A Framework for Reliability Engineering on the Field Scanalyzer System

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Reliability engineering on high-value, low-volume complex equipment poses a significant analytical challenge. Equipment of this type often undergoes rapid development cycles and has complicated interactions between components and subsystems. It can be difficult to perform typical reliability calculations due to time- and cost-limited testing and a shortage of pre-existing literature to use as a baseline for estimates. Implementing reliability growth is nontrivial for this equipment. In a publication by Zhu et al. (2019), semiconductor manufacturing equipment was considered to develop a mechanism for performing reliability engineering activities. In a prior term paper by Demieville (2020, unpublished), the results of the paper by Zhu et al. (2019) were considered for application to the Field Scanalyzer system located in Maricopa, Arizona. This system is a unique piece of scientific equipment with an overall cost in excess of $10 million and is a system of systems with high complexity, clearly meeting the criteria of high-value, low-volume complex equipment.

In this paper, multiple activities were discussed that can lead to performing reliability engineering on high-value, low-volume complex equipment. Design for reliability activities should be implemented ideally during product development so as to take advantage of knowledge from existing products. A reliability quantification plan (RQP) would then be developed to establish goals for desired reliability metrics, such as mean time between failures (MTBF), availability, and maintenance intervals. Reliability block modeling would be performed to quantify reliability metrics and show serial and parallel relationships between subsystems and components. A bottom-up approach, wherein failure, maintenance, and repair data are applied to each block of the model as inputs to compute overall system reliability metrics, is more appropriate for an existing system. For a new system, a top-down approach is more readily computable because the overall system specifications can be allocated to the subsystems using weight factors. The weight factors are estimated from prior knowledge, management and technical goals, and supplier data. A failure mode and effects analysis (FMEA) is performed to identify actual and potential failure modes and determine their root causes. From this analysis, corrective actions can be implemented. Modifications to the system can improve system reliability and result in reliability growth. Estimation of the failure rate of the subsystems and components poses a major challenge for performing reliability engineering on high-value, low-volume complex equipment. In some cases, accelerated life testing (ALT) is an appropriate tool to use for determining subsystem and component failure rates. Failure data is collected under conditions that stress the system past normal operating conditions. A mathematical model is selected to relate the collected failure data to the typical case. Extended testing into production and operation improves the confidence interval of the accelerated life testing. A continuous improving plan (CIP) is developed to create a methodology for implementing changes to the system. Reliability is monitored, failure modes are prioritized, and changes are implemented as appropriate to result in improvements to the system incrementally. A Duane plot is used to track and forecast system reliability growth. By implementing these activities, a template for performing reliability engineering on the Field Scanalyzer system can be developed and reliability growth can occur.

As this system is already in existence, it is necessary to instead perform reliability engineering activities with the system as-is, and attempt to replicate the existing design in the analyses. From a reverse-engineered system, additional activities can be performed. The existing system was constructed with no known reliability criteria. An additional challenge presents itself in the periodic usage of the system. The equipment runs with relatively large gaps in its operation due to the seasonal schedule of agriculture. Within the season, the equipment is not operated constantly, but rather on a schedule with other instruments so as to provide biologically relevant data. Environmental factors play a major role in the failures experienced. The Field Scanalyzer sees high heat, high ultraviolet (UV) radiation, fine dust, seasonal monsoons, and exposure to birds, arachnids, and insects. The existing software implementation is challenging to reverse-engineer due to the undefined interfaces and internal operating mechanisms. Several black boxes are present on the system, wherein the usage, implementation, and mechanism of operation are unknown to the system owner. Documentation is nearly non-existent. Where it exists, it is often incorrect or insufficiently detailed. Multiple instruments are present on the machine. As a result, there are multiple types of data collection events performed with varying methods, times of day, duration, mechanical operation, and electrical operation. Reliability issues pose a significant risk to the continued operation of the machine. If a data collection event is missed, it cannot be recovered as it is unlikely the same environmental conditions will be presented with the same genotypes of plants in the field.

