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ADOPTING COTS TECHNOLOGY FOR UGV WHEEL DRIVE SYSTEM

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ABSTRACT

As the defense industry prioritizes speed of play to allow our warfighters to maintain a decisive edge over our adversaries, creativity is needed to leverage COTS effectively. This paper presents a case study of a fast-paced workflow leveraging modeling and simulation, targeted risk testing, thermal characterization, and accelerated life testing.

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1. INTRODUCTION

Traditional defense industry program workflows have a strong track record of delivering successful outcomes; however, they can be overly burdensome in today's rapidly evolving threat environment. The adoption of Commercial Off-the-Shelf (COTS) solutions emphasizes the use of existing products as-is, or with only minimal modification, in order to reduce overall program risk. Risks associated with modification can include technical complexity, scope growth, qualification impacts, increased recurring costs, supply-chain disruption, and manufacturing instability. Deviating too far from a qualified COTS baseline can quickly erode its inherent advantages, including mature technology readiness (TRL 9) and established manufacturing readiness (MRL 9) encompassing supply chains, tooling, production processes, and test infrastructure. This paper presents an alternative workflow developed to balance rapid execution with disciplined risk management.

2. AGILE WORKFLOW

Conventional development workflows are typically gated and sequential, with the objective of delivering precisely what is specified with a high degree of certainty. MIL-STDs are flowed down as applicable design, analysis and test requirements also often driving 100s of 'Shalls'. Requirements are largely fixed and non-negotiable, often driving "point solutions" that achieve full compliance but result in unique designs with limited opportunities for reuse. A simplified representation of this approach is shown in Figure 1.

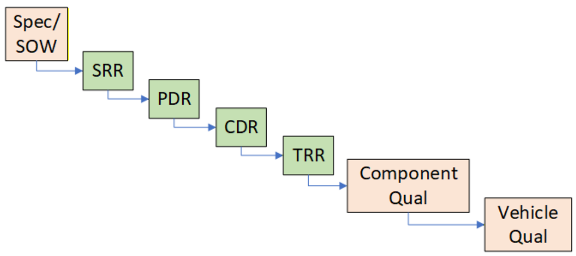

Figure 1 Conventional Workflow

In contrast, a modified Agile development workflow emphasizes the use of COTS building blocks by actively challenging requirements, parallel risk evaluation, allowing minimal design modifications, followed by a focused delta qualification assessment. This rapid development approach enables greater flexibility through concurrent activities and iterative decision-making, as illustrated in Figure 2.

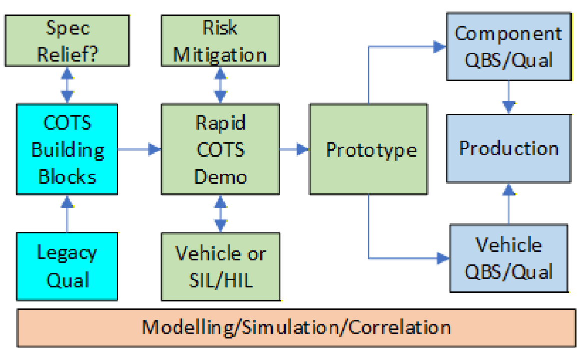

Figure 2 Agile Development Workflows

Figure 2 is a notional workflow with many possible variations but based on core concepts. A key concept in this workflow includes challenging requirements in the form of spec relief. For example, consider the questions all in the context of timing and speed of play:

- Are we certain this be a necessary requirement as written?
- Can you live with 95% of spec?
- Can you live with 80% of spec right *now* using COTS as-is and change later?
- Can you use COTS as-is right now for HIL/SIL and lab integration right now?

Another key concept is risk reduction using COTS. One beauty of COTS is immediate and inexpensive asset availability. COTS elements can be used immediately for example for customer architecture and software development, exploring a unique performance capability, inducing a specific failure mode, testing to a unique environmental condition, etc. The balance of this paper will discuss examples along these lines.

3. SYSTEM DESCRIPTION

Figure 3 below provides a high-level block diagram of the Wheel Drive System, illustrating the power flow left to right from the energy source to the wheel drive.

