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NEW DESIGN FOR RELIABILITY (DfR) NEEDS AND STRATEGIES FOR EMERGING AUTONOMOUS GROUND VEHICLES

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ABSTRACT

Significant Design for Reliability (DfR) methodology challenges are created with the integration of autonomous vehicle technologies via applique systems in a ground military vehicle domain. Voice of the customer data indicates current passenger vehicle usage cycles are typically 5% or less (approximately 72 minutes of use in a twenty-four hour period) [2]. The time during which vehicles currently lay dormant due to drivers being otherwise occupied could change with autonomous vehicles. Within the context of the fully mature autonomous military vehicle environment, the daily vehicle usage rate could grow to 95% or more. Due to this potential increase in the duty or usage cycle of an autonomous military vehicle by an order of magnitude, several issues which impact reliability are worth exploring.

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1. INTRODUCTION

In recent years, it has been a focus of the Army to increase the reliability of military systems. In several recent studies, the measured reliability of a system during test and fielding is much lower than the required and predicted reliability of the system [3,8-9,12]. While there are ongoing efforts to focus on increasing the reliability of military systems, which directly affects the supportability and maintainability, as well as mission effectiveness and preparedness, there are areas where improvements and innovation are needed. The stakes of low reliability on military vehicles are generally higher than that of low reliability on commercial vehicles, in the sense that the threat level and risk of injury and death are higher when in the middle of executing a mission in enemy territory. The risk of poor reliability increases significantly when an autonomous kit is added to an existing military platform, or autonomous robotic systems are deployed for various functions alongside the soldier. Not only does an increase in the number of parts in a system inherently lower reliability, but the absence of adequate miles/hours of test data to determine reliability confidence levels makes reliability assessment of autonomous

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vehicles even more challenging. In this paper, we set out to address some of the challenges and concerns in the area of reliability of autonomous vehicles. We will introduce some methods that can be used as starting points to assess, and design for, reliability. This paper is by no means an all-inclusive solution, and is not meant to serve as any official guidance of what should be followed. With that in mind, the paper focuses only on hardware reliability. Although software reliability is an integral part of autonomous vehicle safety and reliability, that topic will be left to more in-depth discussions by those with more expertise in this area. In the absence of official autonomous vehicle system reliability and safety standards of practice, we are providing lessons learned and insights into some areas of focus that should be considered during the autonomous vehicle system design process.

2. AUTONOMOUS VEHICLE OVERVIEW

2.1. Levels of Autonomy Defined

Society of Automotive Engineers (SAE) define five levels of Autonomous Vehicles (AVs) as follows [17]:

Level 0 – No Driving automation: The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.

Level 1 – Driver assistance: The *sustained* and operational design domain (*ODD)*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the dynamic driving task (DDT) (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.

Level 2 – Partial Driving Automation: The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *object and event detection and response (OEDR)* subtask and *supervises* the *driving automation system*.

Level 3 – Conditional Driving Automation: The *sustained* and *ODD*-specific performance by an *Automated Driving System (ADS)* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.

Level 4 – High Driving Automation: The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.

Level 5 – Full Driving Automation: The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.

2.2. General Autonomous Vehicle Components Defined

Although each autonomous vehicle or robotic platform is unique, most autonomous vehicles in the commercial and military worlds contain the same basic components which enable autonomous behavior. These components are shown in the figure below, and include one or more LiDAR (Light Detection and Ranging) units, cameras for 360 degree view around the vehicle, radar sensors for movement and positioning, and a computer for processing input from all of the sensors and sending commands for movement of the vehicle.

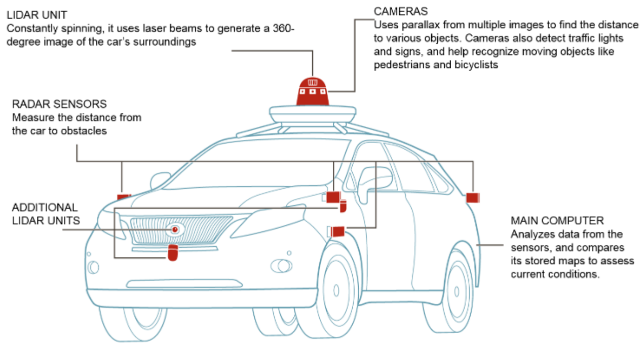


Figure 1: Anatomy of an Autonomous Vehicle [4]

