



SURFACE VEHICLE INFORMATION REPORT

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Report on Unmanned Ground Vehicle Reliability

RATIONALE

Document is being reviewed for Five-Year Review and corrections throughout.

INTRODUCTION

This information report provides information on the state of the art in the status and practice of unmanned ground vehicle (UGV) reliability. It decomposes UGV reliability into the component level (power systems, manipulator/end-effector, and sensors) and the system level (communications and operator control unit), and devotes a section to each of the individual elements in these levels. The following conclusions are drawn: (1) Tools for analyzing the component-level reliability of hardware components subject to physical failure are available from the reliability engineering literature and have been applied to mobile robots in a few cases. (2) However, a more systematic and carefully collected set of field data is required in order to validate these models and make more confident statements about the primary areas of weakness and potential reliability improvement for UGVs. (3) System-level reliability is less amenable than the component level to quantitative analysis. Though some work has been done in system-level analysis, much more is needed, and its possible unification with component-level analysis should be explored in order to achieve something closer to full-system reliability analysis.

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1. SCOPE

This information report is applicable to the reliability characteristics of unmanned ground vehicles.

1.1 Purpose

The purpose of this information report is to review the state of the art in unmanned ground vehicle reliability and to identify needed areas of increased information, analysis, and improvement.

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3. UNMANNED GROUND VEHICLE RELIABILITY

3.1 Overview

The number of land-based robots, or "unmanned ground vehicles" (UGVs), deployed by the U.S. in foreign theaters of war has grown from 150 in 2004, to 4000 by the end of 2006, to 12000 by 2008 [18][64]. These robots perform high-risk missions, reducing the loss of life and limb among service members serving in European Command (EUCOM) and in Iraq, Afghanistan, and other Central Command (CENTCOM) locations [18]. Additionally, the National Defense Authorization Act of 2001 set the goal that by 2015, one third of the operational ground combat vehicles of the Armed Forces be unmanned [54]. Total governmental spending on research, development, and procurement of UMV (Unmanned Marine Vehicle) and UGV systems was projected to reach \$504 million worldwide in 2009 [78], with UGVs absorbing the lion's share.

Given the safety and capability augmentations provided by UGVs, this growth of attention and spending devoted to them is likely to continue to increase rapidly. As ever larger numbers of UGVs are deployed, the need for their consistent and reliable operation will at least become more noticeable, if not more imperative. The relatively scant information available on UGV reliability indicates that it is currently low. In [9], Carlson and Murphy report less than 50% availability and average Mean Time Between Failure (MTBF) of 8 hours for a diverse group of 19 mobile robots from five different manufacturers used at the University of South Florida's Center for Robot-Assisted Search and Rescue. In [81], 5000 UGV systems deployed in Iraq and Afghanistan had average MTBF of 4 to 10 hours, with 20 hours average down time for repair.

There is, therefore, a need to improve the reliability of fielded UGVs. What does it mean for robots to be unreliable? On the one hand, their components fail. On the other hand, they don't consistently do the same thing in simple situations or the right thing in complex situations. There is, for example, a notable gap between the degree of autonomy academic laboratory robots are reported to be capable of, and that which is implemented on robots currently deployed in combat theaters. While part of that gap may stem from a psychological need to keep humans in the loop and a resultant gradualism in the introduction of autonomy, a large part of it is a result of an absence of reliably performing autonomous behaviors.

The standard definition of reliability is “the ability of a system or component to perform its required functions under stated conditions for a specified period of time” [36]. This definition is straightforward, but its application to a complex system with interlocking subsystems of various natures is not necessarily straightforward. We decompose UGVs into component-level elements (power, manipulator/end effector, sensors) and system-level elements (communications, Operator Control Unit (OCU), software). The essential difference between component-level and system-level elements is the amenability of the former to analysis using standard and mature reliability engineering techniques based on MTBF. System-level elements, on the other hand, involve human interaction, algorithms, physical modeling of the battlespace, or other aspects that do not fit as easily, or perhaps at all, into the traditional reliability engineering paradigm. The component-system distinction is not perfectly clean, since, for example, sensors (component level) require algorithms and software to be useful, and communications (system level) use transmitter/receiver devices subject to standard reliability engineering analysis. However, we will maintain it because it highlights the presence in UGVs of elements resistant to conventional reliability analysis, and for the sake of breaking down the problem into smaller pieces.