At a high level, the Field Scanalyzer can be thought of as composed of three major interconnected subsystems: the mechanical subsystem, the electrical subsystem, and the sensing/imaging subsystem. The mechanical subsystem provides the motion for the machine necessary for all instruments to fully utilize their field of regard. The system moves in three dimensions through two sets of railways and a wire rope. Electric motors are used to drive the motion in these dimensions and provide trigger signals to the sensing/imaging subsystem. To provide power to the mechanical and sensing/imaging subsystems, the electrical subsystem manages conversions from the electricity provided by the utility to the types of current and voltage levels necessary for the various components. The sensing/imaging subsystem contains the various instruments used for data collection, the computers that manage the instrumentation and data communication, and the networking necessary for transferring the data across the machine. Multiple instruments are installed in this subsystem. A pair of hyperspectral imagers (HSIs) in the visible and near-infrared (VNIR) range and shortwave infrared (SWIR) range are present. Cameras for visible-spectrum, thermal imaging, and capture of chlorophyll fluorescence are used. Laser line scanners are operated to collect three-dimensional representations of the field. A variety of environmental sensors are also in use to collect supplemental information. With 17 instruments, supporting computers, network hardware, circuit breakers, power supplies, wiring, motors, gearboxes, and more on the Field Scanalyzer, it is a challenging undertaking to reverse-engineer the system.

For the purposes of developing a template for reliability engineering, it is logical to reduce the scope to discuss only a portion of the machine. Within the sensing/imaging subsystem, additional subsystems are present. Looking at one of these mid-level subsystems that is itself composed of lower-level subsystems and individual components would provide a scenario in which a potential user of a template can relate the actions performed to component-level analysis or to subsystem-level analysis. For these reasons, a clear choice of candidate subsystem was present. The HSIs have experienced many failures in their operation. Both instruments have experienced flooding, mirror damage, and dropped frames. The VNIR-range instrument has experienced a failure of its internal Stirling cooler and its triggering cable. The SWIR-range instrument, in contrast, has experienced a failure of its external Peltier cooler. These instruments have been a major source of issues for the Field Scanalyzer. Implementing reliability growth in this area and reducing failure frequency would improve the system’s ability to meet experimental objectives and minimize risk of loss of valuable biological data.

The first step for performing reliability engineering on the HSIs is to create a reliability quantification plan. Goals should be established for relevant reliability metrics. Of primary interest is equipment availability. The instruments should be available for operation at any time during the field season. For this reason, supplier dependent uptime (SDU) is selected as a reliability metric with a goal of 99%, representing uptime barring any input issues, operator delays, facility issues, or other external factors preventing operation. In the most recent field season, this equipment was used 72 times, so this would be a reasonable unavailability to maintain at most one missed data collection event per season. Reliability is another clear metric for success. For analysis, six-sigma reliability would be seen as an excellent goal. Additionally, maintenance intervals would be a valuable metric to improve as they have a direct impact on project costs. These would be best timed to align with scheduled system downtime. For the scope of this paper, reliability engineering will be limited to reliability for conciseness.

The HSIs are a pair of mid-level subsystems. Triggering for these instruments is provided in the form of a pulse wave generated by the encoders on the wheels of the Field Scanalyzer's trolley. Power for these instruments is provided by a pair of power supplies. Circuit breakers and wire are present in the circuit. Data acquisition is performed by a pair of compact hyperspectral data processing units (cHDPUs). Data is transferred via file transfer protocol (FTP) to an onsite cache server before being aggregated and sent offsite for downstream processing. Thus, networking equipment is also essential for these subsystems. A reliability block diagram is shown in Figure 1. This diagram is limited to the portion of the system after a trigger signal is generated and supply voltages are converted to suitable inputs, and before the data is transferred off the cHDPUs. It is apparent that there are many serial and parallel arrangements present. From this diagram, bottom-up reliability allocation can be performed.