With the introduction of new autonomous technologies, and the critical nature of the functions of these technologies, the need for highly reliable and safe operation are of the utmost importance. All vehicle systems, sub-systems and components need to be designed to survive in harsh military environments and be fully tested to demonstrate that they achieve their reliability targets and goals. Autonomous vehicles must be exposed to the stresses they will encounter in the conditions of the real world in order to fully evaluate the reliability the vehicle will experience in the field. Environmental stresses like shock, vibration, extreme temperatures and humidity need to be considered, in addition to the situational stresses unique to the autonomous domain.

3. EFFECTS OF REDUNDANCY ON A VEHICLE SYSTEM

3.1. Basic Reliability Equations

When calculating the reliability of a complex system, the calculation depends on whether or not critical functions will stop working if one component ceases to perform its ideal function, or if there is redundancy built into the system. A *series structure* is a system that is functioning if and only if all of its *n* components are functioning [13]. The overall reliability of the system is given by Equation 1 below [11, 14]:

$$R_s = \prod_{i=1}^{n} R_i = R_1 * R_2 * \ldots * R_n \qquad (1)$$

For example, if there are five components in an autonomous vehicle in series, the overall reliability of the system would be:

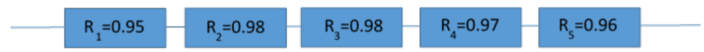


Figure 2: Components with a Series Relationship

$$R_s = \sum_{i=1}^{n} R_i = R_1 * R_2 * R_3 * R_4 * R_5 = 0.95 * 0.98 * 0.98 * 0.97 * 0.96 = 0.833 \qquad (2)$$

For a system with four levels of redundancy, meaning there are five components that can perform the same function, the reliability significantly improves, as shown in Figure 3 below. A *parallel structure* is a system that is functioning if at least one of its *n* components is functioning [12].

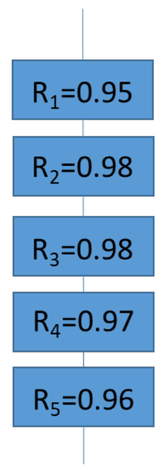


Figure 3: Components with a Parallel Relationship

$$R_s = 1 - \prod_{i=1}^{n} (1 - R_i) = 1 - (0.05 * 0.02 * 0.02 * 0.03 * 0.04) = 0.99999998 \qquad (3)$$

Complex systems can also be made up of a combination of series and parallel systems, such as the following system with, say, two LiDAR systems in series, and other redundant positioning components.

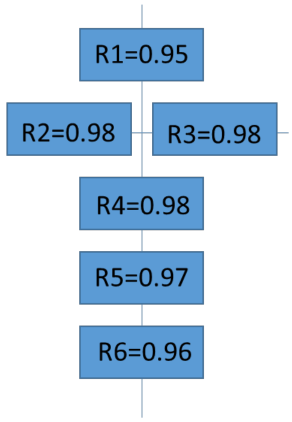


Figure 4: Components with a mix of Series and Parallel Relationship

$$R_s = 1 - \prod_{i=1}^{n}(1 - R_i) = 1 - (0.05 * 0.0396 * 0.02 * 0.03 * 0.04) = 0.99999995 \quad (4)$$

3.2. LiDAR Redundancy Analysis

LiDAR is a laser light technology that measures distance to a target using the times it takes to reflect the light, as well as wavelength information. It can be used to create a 3-D image of the object under surveillance. Since Lidar technology parameters (physical size, capability, cost, etc.) are evolving at an exponential growth rate, they represent a very difficult and unique reliability challenge. Even if the reliability of an individual LiDAR unit design has been tested and validated, the level of redundancy greatly depends on the placement of the LiDAR units. As can be seen in the figures below, although a vehicle may have more than one LiDAR unit, it may not be considered redundant in all fields of view. Redundancy means that there is a backup component or system available to take over, should the original component/system fail. However, because LiDAR systems are placed in different locations on the vehicle, they each have different fields of view. Only certain portions of the field of views can be considered redundant, as can be seen in Figures 6 and 7.