A different approach to achieving UGV reliability is outlined in Appendix A. That article is entitled “Complementary Perspectives on Robot Reliability.”

The remainder of this overview section is structured as follows: 3.1.1 describes the state of the art in UGV reliability; 3.1.2 summarizes the subsequent subsections of Section 3, each of which is devoted to one of the component-level and system-level elements enumerated above; 3.1.3 describes approaches to improving UGV reliability, whereas 3.1.4 enumerates challenges facing attempts to improve and analyze UGV reliability; 3.1.5 presents conclusions.

3.1.1 State of the Art in UGV Reliability

This section gives a brief overview of the state of the art in reliability engineering as it applies to UGVs. It describes four levels of analysis: component, unit, team, and system. The component and unit (i.e., a single robot) levels may be analyzed straightforwardly using conventional reliability engineering. The team level (multiple robots) requires an extension of these techniques that has been developed in recent work. The system level is the most difficult and least studied level of analysis.

The component level involves reliability analysis of a single component, such as a ball bearing, an integrated circuit, or a motor. Such components may in turn be made up of other components, such as a DC motor's consisting of armature, shaft, bearing, and brushes, but may still be regarded as a component if the available reliability information from the manufacturer or field data is not broken down to the sub-component level. Such components may be characterized by a MTBF or the reciprocal of the MTBF, usually represented as λ , the failure rate. The reliability engineering bathtub curve characterizes a component's life cycle with three phases: infant mortality, useful life, and wear-out. The typical practice is for components to be “burnt in” at the factory, so that they are finished with infant mortality and into the useful life phase once supplied to users. A constant failure rate characterizes the useful life phase, and though other distributions may be used, the exponential distribution is used most commonly to express the resultant reliability, i.e., the probability that the component will survive for an amount of time t , as:

$$R(t) = e^{-\lambda t} \quad (\text{Eq. 1})$$

The unit level involves reliability analysis of a single robot or UGV and can be determined straightforwardly by combining the reliabilities of each component either in series (wherein all components must function simultaneously for the unit to survive) or in parallel (wherein multiple components are redundant and can be swapped in as spares). In series, the overall unit reliability is simply the product of the component reliabilities. In parallel, the overall unit reliability is one minus the product of the complements ($1 - R(t)$) of the component reliabilities. These well-explored results are presented in numerous standard reliability engineering textbooks, such as [50].

The team level involves reliability analysis of multiple robots operating together with the possibility of being reassigned or repaired in the event of robot or component failure. This requires an extension of the standard reliability engineering methods described above, which assume independent reliabilities of the components to be combined. In the team-level case, the reliability of a given robot or its components is dependent, since it is affected by the possibility of reassignment when other robots fail or swap-in of a spare module when one of its components fails. While it is possible to derive analytical solutions for simple missions and scenarios, this becomes quite difficult for more complex missions. An alternative approach is to run a stochastic simulation on a state machine created to represent the appropriate mission sequence. The results shed light on such questions as whether to use a small number of higher-reliability versus a large number of lower-reliability robots, or what the optimal number and reliability level of robots to use is in order to achieve a given mission specification [71][68].

The foregoing assumes the ability to use and build upon component-level reliability, which is typically based on hardware failures resulting from wear over time. System-level reliability analysis includes components difficult or impossible to analyze using the above techniques: human-machine interaction, communications, controls, and software, although some researchers have proposed limited software reliability models using statistical techniques. Performing “total-system” reliability analysis by integrating component-level and system-level analysis is a worthy goal. This report organizes and reports on existing work with an eye to this goal.