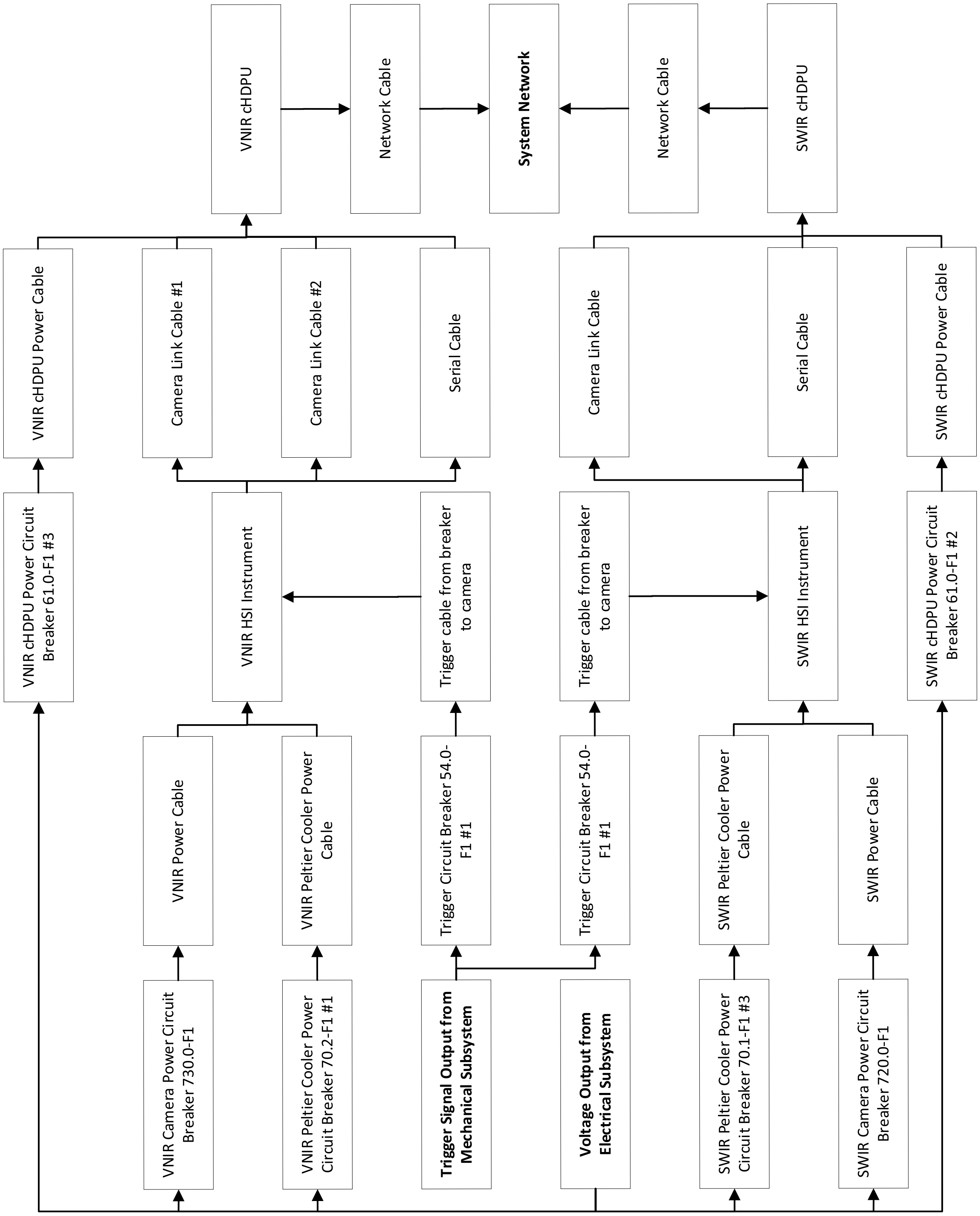

Figure 1: Reliability Block Diagram of Region of Interest

Figure 2 shows the same reliability block model with components replaced by reliability identifiers. In Figure 3, the model is simplified by a small level. Continuing the simplification results in the equation for system reliability of the region of interest, as defined in equation 1.