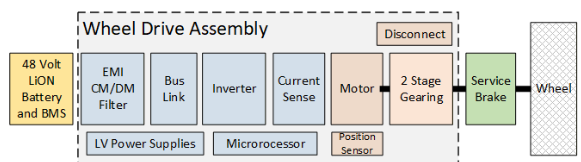

Figure 3 Wheel Drive System Block Diagram

The Wheel Drive System employs distributed architecture at the UGV level by fully integrating the motor, drive electronics, and gearing into a single assembly. This high level of integration results in a traction drive system that is smaller, lighter, more efficient, and more cost-effective overall. Figure 4 is a picture of the final product.

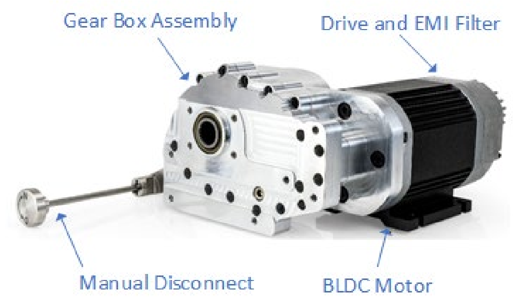

Figure 4 Wheel Drive System

For an UGV with N driven wheels, N Wheel Drive Systems make up the vehicle traction system. A VCC controls and coordinates the outer loops on all N wheel drives.

4. MODELING AND SIMULATION

Modeling and simulation are performed using MATLAB® Simulink and are based on a detailed, validated representation of Allient COTS building blocks (correlation examples shown in Figures 12, 13 and 16). The model captures unique software, electrical, motor, gearing and kinematic performance and thermal behavior, incorporating time-based loss mechanisms. A short summary of modeled physics includes:

- Battery electrical characteristics including SOC% and input impedance
- Drive losses, including quiescent, conduction, and switching losses
- Motor losses, including eddy current and hysteresis effects, as well as copper losses with temperature-dependent behavior
- Gear system losses, including static friction and both forward- and back-driven efficiencies
- Thermal resistance and thermal time constants for critical hotspots, such as MOSFET junctions and motor stator temperatures
- Software implementation as related to performance and thermal protection
- Representative duty cycles, mission profiles, and boundary conditions

Because the traction system is the primary consumer of power and energy in the hybrid vehicle, particular emphasis is placed on optimizing all contributors to total system losses for specific missions and duty cycles. Small, low-risk optimizations can meaningfully reduce losses and translate directly into increased vehicle range.

Representative system level modeling results are included here for reference.

Figure 5 below presents a representative model output for a wheel drive system operating at a constant ambient temperature, illustrating drive, motor, and gearing losses under first-quadrant operation.

Figure 6 below shows a model prediction of total battery current and power draw given the wheel power delivered considering sum of all losses in the system at quasi-static operating points.

Both of these outputs show overlapping lines of constant power for context of battery current draw per wheel drive, etc.

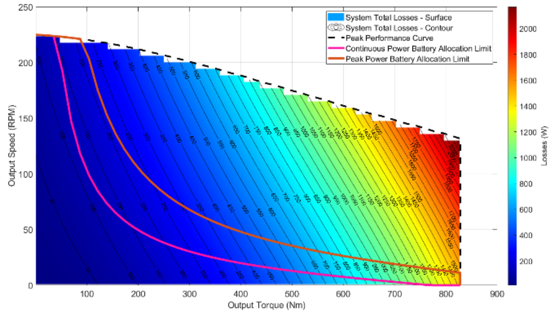

Figure 5 Example Q1 Total Losses

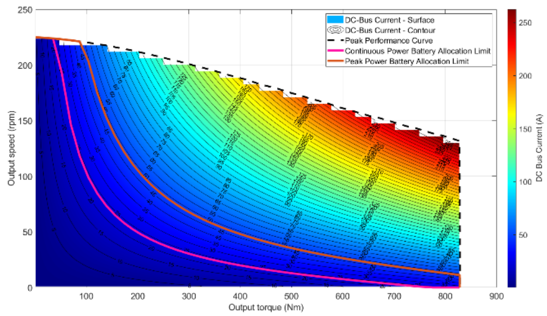

Figure 6 Example Q1 Bus Current

5. WHEEL DRIVE SYSTEM DESIGN

Referring to Figure 3, only minor Form and Fit component level changes were made to the Bus Link, Inverter and Current Sense circuits (3-part numbers in all). The motor was used as-is without any changes.