3.1.2 Summary of the Subsections

This section gives a brief description of each of the major subsections in Section 3 and organizes them under the component-level and system-level headings described above, moving from the more well-understood component level to the less studied and more complex system level.

The existing data on mobile robot failures suggest general conclusions about the categories discussed in the sections. For example, in considering 19 University of South Florida robots, [9] found that 35% of the failures among them occurred in the actuators or related components, 26% in the computers or software, 13% in the power subsystem, 12% in communications, and 10% in sensing. Similarly, [23] reported that 10 out of the 18 most common failures in small field robots used by the U.S. military in Iraq were in the actuator subsystems. These data, while too sparse to use as the basis for a prioritization of the categories below, are suggestive of the importance to reliability of: (1) component-level elements that include actuators (e.g., the manipulator/end-effectors discussed in Section 3); and (2) both component- and system-level elements.

3.1.2.1 Component Level

3.2 - Power Systems. This section points out two facts that highlight the need for additional work and effort in this area. First, there are many potential manufacturing and assembly errors leading to power system failure that can be eliminated or greatly reduced by well-designed and implemented quality control, but the U.S. Army Test Operating Procedure for UGVs [75] does not address power systems and only cursorily mentions batteries and fuel. Second, although one study of 5000 currently fielded UGVs in Iraq and Afghanistan reports a 4 to 10 hour MTBF versus a desired 96 hours, the relative contribution of power system reliability to this aggregate MTBF is not clear, and few data on specifically power system reliability of fielded UGVs are available. If the needed manufacturer and field reliability data can be acquired and analyzed, then power systems is an area that lends itself to established reliability engineering analysis.

3.3 - Power Train and Running Gear. This section summarizes the results from the relatively few studies on UGV reliability in several contexts, including search-and-rescue robotics, museum robots, and the DARPA PerceptOR program. In all but one of the studies (CRASAR), the number of robots considered was too small to give confidence in the statistical significance of the results. In the CRASAR study, the most common mode of failure (36%) was the effector category, which included thrown and slipped tracks, mobility mechanism failures, and sheared pins and gears, all of which belong under the “power train and running gear” heading. This section also summarizes the principal methods of quantitative reliability analysis and closes by observing that the relative paucity of data on UGV power train and drive system reliability suggests the need for a much more purposeful and comprehensive data acquisition effort in this area.

3.4 - Manipulators and End-Effectors. This section provides a good example of the application of component-level reliability analysis to determine the reliability of aggregate assemblies; in this case, the manipulators and end-effectors that are used on the widely employed PackBot and Talon robots. MTBF values from typical components making up such assemblies are combined using fault trees, which are a graphical method for capturing the serial or parallel combination of component reliabilities using the OR and AND gates of Boolean logic, to derive overall reliabilities (i.e., probability of continued operation) for a specified period of time. The authors note that the greatest challenge (at the component level) is the acquisition of accurate and current reliability data, rather than the analysis itself.

3.5 - Sensors. This section describes both hardware and software reliability. It cites two causes for the hardware failure of computers, sensors, and other related electronic devices: destructive voltage variations and heat. Each of these can be ameliorated through improved design and modeled from a component-level reliability engineering standpoint. Electronic device components typically undergo rigorous testing, so component-level MTBF data, from which aggregate device MTBF may be calculated should be available. The modeling of software reliability (e.g., for sensor interpretation and fusion algorithms), which belongs at the system level in the classification proposed here and is, therefore, further discussed below, is more difficult and less frequently attempted, though some studies exist [34].

3.1.2.2 System Level

3.6 - Communications Systems. This section deals with multiple aspects of communications reliability: hardware, software settings, transmit power, environment, and network topology. Basic communications hardware is amenable to straightforward reliability engineering analysis, while overall communications reliability analysis is difficult due to the complexity of RF modeling in 3D environments and the dynamic nature of radio networks. Nevertheless, this section argues that statistical characterization based on simulation and testing can give system performance bounds with quantifiable confidence levels.

