system works} \\ 0 \text{ if system failed} \end{cases}, \text{ and}$$

$\Phi = \Phi(\mathbf{x}) = \Phi(x_1, x_2, \ldots x_n)$ is the structure function of the system.[194]

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[194] Kuo, W., and Zuo, J. M., *Optimal Reliability Modeling*, John Wiley & Sons, 2003, page 87.

A series system with n components, works if and only if each of its n components work, and fails whenever any of its components fails. The structure function for a series system is

$$\Phi = \Phi(\mathbf{x}) = x_1 \cdot x_2 \cdot \ldots \cdot x_n = \prod_{i=1}^{n} x_i$$ [195].

It cannot usually be predicted with certainty whether or not a given component will be in a failed state after t time units. So we interpret the state variables of the n components at time t as random variables, and we denote them as $X_1(t), X_2(t), \ldots X_n(t)$.

Now we focus on the following probabilities:

$P(X_i(t) = 1) = p_i(t)$ for $i = 1, 2, \ldots n$, which is the component's i reliability, and $P(\Phi(X(t)) = 1) = p_s(t)$, which is the system's reliability.

For the state variables $X_i(t)$ for $i = 1, 2, \ldots n$, we have $p_i(t) = \mathrm{E}[X_i(t)] = 0 \cdot P(X_i(t) = 0) + 1 \cdot P(X_i(t) = 1),$ for $i = 1, 2, \ldots n$

For the system reliability at time t, we have:

$p_s(t) = \mathrm{E}[\Phi(\mathrm{X}(t))]$ where $\mathrm{X}(t) = (X_1(t), X_2(t), \ldots X_n(t))$,

Assuming that $X_1(t), X_2(t), \ldots X_n(t)$ are independent, the system reliability is $p_s(t) = \prod_{i=1}^{n} p_i(t)$ or $R(t) = r_1(t) \cdot r_2(t) \cdot \ldots \cdot r_n(t) = \prod_{i=1}^{n} r_i(t)$, where *R(t)* is the system's reliability and *r_i(t)* is the *i*th component's reliability for a series system.[196]

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[195] Hoyland, page 99.

[196] Ibid, page 127-129.

g. Series System Reliability Function and MTTF[197]

From Table 32 we find the failure rate function for the system is

$$z(t) = -\frac{d}{dt}\ln(R(t)) = -\frac{d}{dt}\ln(r_1(t) + r_2(t) + \cdots + r_n(t))$$

which is $z(t) = z_1(t) + z_2(t) + \cdots + z_n(t)$.

So the failure rate for a series system equals the sum of the failure rates of all its components. As a result, the failure rate of the system is greater than the failure rate of any of its components, and the whole system is driven by the worst component, which is the one with the larger failure rate or the least reliability.

From the above, we can conclude that if we want to optimize a series system reliability, we must reduce the number of the components, and if that is not possible, then we must enhance the reliability for the worst component.

For example, and to simplify, we may assume that each of the components in our system has an exponential lifetime distribution. Then the system also has an exponential lifetime distribution. If $z_i(t) = \lambda_i$ is the failure rate for component *i,* then the failure rate for the system is $Z(t) = \lambda_s = \sum_{i=1}^{n} \lambda_i$, and the reliability function of the system becomes: $R(t) = e^{-\lambda_s \cdot t}$. Then (E) becomes: $MTTF_s = \int_0^\infty e^{-\lambda_s \cdot t} dt = 1/\lambda_s$.

h. Quantitative Measures of Availability

The quantitative measures of availability are listed in the following table.[198]

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[197] Kuo, pages 107-108.

[198] RAC *Toolkit,* page 12.