Only the gear system, manual disconnect and overall assembly are custom designed and in accordance with best engineering practices. These practices include detailed design analysis, applying appropriate safety factors, robust tolerancing, informed by experience from similar legacy designs.

Gear system design and analysis are performed using MASTA and KISSOFT. A representative gear system model is shown in Figure 7.

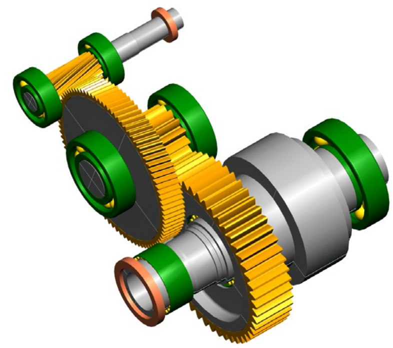
Figure 7 Gear System Design

These tools enable comprehensive load path analysis, including axial, tangential, and radial thrust loads, shaft and bearing analyses, damage and safety factor assessments, and life predictions across a range of duty cycles and mission profiles. A typical load path analysis is illustrated in Figure 8.

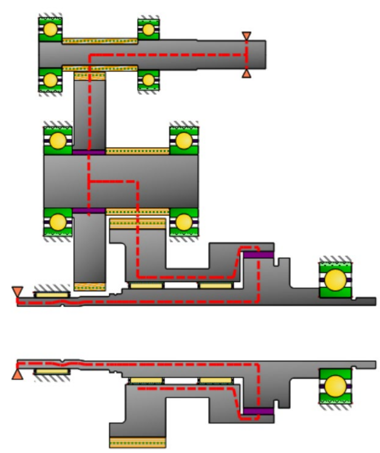
Figure 8 Load Path Analysis

6. SPECIAL TEST METHODS

Inertia Dynamometer

A simple inertia dynamometer (dyno) is employed as a primary tool for risk mitigation. This type of dynamometer provides a passive, reliable, and energy-efficient method for loading the Wheel Drive

System. The rotational inertia of the inertial wheel is selected as the vehicle-equivalent wheel rotational inertia divided by N, where N represents the number of driven wheels on the UGV. A block diagram of the inertia dyno is shown in Figure 9.

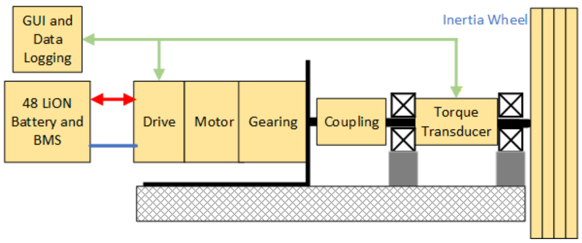

Figure 9 Inertia Dyno Block Diagram

This loading approach enables full four-quadrant operation and realistic Wheel Drive System loading including maximum acceleration, maximum deceleration, and representative duty-cycle conditions. The vehicle’s kinetic energy at gross vehicle weight GVW is effectively replicated by the rotating inertia, resulting in comparable power and energy flow at the dynamometer and vehicle levels. Because the dyno is entirely passive, it avoids the wear, thermal limitations, and maintenance concerns associated with active dynamometer systems. Finally, this dynamometer serves as a powerful tool for reproducing vehicle level integration problems should they arise. An image of the Inertia Dyno is shown in Figure 10.

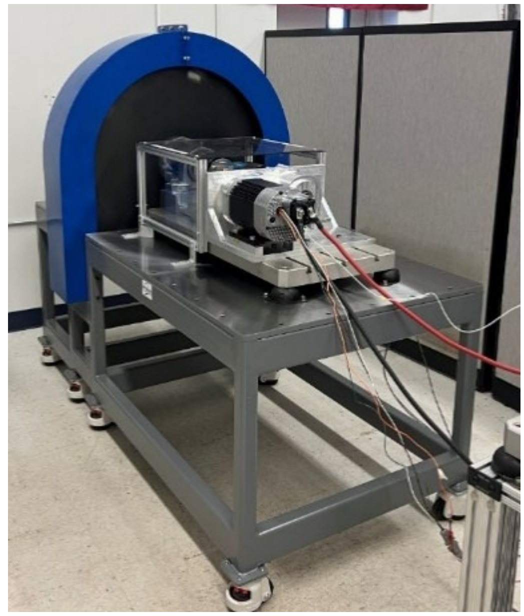

Figure 10 Wheel Level Inertia Dyno

Data extracted from this entirely passive inertial load was used to validate the simulation model. Afterwards, with this accurate model, effects like grade and wheel drag were analyzed via simulation, guaranteeing representatively accurate results.