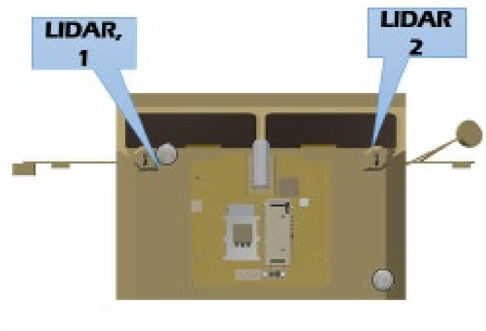
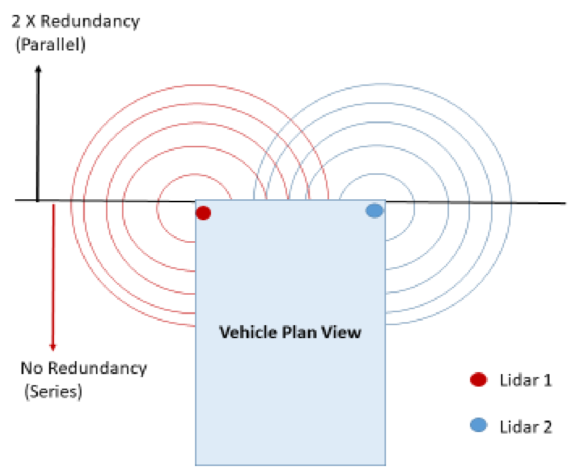
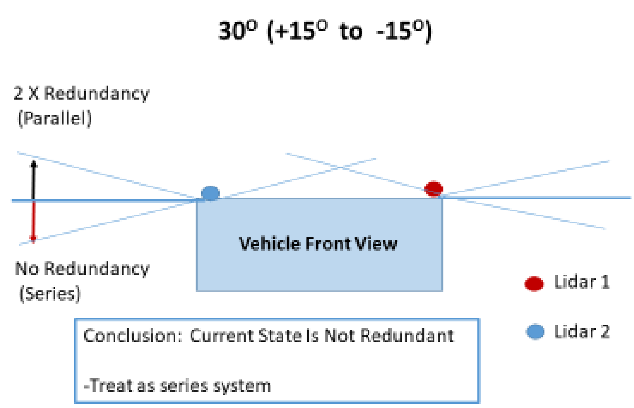


Figure 5: Example LiDAR Placement on an autonomous Ground Vehicle





Figures 6 & 7: Redundant and Non-Redundant LiDAR Field of View

4. RELIABILITY CHALLENGES ASSOCIATED WITH AUTONOMOUS VEHICLES

The recent shift of focusing on using autonomous vehicles for contemporary ride sharing scenarios may cause the creation of an entirely new vehicle usage profile. As the period of operation is no longer constrained by operator fatigue or availability, autonomous vehicles have the potential to operate 24 hours a day, 7 days a week. For example, in the current state, customer data indicates current vehicle usage cycles are typically very low, perhaps 5% or less. In other words, out of a 24 hour day, the average vehicle is actually driven only 60 minutes or less. Therefore, approximately 95% of the day, the vehicles lay dormant and unused [2, 18]. If Level IV autonomy is one day achieved, within the context of the fully mature Autonomous Vehicle environment involving structured car sharing, the daily usage rate could grow conceivably to 95% or more. In the military, this could greatly impact supply transport and free up military drivers for more strategic roles.

For a mixed, primarily urban duty cycle, with 30 miles per hour (mph) mean speed and a 5% customer usage profile, approximately 13,000 miles per year would be driven by an autonomous vehicle. This adds up to 39,000 over a typical three year usage span. If in the future there is a shift to a fully autonomous domain, autonomous driving would result in a mileage accumulation of approximately 700,000 miles over a typical three year usage span in a mixed, primarily urban duty cycle with 30 miles per hour mean speed [10]. For military vehicles, the mileage accumulation may be slightly less, but still a significant increase.

In addition, unique reliability requirements specific to autonomous vehicle systems and subsystems may emerge. For example, autonomous sensors need to verify position and alignment over the life of the vehicle to ensure reliability, robustness and safety. The LiDAR system, Radar, Cameras, and Inertial Measurement Systems must validate alignment over life. Sensor alignment may be validated relative to a fixed reference on the vehicle or to other sensors and Inertial Measurement System alignment may be validated relative to the alignment of another inertial measurement system.