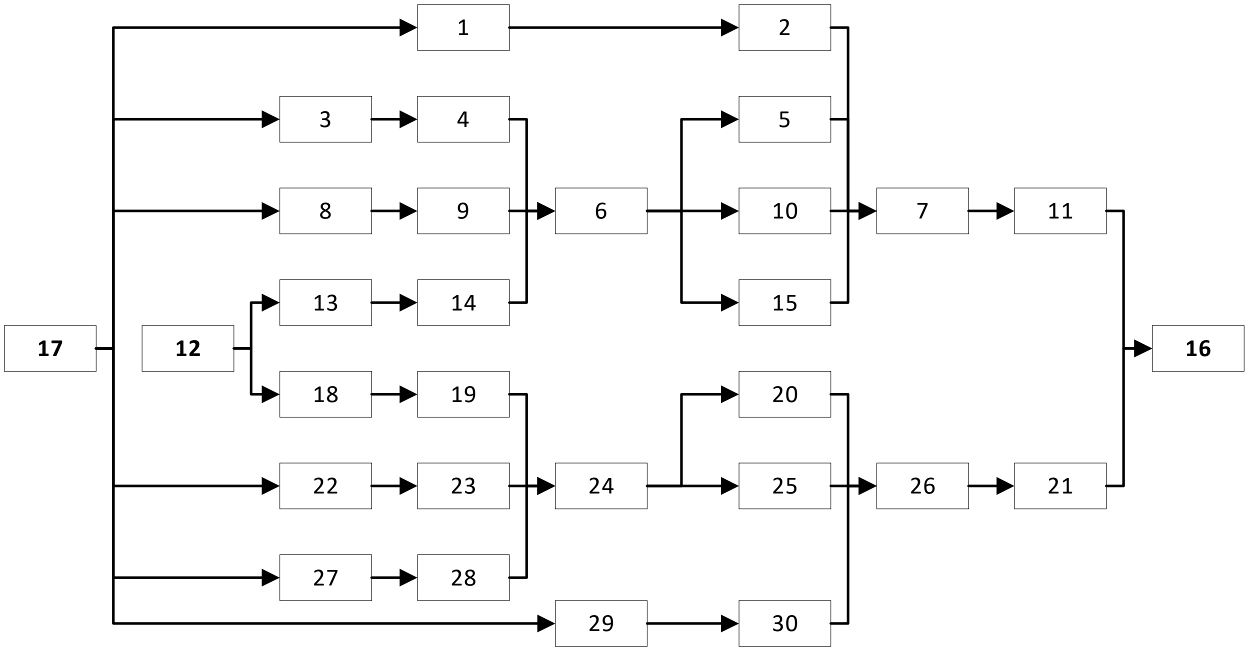

Figure 2: Reliability Block Diagram with Numeric Identifiers

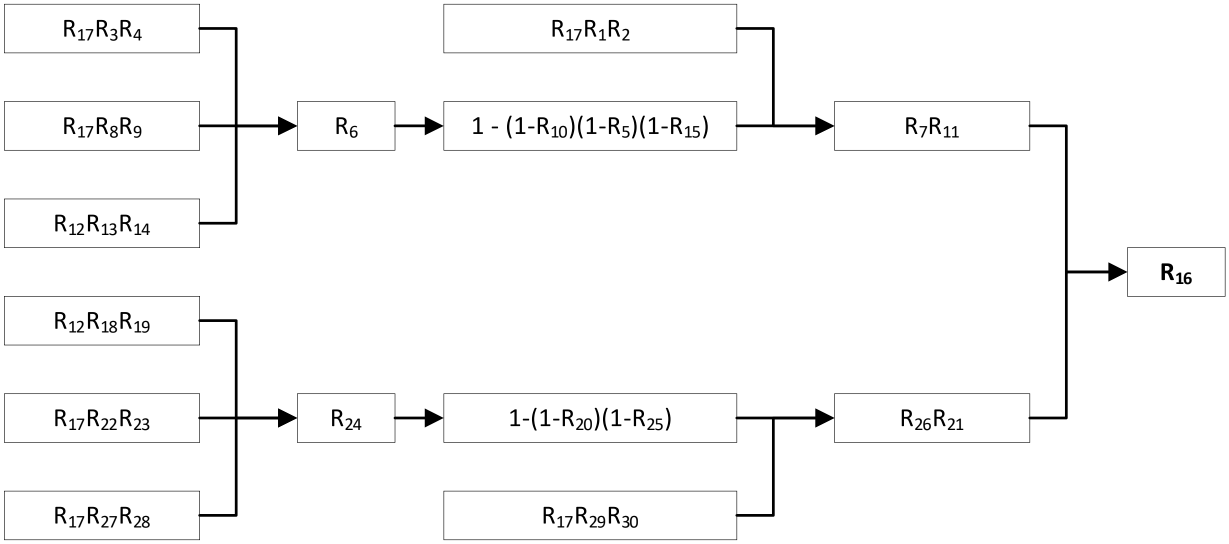

Figure 3: Simplified Reliability Block Diagram

$$R_{system} = zR_{16} \tag{1}$$

Where:

$a = 1 - R_{17}R_3R_4$
$b = 1 - R_{17}R_8R_9$
$c = 1 - R_{12}R_{13}R_{14}$
$d = 1 - R_{10}$
$e = 1 - R_5$
$f = 1 - R_{15}$
$g = 1 - R_{17}R_1R_2$
$h = R_7R_{11}$
$i = 1 - R_{17}R_{22}R_{23}$
$j = 1 - R_{12}R_{18}R_{19}$
$k = 1 - R_{17}R_{27}R_{28}$
$l = 1 - R_{20}$
$m = 1 - R_{25}$
$n = 1 - R_{17}R_{29}R_{30}$
$o = R_{26}R_{21}$
$p = 1 - abc$
$q = 1 - def$
$r = 1 - ijk$
$s = 1 - pqR_6$
$t = 1 - lm$
$u = 1 - sg$
$v = 1 - rtR_{24}$
$w = 1 - uh$
$x = 1 - nv$
$y = 1 - ox$
$z = 1 - wy$

Equation 1 represents the reliability of the system assuming no maintenance or repair is performed. For each component, preventive maintenance can be accounted for with equation 2, where T is the interval of time between preventive maintenance events. Component reliability can be determined by analyzing the failure time distribution for each component to determine a candidate distribution and evaluating the goodness-of-fit to the data. Reliability is then calculated as the probability that the time to failure is greater than or equal to the time at which reliability is being evaluated.

$$R_{component,preventive\ maintenance}(t) = R_{component}(T) * R_{component}(t - \alpha T), \tag{2}$$

$$for\ \alpha T \leq t < (\alpha + 1)T, \alpha = 0, 1, 2, \ldots$$

Determining an appropriate measure of reliability is challenging. While supplier and in-situ historical failure data provide some information for determining reliability, limitations are still present as there is a shortage of test data. Accelerated life testing, while valuable, is not always appropriate or affordable. In these cases, it may be more valuable to perform Bayesian reliability analysis on the existing data. With knowledge of similar implementation of the same components, it is possible to construct a prior distribution for a component's reliability. With the likelihood data obtained from the system, a Bayesian analysis can then be used to find the posterior distribution for the reliability. Overall, this will provide a better result for evaluating system reliability and reduce over- or under-estimation of the desired metrics, which is essential for evaluating against defined criteria.