7. FMEA AND RELIABILITY

The COTS baseline (motor and drive) benefits from an established FMEA supported by successful environmental and life-cycle testing. The legacy design is further validated by an extensive field service history, with demonstrated field failure PPM rates that outperform (i.e., are lower than) customer and application requirements.

The COTS motor and drive assembly has undergone accelerated life testing in accordance with ISO 16750-1:2006 (Road Vehicles — Environmental Conditions and Testing for Electrical and Electronic Equipment). The test regimen included thermal cycling, torque and speed cycling, and periodic cold-soak starts. A total of 1,588 accelerated test cycles were completed, corresponding to an equivalent operational life of approximately 45,000 hours per ISO methodology.

The motor and gearing components have been designed and analyzed with sufficient safety margins such that their contribution to system FIT rates is considered negligible (effectively zero). Consequently, overall system reliability is dominated by the electronic PCBAs, which have an MTBF of 6,788 hours as calculated per MIL-HDBK-217FN2 under conservative (worst-case) operating conditions. Notably, field PPM performance indicates a higher effective MTBF, which is typical for robust designs operating within well-characterized use environments.

8. RISK MITIGATION ACTIVIES

The legacy COTS baseline product is currently used in a hydraulic power-assisted steering system for on-road man rated vehicles. Although the natural operating environments are similar, the application differs significantly, resulting in use conditions that are different from those of a Wheel Drive System. To address these differences, a carefully selected set of risk-reduction activities was executed with a “fail-fast” prioritization to identify potential shortcomings as early as possible.

Voltage Range and Derating Analysis

The legacy application operates from a nominal 28-VDC power source, whereas the UGV application is based on a nominal 48-VDC lithium-ion battery system. An impact assessment was conducted to evaluate the implications of this increased operating voltage.

From the motor perspective, the associated risks were assessed as minimal, as the insulation systems and electrical connectors provide ample margin based on standard component selections.

From the drive electronics perspective, a limited number of electronic components were updated to achieve the required voltage derating margins at the higher operating voltage, ensuring adequate margin at 100% state of charge (SOC). No printed circuit board (PCB) changes were required, thereby minimizing design change risk.

Thermal Protection

The legacy application experiences less dynamic and transient loading compared to the operating conditions of a traction system. Consequently, the thermal management strategy required modification. The implemented thermal protection scheme combines drive and motor temperature warnings and faults with an I^2T algorithm featuring foldback protection. The I^2T algorithm (pronounced “I-squared T”) estimates the thermal energy being dissipated by the motor over time (phase current squared multiplied by time) to predict and prevent localized overheating.

Thermal Failure Test

The primary thermal failure mode of interest is the response of COTS components to an unlimited (in time) peak phase current command—specifically, how, where, and when a failure occurs. Potential weak points include electronics (components, PCBs, traces, filters, etc.), cable assemblies (sockets, pins, wires, etc.), and motors (insulation systems between phase-phase or phase-chassis). Accurately predicting both the location and timing of such failures is effectively impossible through analysis alone.

Given the availability of COTS assets, destructive testing is the most effective approach. The worst-case scenario is a pure stall condition (no rotation) with the motor at a specific electrical angle, where one phase pair experiences 100% of peak phase current. This condition is generated using a specialized software configuration that simulates the locked rotor stall condition and disables all thermal protections.

This test was conducted with the root cause being overhearing of the stator and ultimately a failure model leading to open circuit condition on the stator. Figure 11 shows the corresponding stator temperature during the test. After exposure to peak phase currents the stator essentially became open circuit after about 40 seconds when starting at 25°C.