3.7 - Operator-Robot Interface and Interaction - OCU. This section makes the following three main points. First, for all currently fielded UGVs, the human operator is part of the feedback loop representing the UGV's control, important components of which are communications and degree of autonomy. Second, key potential failure points are lack of operator situational awareness, response delays, and wrong/inappropriate operator responses. Third, human-in-the-loop reliability analysis is relatively immature and may profit from augmentation with techniques from the field of Cognitive Task Analytics [15]. From the reliability standpoint, the presence of a human operator in the loop is a two-edged sword: on the one hand, the human's ability to react intelligently and resourcefully to an immense range of situations increases system reliability; on the other hand, that same ability to respond creatively makes the human's role difficult to quantify and link to the better-understood component-level analysis.

Appendix A - Complementary Perspectives on Robot Reliability. This appendix provides a different view and food for thought on achieving UGV reliability.

3.1.2.3 Software

Software pervades the system level (controls, communications, human-machine interaction) and renders useful the component-level devices (power system, manipulator/end-effector, computers, sensors, mobility platform) whose hardware aspects can be straightforwardly modeled via standard reliability engineering methods. However, software reliability is different in nature from hardware reliability; the latter involves the effects of wear over time, while the former is compromised primarily by a combination of human design error with system complexity. The appropriateness of using statistical methods to model software reliability without severe restrictions is unclear, though there is a literature on this topic which may be consulted [34][47][77]. Though this report does not include a separate section on software, future reports or updates to this report should consider the subject of software as an important cross-cutting system aspect with high potential impact on reliability.

3.1.3 Approaches to Improving UGV Reliability

The individual sections mention various approaches to improving UGV reliability. These and some additional approaches are summarized here under component-level and system-level headings.

3.1.3.1 Component Level

- Improved manufacturing processes. This refers to at least two distinct phenomena. On the one hand, improved manufacturing, particularly quality control, processes can reduce the number of components that suffer infant mortality. On the other hand, innovations in design, materials, etc., can result in producing higher-reliability components at lower cost. Economies of scale may play a beneficial role in this respect as the military has a demand for increasing numbers of robots and the components from which they are assembled.
- Use higher-reliability components. All other things being equal, this increases cost, but it is an effective way to increase reliability if the money is available and one has sufficient data or insight to determine which components' reliability increase will have the biggest impact on overall system reliability.
- Redundancy. Like using higher-reliability components, this increases cost, both design and component. If funds are available, the question of which approach is better, higher-reliability components or redundancy, can be answered using standard reliability engineering techniques. Redundancy may also increase weight, volume, and power requirements, and it may reduce performance.
- Mission-based team design for reliability. Given a mission specification and the need to assemble a team of robots to perform it, how does one maximize probability of mission completion given choices of number of robots, reliability level of components, cost of the mission, etc.? Techniques for this are described in [71][72].

3.1.3.2 System Level

- Improved system engineering. The phrase “system engineering” can apply to many things, but the particular emphasis here, given the heavy human operator participation in currently fielded UGVs, is on the design of the human-UGV interface. Among other things, it should provide intuitive situational awareness and user input.
- Improved operator training. The need for operator training complements an intuitive user interface by working on the other end of the human-machine interaction problem. Ideally, the profitable use of fielded UGV systems should be quickly learnable by users, with further training enhancing, rather than enabling, system usefulness.

The rapidly increasing pace of UGV deployment offers an excellent opportunity for data collection and systematic improvement of UGV reliability. Carefully collected data from the field can be used to identify the components with highest reliability impact, refine reliability prediction models, and generate best human-machine interaction practices. These improvements can be fed into next-generation UGVs, and the resultant iterative cycle can significantly improve UGV reliability.