A failure mode and effects analysis (FMEA) is performed to identify all possible failure modes, their overall system impact, and mitigating actions. An example of a failure mode effects analysis for the VNIR HSI can be seen in Table 1. By performing this analysis for all components and updating it as necessary, it is possible to account for actual and possible failures and include their impact on system reliability. Failure modes and their effects are identified. Ranking is assigned to each failure mode in terms of its likelihood of occurrence, severity, and detectability. Potential causes are explored and mitigation actions prescribed. Knowing deficiencies of the system, it is possible to develop a CIP to provide a pathway for reliability growth. This takes the form of establishing and carrying out processes to meet a desired change in the system. Data and results are gathered and analyzed to determine whether the actions performed enact the change desired. If additional work is needed, the methodology is adjusted to permit it to occur. As these actions are implemented, reliability should be reevaluated and graphed on a Duane plot to track reliability growth. An issue common to both HSIs is flooding of the instrument enclosures. When this occurs, data acquisition is unable to occur until a rigorous cleaning and drying process has been performed. Mineral deposits present in the water affect the quality of the data and may cause premature failure of components. The cleaning process is risky and requires delicate action, but faces additional challenges in that it must occur within the field. Significant costs are incurred if data acquisition is disrupted. A continuous improvement plan may seek to improve the environmental protection of the enclosures. In this scenario, an appropriate CIP may be:

1. Plan: Improve environmental protection of HSI enclosures.
2. Do: Install sheet aluminum shield to divert rainwater.
3. Check: Simulate a rainfall event to test the efficacy of the aluminum shield.
4. Adjust: If efficacy is insufficient, redesign aluminum shield or replace with more effective solution.

Table 1: FMEA for HSI VNIR

Reference ID	1.0	2.0	3.0	4.0	5.0
Failure Mode	Flooding of instrument enclosure	Failure of internal Stirling cooler	Damage to internal mirror	Dropping of frames	Failure of trigger cable
Failure Effects	Loss of acquisition capabilities; cascading damage to other internal components (e.g., mirror, camera)	Loss of acquisition capabilities	Degradation of data quality	Loss of data	Loss of acquisition capabilities
Severity (S)	10	8	4	6	8
Probability (P)	2	2	4	8	6
Detectability (D)	1	7	1	1	5
Risk Priority Number (S*P*D)	20	112	16	48	240
Potential Causes	Improper sealing of enclosure	Operation of cooler beyond design life; mechanical failure	Environmental ingress; improper cleaning	Network latency; insufficient cHDPU resources	Cut cable; loose connectors; poor solder joints
Mitigation Actions	Replace or install environmental protection as necessary	Perform preventive maintenance at manufacturer-designated interval; inspect frequently	Replace or install environmental protection as necessary; implement proper cleaning procedure	Minimize unnecessary cHDPU and network activity	Replace and repair connectors as needed to ensure continuity

As a result of the activities described in this paper, a framework for performing reliability engineering on the Field Scanalyzer is established. A reliability quantification plan was discussed and an example provided. A reliability block model for a portion of the system was created and evaluated to develop an equation for system reliability. The relationships between subsystems and components were shown and simplification steps were illustrated. A failure mode and effects analysis was performed on one problematic subsystem of the Field Scanalyzer. A continuous improving plan was created for one failure mode of the VNIR HSI. Through these activities, reliability growth can occur on the Field Scanalyzer system. The lessons learned can be applied to both the lower-level, same-level, and higher-level subsystems, serving as a framework for performing reliability engineering on the Field Scanalyzer.

References:

Demieville, J. (2020). *Term Paper – Reliability Engineering for High-Value Low-Volume Complex Equipment*. Unpublished Material.

Zhu, L., Jin, X., Burkhart, C., Roham, S. (2019). *Reliability Engineering for High-Value Low-Volume Complex Equipment*. 2019 Annual Reliability and Maintainability Symposium (RAMS), 1-7.