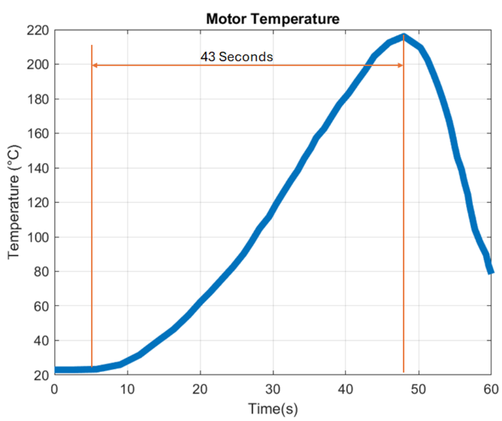

Figure 11 Thermal Failure Test

Four Quadrant Operation

In this context, “four quadrants” refers to the drive system’s torque and speed output across all combinations of positive and negative torque and speed: +/+, +/-, -/+, and -/-. This corresponds to wheel torque and speed, independent of service brake torque.

The legacy application operated solely in the first quadrant. Transitioning to four-quadrant operation introduces additional risks for software, electronics, connectors, and the motor itself. Ensuring efficient bidirectional flow of current, power, and energy is therefore critical and require verification.

In this application, the motor and drive are capable of approximately 2X the speed of the legacy system, and allowable peak phase currents around 1.5X higher. As a result, the net mechanical output and electrical input power can be roughly three times that of the legacy system.

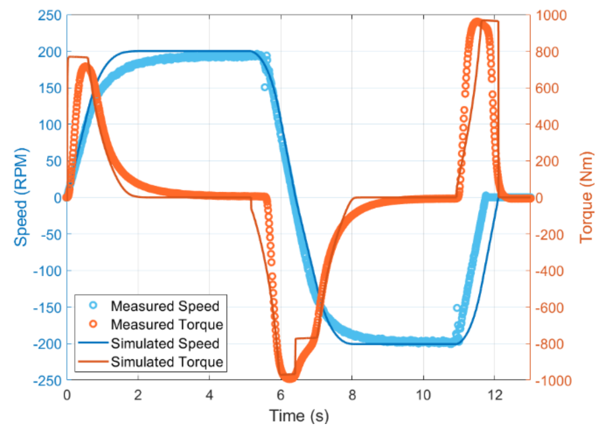

Figure 12 Torque and Speed Time Series for 13-Second Repetitive Acceleration/Deceleration Duty Cycle

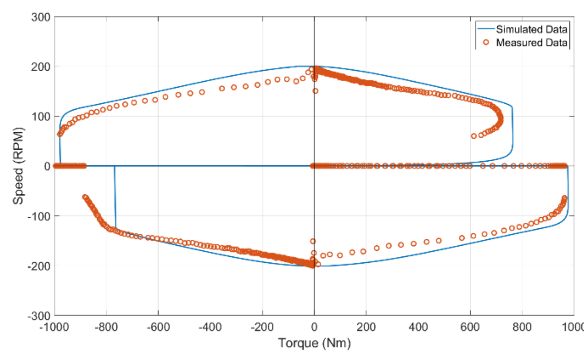

Figure 13 Example 4-Quadrant Operation

Figure 12 illustrates an example acceleration/deceleration profile, with the measured time series mapped against the model-predicted four-quadrant performance. This dataset captures a full 13-second repetitive duty cycle, generating power in all four quadrants.

Figure 13 plots the same wheel torque and speed time series data on torque versus speed axis with a model-based performance estimate the same 13 second duty cycle.

While the overall performance is largely symmetrical, the effects of forward and backward gear system efficiency are evident. In quadrants 1 and 3 (forward drive), all gear system losses must be overcome, whereas in quadrants 2 and 4 (regenerative or back drive), gear losses contribute to additional wheel torque opposing motion. As a result, with comparable voltage and phase current limits (torque limits), the ‘area under the torque-speed curve’ is greater in the regenerative quadrants (2 and 4), as expected.

Battery and BMS Performance

Battery and Battery Management System (BMS) behavior can vary significantly between systems. For testing, a representative Li-ion battery and BMS were used, with input cable impedance characteristics similar to the intended application. No anomalous behavior, warnings, or issues – such as inrush current spikes or bus transients – were observed during testing.

Other risk mitigation activities included -40 cold soak start and others to be listed.

Cyclic Testing

There are several fundamental purposes of cyclic testing:

1. Full 4 quadrant power and energy flow
2. Thermal performance / model validation
3. Durability testing of the newly designed gearing system.

Thermal validation is essential to allow the model to accurately *predict* transient and steady-state implications of varions duty cycles and missions.