3.1.4 Challenges Facing UGV Reliability Improvement and Analysis

There are various challenges facing the systematic improvement of UGV reliability:

- Scarcity and perishability of manufacturer reliability data. Component-level reliability analysis depends for its accuracy on accurate and current reliability data on manufactured components and suffers to the extent that these data are unavailable or out of date.
- Dependence on loading and environmental conditions. Manufacturer MTBF data is typically provided for a single set of operating conditions (e.g., mechanical load or temperature). Extrapolation to a different set of operating conditions is not necessarily linear and requires an additional stage of modeling. Such models are available for some components and conditions, but this is an area in which further work is needed. An additional and related challenge in terms of retrospective reliability calculation is the determination of what amount of time an individual component in a given system has been exposed to a given set of conditions. For example, end-effector components are under significantly greater load when they manipulate an object than when they do not.
- Lack of methodically collected data from the field. As mentioned above, there is not much literature reporting on reliability of deployed UGVs. Creative ideas that limit or eliminate the amount of clerical work service members have to perform could be implemented, such as “black boxes” that record salient data, though cost is always a factor.
- Lack of analysis tools for system-level reliability. As mentioned above, whereas component-level reliability analysis is well understood, system-level reliability analysis to include human-machine interaction is less well understood and less amenable to quantitative methods.
- Difficulty and complexity of performing full-system reliability analysis. Full-system reliability analysis would provide a comprehensive quantitative approach to the unified component-level and system-level elements that make up the full UGV system. This is a worthy goal, but much work remains to be done, primarily on the system-level side, in order to make progress towards it.

3.1.5 Conclusion

UGV deployment is increasing geometrically, but UGV reliability is not. Tools for analyzing the “component-level” reliability of hardware components subject to physical failure are available from the reliability engineering literature, and have been applied to mobile robots in a few cases. However, a more systematic and carefully collected set of field data is required in order to validate these models and make more confident statements about the primary areas of weakness and potential reliability improvement for UGVs. “System-level” reliability (human-machine interaction, controls, communication, software) is less amenable than the component level to quantitative analysis. Though some work has been done in system-level analysis, much more is needed, and its possible unification with component-level analysis should be explored in order to achieve something closer to full-system reliability analysis.

3.2 Power System

This subsection describes the current state of UGV power system reliability, summarizes techniques for reliability assessment, and considers approaches for improving the reliability of power systems. It concludes with recommendations for improving the state of knowledge of UGV power system reliability and establishing standards and design paradigms for UGV power systems.

3.2.1 Introduction

It is desirable to understand the reliability of robotics systems and to establish design guidelines for UGV reliability engineering. This paper focuses on the state of knowledge of reliability of electrical, battery, and power systems of UGVs and provides recommendations.

With the advent of the Global War on Terrorism in Afghanistan and Iraq, military operations have shifted to a combination of desert, mountainous, caves, and Military Operations in Urban Terrain (MOUT). The enemy is very intelligent and capable of using these various terrains and low-tech but sophisticated weapons such as Improvised Explosive Devices against us. As a result, our military has in the last decade become more interested in Unmanned Aerial Vehicles (UAV) for reconnaissance, targeting, and execution of ground targets. Also, UGV utilization has become increasingly popular in Explosive Ordinance Disposal (EOD) and Reconnaissance missions.

The author of *Wired for War* [64], recently stated in an article that, "When U.S. forces went into Iraq, the original invasion had no robotic systems on the ground. By the end of 2004, there were 150 robots on the ground in Iraq; a year later there were 2400; by the end of 2008, there were about 12000 robots of nearly two dozen varieties operating on the ground in Iraq." [64]

The growth in the number of fielded UGVs and an increasing interest in weaponizing them brings a strong need for reliable UGV systems. This presupposes an understanding of UGV reliability and standards for achieving a high level of reliability.