5. DESIGN FOR RELIABILITY STRATEGIES FOR AUTONOMOUS VEHICLE DESIGN

5.1. Taguchi Methods and Noise Factors

We define Taguchi Methods / Robust Design as a systematic approach to ensure that the system, sub-system, or component performs its intended function over its useful life under actual usage conditions. Practical definitions of key concepts are:

-Robustness: Low functional variation in the presence of noises

-Parameter Design: Adjusting control factors to achieve robust/optimal designs

-Tolerance Design: Reduction of the magnitude of the effect of noise or upgrading the design to achieve robustness

-Ideal Function: The primary function intended

-Control Factors: Attributes/features of the design that can be adjusted/changed by the engineer (materials, dimensions, etc.)

-Noise Factors: Sources of variation that inhibit the ideal function

One example of a unique autonomous noise factor might be interference from cell tower emissions that confuses critical sensors leading to higher risk conditions.

In terms of Taguchi defined “Noise Factors”, “outer” (customer conditions including environment, interfacing components), “inner” (age, wear) and “between” (manufacturing variation, tolerances) would have to be optimized to achieve a robust state.

Strategies for application of Taguchi methods to improving Autonomous Vehicle reliability include:
-Change Concept: Add or change design parameters to improve system capability or control variation
-Strengthen Design: Upgrade or strengthen material, etc. (shift the mean)
-Perform Parameter Design: Select optimal design parameter settings to desensitize system response to noise (NOT an attempt to control sources of variation)
-Perform Tolerance Design: Select strategic design parameter tolerance to reduce transmitted variation

5.2. DFMEA/FMECA

A Failure Modes Effects and Criticality Analysis (FMECA) is a Design for Reliability method used to consider each failure mode of a component of a system and to define the effects of that failure mode on system operation. Failure modes can be defined at any level of indenture. The failure modes are categorized according to the severity of their effects. If using the calculation of the Risk Priority Number (RPN), each failure mode is scored according to its probability of occurrence, severity and probability of detection. The product of all three scores constitutes the RPN score.

A FMECA, Design Failure Mode and Effects Analysis (DFMEA) and Fault Tree can be used to determine whether or not the redundant systems are fully independent, such that the failure mechanism of one does not also affect the others. It is critical to verify latent faults in the primary, secondary and tertiary systems, and that they are detectable at all times, throughout the vehicle life cycle. Safe and reliable operation require that we investigate the effects of transferring from the primary system to the secondary system to ensure no additional risk is created with the existence of redundant systems. Test plans need to be extensive and thoroughly designed in order to confirm that the detection methods on the autonomous technology are sufficient to detect events when second or third level redundant components start to operate.

5.3. Scope Tree

Although the reliability of autonomous components and kits will affect the overall reliability of the legacy system, we recommend the approach of limiting the scope of the Design for Reliability activities on the critical AV “applique” systems, subsystems and components. In focusing on these components and ensuring that they have the highest reliability possible before integration onto the legacy system, we are lowering the risk of decreasing the reliability to a detrimental level. By the very fact of introducing additional components onto the legacy system, the reliability of the overall system will decrease. However, narrowing the scope to the “new” autonomous components will give designers insight into areas where they still have freedom to update the design. The scope tree below outlines the recommended areas of focus for DfR activities. Other RAM activities, such as a Failure Reporting, Analysis, and Corrective Action System (FRACAS), Verification Testing, are integral parts of an autonomous kit’s evaluation, and should be done when the components are integrated onto the legacy platform.

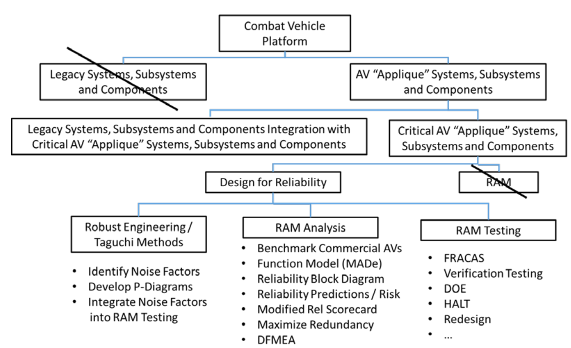


Figure 8: DfR Strategies for Emerging Autonomous Ground Vehicles

5.4. Reliability Block Diagrams

A Reliability Block Diagram (RBD) shows the logical connections between the components within a system, as well as the failure logic between the components. The RBD is not necessarily the same as the functional model, and different RBD models can exist for different system failure definitions. A reliability block diagram is used to decompose the system components into series and parallel arrangements. RBDs can be used for determining the proper level of redundancy in a system, as well as the propagation of failure through a system.