The primary objective of durability testing is to identify any unexpected failure modes or life-limiting factors. Potential life limitations are typically associated with thermal expansion and contraction (CTE) cycles, electronics, bearings, shafts, insulation systems, gear wear, lubrication breakdown, and similar stressors.

For the case study at hand, although the gearing system leverages design and manufacturing expertise, it is uniquely sized and packaged to meet specific requirements of the application, so the cyclic testing addressed key considerations including:

- Lubrication type, quantity, effecitveness
- Four-quadrant energy and power flow through drive
- Realistic shaft, gear, bearing and assembly axial and radial loading
- Realisitc thermal use conditions.
- Operational speeds up to twice those of the legacy system

Thermal performance and model validation

Figure 14 shows 2 cycles of one of the Durability test cycles while Figures 15 and 16 show example thermal measurements of motor stator and PCB hot spot near output stage drive MOSFETS.

This data is used to help calibrate our MATLAB® Simulink model by inputting the same durability cycle with properly correlated thermal parameters. Figure 16 shows the resulting correlation.

We leveraged the validated model of the COTS motor and drive to make the wheel drive assembly sizing more agile, a correlated model for this system is very powerful to predict performance under other missions, boundary conditions.

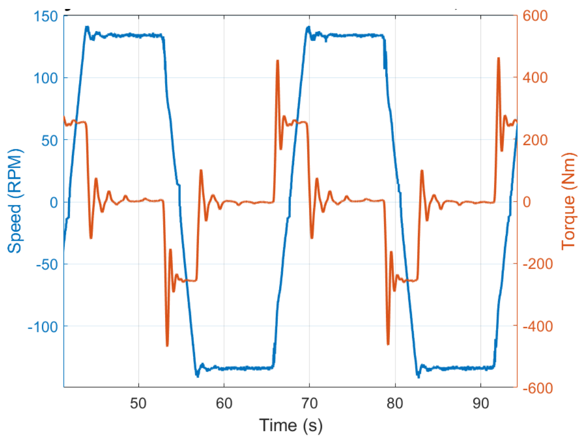

Figure 14 Wheel Torque and Speed during Durability Test

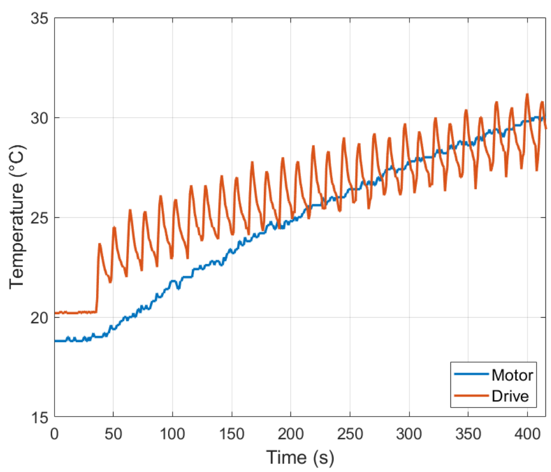

Figure 15 Durability Test Temperatures (zoom in)

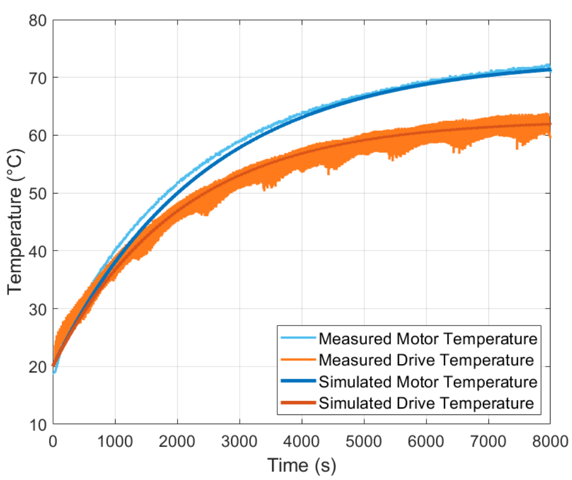

Figure 16 Durability Test Temperatures

In addition to thermal measurements and model validation, another useful tool includes thermal imaging whereby we can look for unexpected hot spots. The figure below includes some examples.