3.2.2 Common Failure Modes of UGV Power Systems

UGV power system failures can be classified into three major groups: (1) failures that are due to poor workmanship and initial burn-in, commonly referred to as infant mortality failures, (2) random failures during the useful life of the UGV, and finally, (3) wear-out failures at the end of the useful life of the vehicle. The failure rate over the life of the UGV can be plotted against time and results in a bucket or bathtub curve with high failures early in the shakedown period, relatively constant random failures during the useful life and again increasing failure rate as components begin to wear out at the end of life.

Some of the common early failures experienced are:

- Poor crimps on terminals (hard to catch)
- Loose screws on terminals (battery, controller, etc.)
- Terminal size too large for the wire gauge
- Incorrect wire gauge or terminal size (too small)
- Cracked or broken control cable connectors
- Lack of latching device on connectors
- Mechanically damaged or cut wires
- Wires or components shorting to the frame
- Loss of battery or battery cable becomes unplugged
- Damaged or prematurely discharged battery

- Metal debris in electrical devices
- Cold solder joint on electrical device terminal
- Broken terminal pins on control wire connections
- Incorrect fuse size or non-functioning fuse
- Non-keyed connectors installed wrong

These types of failures are typically caught through a good quality control program, during acceptance testing, or early in the life of the vehicle. Good design and manufacturing practices can avoid these types of failures. Note that the U.S. Army Test Operating Procedure for UGVs [75] does not address power systems and only addresses batteries and fuel in passing.

Some of the symptoms of power system failures:

- UGV lacks the power or speed it used to have
- UGV only turns in one direction or will not move at all
- Sparks, smoke, or burning insulation/component smell is present
- Metal or plastic debris is present on the robot (evidence of grinding, scraping, slipping gears, etc., via visual inspection)
- Electrical connections or wires are hot to the touch or melt insulation on terminals or wires
- Motors overheat and circuit breakers/fuses open
- Main power supply circuit breaker opens

3.2.3 Review of Current Work

A review of the literature revealed that there is very little available data specific to UGV Power System reliability. Refer to [9], written in 2005, which discusses how UGVs fail in the field. They established a taxonomy for UGV failures which identified five physical and two human failure modes. The physical were: effector, sensor, control system, power, and communications. The human modes were: design and interaction.

Based on an analysis of the data from 10 studies of field failures of UGVs, the authors found that power accounted for few of the failures at about 9%, with effectors and control system accounting for the bulk of failures. Some of the studies were looking at search and rescue missions, where the units were not operated for long periods of time. Mission duration was on the order of 24 minutes. Other studies, in which there were longer-duration missions, showed that batteries and connections accounted for 50% of the power system failures. Overall, the MTBF from all causes was from 6 to 20 hours of operation [9].

In [4], UGV lessons learned are discussed. Power density, power management, and power duration are highlighted as key technology issues.

In [43], it was found that there were three primary failure modes: control, power, and communications. Control accounted for 50% of the failures, with power and communications each accounting for 25%. Some of the power failures were gradual and resulted in dropouts in control or communications. Endurance testing was recommended to identify and correct the causes of failure before fielding of UGV. The sample size was relatively small.

A TARDEC power systems briefing [74] identified UGV power systems as an important research area and identified power system requirements in the range from 100 W to 10 kW. A University of Michigan Ground Robotic Research Center briefing [81] identifies current portable UGV power utilization in the range of 200 to 500 Wh, with a goal of 800 Wh to 50 kWh of energy storage. He further goes on to define reliability for UGVs and notes that with over 5000 UGV systems deployed in Iraq and Afghanistan, the MTBF is 4 to 10 hours with average 20 hours of down time for repair. Current UGV power systems are not capable of sustaining the endurance required for typical military operations. The desired UGV MTBF is 96 hours, with current capabilities in the 4 to 10 hour MTBF range.

3.2.4 Reliability Engineering for UGV Power Systems

Two primary methods were identified in the literature for reliability assessments. The first is fault tree analysis [83], which was later modified to add an interval method to account for data uncertainty [12]. The fault tree is composed of a hierarchy of failure with blocks representing the components' probability of failure and and/or logic gates representing the combination of effects to cause a higher-level failure (see Figure 1).