5.5. AMSAA Score Card

The U.S. Army Materiel Systems Analysis Activity (AMSAA), now called the Data Analysis and Activity Center (DAAC), has developed a set of Reliability Growth tools which includes a unique Reliability Program Scorecard. This tool is made available at no charge for US government personnel and government contractors [16]. The reliability growth tools are the latest evolution of the AMSAA reliability growth suite and include the new reliability growth planning models. The reliability growth planning, tracking, and projection models are easy to use and help the user by performing multiple data checks. The AMSAA reliability scorecard can be applied to assess an Autonomous Vehicle system's reliability program.

The AMSAA Reliability Scorecard examines and evaluates an Autonomous Vehicle system or subsystem supplier's use of reliability best practices, as well as the supplier's planned and completed reliability tasks. The Scorecard is critical to tracking the achievement of reliability requirements and rating the adequacy of the overall Autonomous Vehicle Reliability Program. An early Scorecard assessment may be based solely on a Reliability Program Plan, but as time progresses, the Scorecard assessment will become more accurate if information from technical interchange meetings, a Reliability Case Report, and results from early reliability tests, are included. The Reliability Case Report documents the supplier's understanding of the reliability requirements, the plan to achieve the requirements, and a regularly-updated analysis of progress towards meeting the requirements.

There are 40 separate elements among the eight categories in the AMSAA Reliability Scorecard. The eight categories are: Reliability Requirements and Planning, Training and Development, Reliability Analysis, Reliability Testing, Supply Chain Management, Failure Tracking and Reporting, Verification and Validation, and Reliability Improvements. Each element within a category can be given a risk rating of high, medium, or low (red, yellow, or green) or not evaluated (gray). The Scorecard weights the elements, normalizes the scores to a 100-point scale, and calculates an overall program risk score and eight category risk scores. An example of one of the 40 elements contained in the scorecard is shown below [16].

#	Element	High Risk Criteria	Medium Risk Criteria	Low Risk Criteria	Rating	Rationale	Suggestions to Decrease Risk
1	**Routinely builds and updates Reliability Case/Reliability Program Plan for Autonomy Kit during product development**	Autonomy Kit Developer has no Autonomy Kit Reliability Case/Reliability Program Plan or the plan contains minimal content.	The Autonomy Kit Reliability Case/Reliability Program Plan does not demonstrate that the Autonomy Kit Developer has an understanding of the reliability requirements, the plan to achieve the requirements is questionable in terms of implementation, and/or progress towards meeting the requirements is documented sporadically. The Reliability Case does not provide the customer assurance that the contractor is pursuing the reliability best design practices or testing activities. The reliability plan is questionable in terms of realistic timelines, testing, and product design activities to produce a product that meets the reliability requirements.	The Autonomy Kit Reliability Case/Reliability Program Plan documents that the Autonomy Kit Developer has a clear understanding of the reliability requirements, the plan to achieve the requirements is reasonable and achievable, and progress towards meeting the requirements is regularly updated. The Reliability Case provides the customer assurance that the contractor is aggressively pursuing design practices and testing activities consistent with industry high performers. The Autonomy Kit Developer has a reliability program plan that is based upon realistic timelines, testing, and product design activities that will produce a product that meets the reliability requirements.			

Figure 9: Example of AMSAA Scorecard Criteria [16]

6. CONCLUSIONS

In order to provide our men and women in uniform with autonomous systems that are state-of-the-art, reliable and maintainable, we must carefully consider how the introduction of autonomous technologies will affect reliability, and if the reliability of the designed systems will withstand the operational environment of these systems. In this paper, we introduced some issues surrounding designing reliable systems for autonomy. Applying some of the introduced techniques will not guarantee a 100% reliable system, but it will ensure that high risks associated with reliability of the autonomous components are considered, tracked and an area of mitigation while designing the system.

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