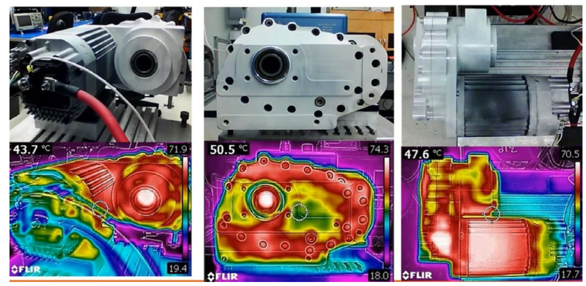

Figure 14 Thermal Imaging Validation

9. QUALIFICATION BY SIMILIARITY

The rapid development schedule may not allow for traditional, full *component*-level qualification (e.g., MIL-STD-810, MIL-STD-461). In this case, the legacy baseline product has already been qualified to on-road, non-military environmental and EMI standards.

The motor and drive are designed and tested to commonly accepted passenger car and heavy equipment standards, such as ISO, SAE, and CISPR. Direct comparisons between standards are often challenging, and establishing “better than” or “less than” compliance statements is not straightforward. However, in nearly all cases, equivalent test methods exist that reflect the original design intent.

The purpose of **qualification by similarity** is to ensure that no critical environmental or operational conditions are overlooked, and that any differences between the legacy and new application remain within acceptable limits. Appendix A provides a representative Qualification by Similarity matrix.

10. CONCLUSIONS

In our experience, early creative programmatic engagement with vehicle primes can deliver speed of play leveraging COTS. Effective collaboration requires a different mindset than traditional defense industry program workflow. This mindset works best by challenging requirements, utilizing model-based engineering methods and timely and targeted risk mitigation activities.

To summarize the impact of proposed Agile Workflow as described in Section 2 and as illustrated in Figure 2:

- A fully documented '***Rapid COTS Demo***' was provided to customer HIL/SIL lab in ***3 weeks*** ARO.
- A functional equivalent ***Prototype*** was delivered ***12 weeks*** ARO.
- ***Production*** hardware was delivered ***6 months*** ARO.

The net result of the Agile workflow was production hardware delivery in less than one year. In the conventional workflow this would have taken at least two years.

The 'Fail-fast' mindset is well suited for COTS based programs where COTS assets are readily available. Leveraging what you have, only designing what is needed, utilizing qual by similarity and finally; be ready to negotiate divergences or short coming to achieve speed of play.

11. REFERENCES

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12. CONTACT INFORMATION

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ACRONYMS

Acronym	Definition
ARO	After Receipt of Order.
BMS	Battery Management System
CDR	Critical Design Review
CISPR	International Special Committee on Radio Interference
CM	Common Mode
COTS	Commercial Off the Shelf
DM	Differential Mode
EMI	Electromagnetic Interference
FMEA	Failure Mode Effects Analysis
GVW	Gross Vehicle Weight
HIL	Hardware in the loop
ISO	International Standards Organization
LiON	Lithium Ion Battery
MOSFET	Metal Oxide Field Effect Transistor
OTS	Off the Shelf
PDR	Preliminary Design Review
PPM	Parts Per Million (failure rates)
QBS	Qualification By Similarity
SAE	Society of Automotive Engineers
SIL	Software in the loop
SOC	State Of Charge
SRR	System Requirements Review
TRR	Test Readiness Review
UGV	Unmanned Ground Vehicle
VCC	Vehicle Control Computer
VDC	Volts Direct Current

APPENDICES

Appendice A

	Qualification Standard	
	Typical Defense Qual	Legacy Qual
Ambient temperature, max.	55°C	80°C
Ambient temperature, min.	-40°C	-40°C
Storage Temperature	-40°C to 85°C (Negotiable limits)	ISO 16750-4
Ingress Protection IP rating	ISO 20653 IP67 Dunk Test	ISO 16750-4
Ingress Protection IP rating	ISO 20653 IP6K9K Steam Pressure wash	ISO 20653 IPX9K
Climatic Conditions	SAE J1455 & J2721 ISO16750-4	ISO 16750-4
Chemical Conditions	SAE J1455 & J2721 ISO16750-5	ISO 16750-4
Shock & vibration	SAE J1455 Vibration, ISO 16750-3	IEC 60068-2-64,
Impacts & bombardment	SAE J1455 Vibration, ISO 16750-3	ISO 16750-4
Operational Elevation	-282 ft to 10,600 ft referenced to sea level	NA

Figure 158 Example Qual by Similarity Matrix