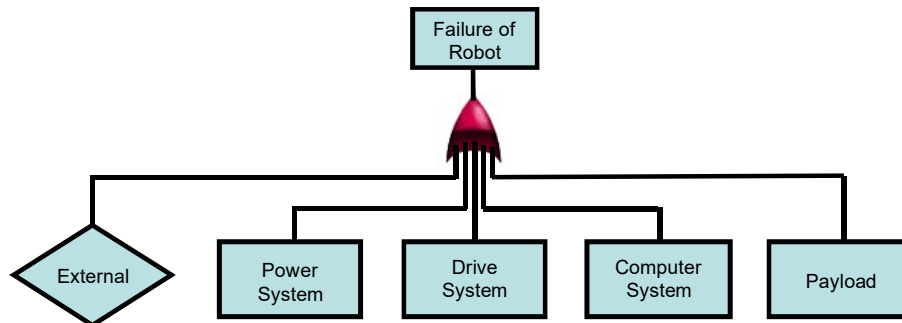


Figure 1A - Robot fault tree

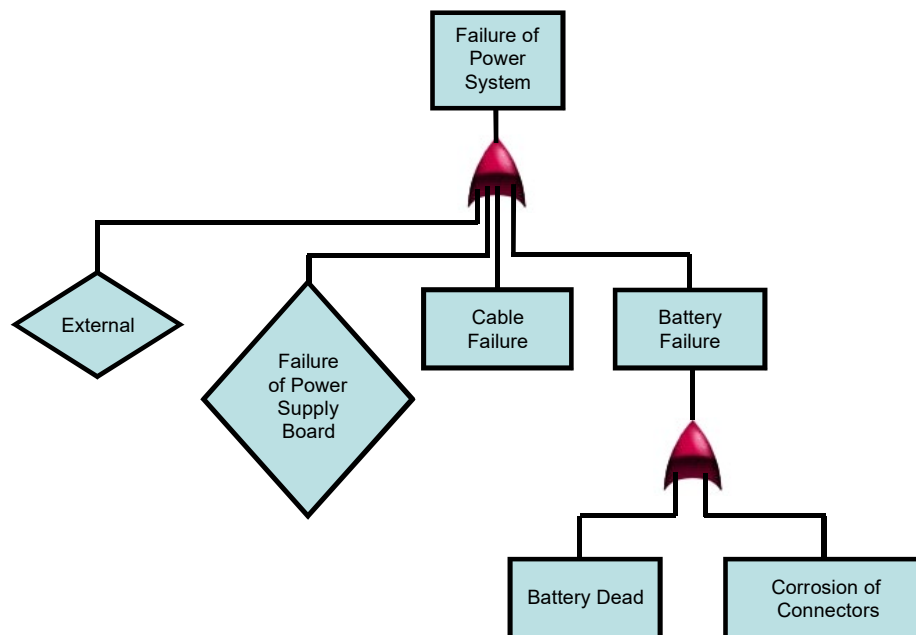


Figure 1B - Power system fault tree

The second method [69][70] establishes a reliability model based on the bathtub or bucket curve depiction of the life of the UGV and a modular architecture. In this method, the model is established for the flat useful life part of the curve and assumes a relatively constant hazard or failure rate for the modules of interest. Both of these methods require reliability data for the MTBF of the electrical and electronic components. One source of historical data for these components is the Reliability Information Analysis Center (RIAC) Electronic Parts Reliability Report [61].

3.2.5 Summary

Very little literature was found specific to power system failure in UGV systems. In the couple of articles found, the failure rates for power systems ranged from 9 to 25% (circa 2005 to 2006). Data were not found that could be used for a detailed study, and no recent papers on the subject were found. Since there has been a significant growth in military-fielded UGVs since the 2005 to 2006 reports [9][43], it is important to do a more detailed study with current data.