Measure	Equation	Reliability & Maintainability considerations
Inherent Availability	$A_i = \frac{\text{MTBF}}{\text{MTBF+MTTR}}$	Assures operation under declared conditions in an ideal customer service environment. It is usually not a field-measured requirement.
Achieved Availability	$A_a = \frac{\text{MTBM}}{\text{MTBM+MTTR}_{\text{active}}}$	Similar to A_i
Operational Availability	$A_o = \frac{\text{MTBM}}{\text{MTBM+MDT}}$	Extends A_i to include delays Reflects the real world operating environment Not specified as a manufacturer-controllable requirement
MTBF = Mean Time between Failure MTTR = Mean Time to Repair MTBM = Mean Time between Maintenance $\text{MTTR}_{\text{active}}$ = Mean Time to Repair MDT = Mean Downtime (corrective maintenance only)		

Table 33. The Quantitative Measures of Availability (After RAC *Toolkit*, page 12)

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APPENDIX E: LIST OF ACRONYMS AND DEFINITIONS

AAV - Advanced Air Vehicle

ACTD - Advance Concept Technology Demonstrations

AEA - American Engineering Association

APU - Auxiliary Power Units

ATA - Air Transport Association

BDA - Battle Damage Assessment

BS - British Standard

CAA/UK - Civil Aviation Administration from the UK

CHAE - Conventional High-Altitude Endurance

CP – Counter-proliferation

DARPA - Defence Advanced Research Projects Agency

DS - Discard

EO - Electro-Optical

EPRI - Electric Power Research Institute

ERAST - Environmental Research Aircraft and Sensor Technology

FAA - Federal Aviation Authority

FMA - Failure Mode Analysis

FMCA - Failure Mode and Critical Analysis

FMEA - Failure Mode and Effect Analysis

FMECA - Failure Mode Effect and Criticality Analysis

FRACAS – Failure Reporting And Corrective Action System

FTA - Fault Tree Analysis

GCS – Ground Control Station

GPS - Global Positioning System

HAE - High-Altitude Endurance

ICAO - International Civil Aviation Organization

IN/FC - Inspection/Functional Check

INS – Inertial Navigation System

IR - Infrared

ISC - Industry Steering Committee

ISO - International Standard Organization

JSF - Joint Strike Fighter

L/HIRF - Lightning/High Intensity Radiated Field

LOS - Line-Of-Sight

LU/SV - Lubrication/Servicing

MAV - Micro-Air Vehicle

MDT - Mean Downtime

MR - Mishap Rate

MRB - Maintenance Review Board

MRBR - Maintenance Review Board Report

MSG-3 - Maintenance Steering Group-3

MSI - Maintenance Significant Items

MTBCF - Mean Time Between Critical Failure

MTBF - Mean Time Between Failure

MTBM - Mean Time between Maintenance

MTTR - Mean Time to Repair

MUAV - Micro UAV

NASA - National Aeronautics and Space Administration

NAWC/AD - Naval Air Warfare Centre Aircraft Division

NPS – Naval Postgraduate School

NRL - Naval Research Laboratory

O&S - Operation and Support

OBC - Onboard Computer

OBC - Onboard Computer

OP/VC - Operational/Visual Check

OTHT - Over The Horizon Targeting

PM - Planned Maintenance

QFD - Quality Function Deployment

RC - Radio Control

RCM - Reliability Centered Maintenance

RECCE - Reconnaissance mission

RPN - Risk Priority Number

RPV - Remote Piloted Vehicles

RS - Restoration

RSTA - Reconnaissance Surveillance and Target Acquisition

SAE - Society of the Automotive Engineers

SAR - Synthetic Aperture Radar

SARP - Standards and Recommended Practices

SEAD - Suppression of the Enemy Air Defences

SIGINT – Signal Intelligence

SSI - Structural Significant Items

STAN - Surveillance and Tactical Acquisition Network

SUAV - Small Unmanned Aerial Vehicle

TAAF - Test, Analyze and Fix

TR - Tactical Reconnaissance

TUAV - Tactical UAV

UCAV - Unmanned Combat Aerial Vehicle

UHF - Ultra High Frequency

VR - Vendor Recommendations

VTOL - Vertical Take-Off and Landing

WG - Working Group

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