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Reliability of a Lunar Excavator

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RELIABILITY OF A LUNAR EXCAVATOR

A Capstone Experience / Thesis Project

Presented in Partial Fulfillment of the Requirements for

the Degree Bachelor of Science with

Honors College Graduate Distinction at Western Kentucky University

By

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ABSTRACT

Reliability Engineering is a field of engineering that studies the ability of a system (or component of a system) to function properly under specific conditions for a specific period of time; reliability analysis of such a system can take many forms. This thesis presents a quantified reliability study of a system that the author along with a team of Western Kentucky University Engineering students (designated Team ARTEMIS) designed, built, tested, and entered for competition in the Inaugural National Aeronautics and Space Administration (NASA) Lunabotics Mining Competition in May 2010. A detailed quantitative analysis has been completed using both a Failure Mode, Effects, and Criticality Analysis (FMECA) and a Reliability Block Diagram (RBD) system model to identify high priority items within the system calling for improvement. The results and conclusions drawn from this study will be utilized by the second generation Western Kentucky University Lunabotics Team—on which the author will take a lead role—for the next iteration of the system in order to perform critical redesign activities. Additionally, NASA and/or other space exploration organizations could use this study should this particular design be employed in the future for actual lunar excavation.

Keywords: engineering, reliability, systems, lunar excavation, NASA, Western Kentucky University

This study is dedicated to ARTEMIS and to Artie himself. We'll get 'em next time!

ACKNOWLEDGEMENTS

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FIELDS OF STUDY

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CHAPTER 1

INTRODUCTION

In the world of engineering, reliability is defined as "the probability that an item will perform a required function without failure under stated conditions for a stated period of time." [1, p. 3] A system can be designed and analyzed in terms of reliability and its optimization by making use of various analysis and modeling techniques. Two specific techniques have been implemented to analyze a system that the author helped to design and build in order to determine items to improve or add with the next iteration of the system.

Background

During the Fall 2009 and Spring 2010 semesters a team of Western Kentucky University Engineering students (designated Team ARTEMIS) designed, built, and tested a device (designated ARTEMIS Prime) to compete in the 1st Annual National Aeronautics and Space Administration (NASA) Lunabotics Mining Competition in May 2010. According to competition specifications, the team was to design, build, and operate a remotely controlled device capable of excavating, transporting, and discharging lunar regolith simulant into a collector in the competition arena. During competition, teams were

allowed 15 minutes to deposit as much regolith as possible. To simulate remote operation on the moon, the device operator was isolated from the excavator during competition, limited to the visibility provided by an overhead camera provided by the competition as well as any onboard cameras. Official design specifications and competition rules detailed the following non-exhaustive list of specifications:

- maximum device dimensions: 2 meters by 0.75 meter by 1.5 meters

- maximum system mass: 80.0 kg

- that all power be provided by the onboard system

- either telerobotic or autonomous operation

- maximum communication bandwidth: 5.0 Mbps

- minimum mass of excavated material: 10 kg [2, pp. 2-4]

The team designed the device to be capable of collecting approximately 250 kilograms of regolith during the 15-minute competition attempt.

As the competition challenge was divided into three main tasks—drive, dig, and deposit—the resultant device was divided into functional sub-systems of the same names. After considering several conceptual designs for each sub-system and for integration of the sub-systems and performing preliminary tests, the basic form of each system was decided upon. The drive sub-system—functioning to transport the device across the simulated lunar surface and to navigate obstacles—took the form of a set of tracks (Figure 1) purchased from a company specializing in track system design and manufacture; tracks were chosen (rather than wheels) for their superior turning ability,

weight, and cost effectiveness. Figure 2 depicts the integration of the tracks into the

overall system. The dig sub-system—

functioning to remove regolith simulant

from the competition surface and to store it

within the device—took the form of a front-

end loader mechanism that employs a series

of linkages that allow the scoop to achieve

Figure 1 (Above): Tracks as purchased

the desired motion (to lifting / lowering and

turning) using a single linear actuator; this is depicted in Figure 3. The scoop was chosen
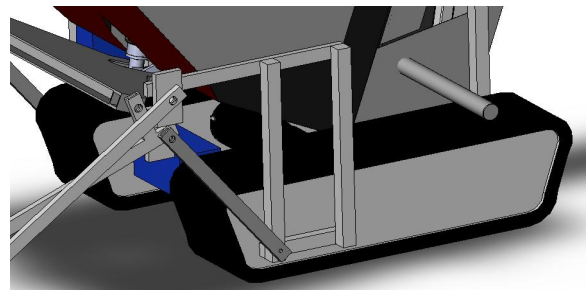
Figure 2a (Above, Left): Tracks as integrated into SolidWorks Model

Figure 2b (Above, Right): Tracks as integrated into actual device

Figure 3a (Below, Left): Scoop mechanism as built

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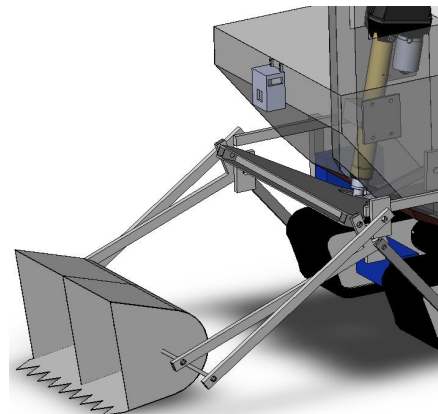
based upon weight and power consumption. The deposit sub-system—functioning to move excavated regolith simulant from the device to the competition collector—took the form of a conveyor equipped with scoops; Figure 4 depicts this subsystem. The conveyor was chosen for its efficiency and reliability (as it was purchased from a company specializing in conveyor design and manufacture). These sub-systems each connected to the collection hopper, shown in Figure 5, which facilitated both system integration and regolith storage. This hopper was designed and built custom to optimize regolith collection while facilitating efficient regolith removal via the conveyor (deposit subsystem).
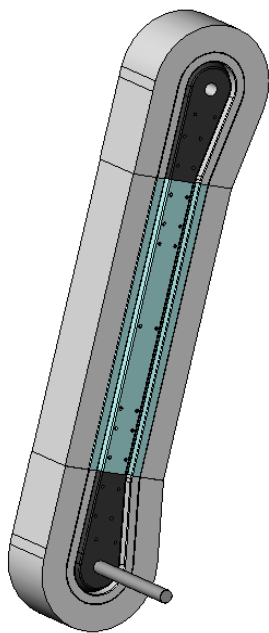
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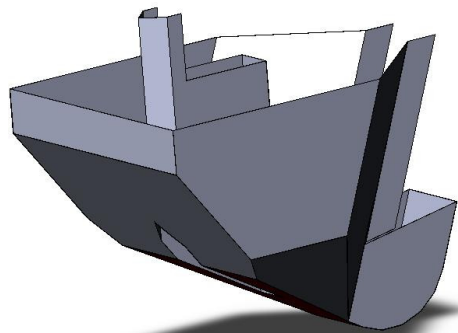
The control system for the device was based upon internet protocol (IP) control through a laptop interface. The system was powered with 24 Volts—dictated by the motors actuating the tracks—and all electrical and other electromechanical components were chosen based upon this voltage. Each major sub-system employed a separate motor

controller based upon current needs. Additionally, two cameras were installed to aid the operator in effectively controlling the drive, dig, and deposit functions. Figures 6 and 7 depict the final device design and the final device itself.
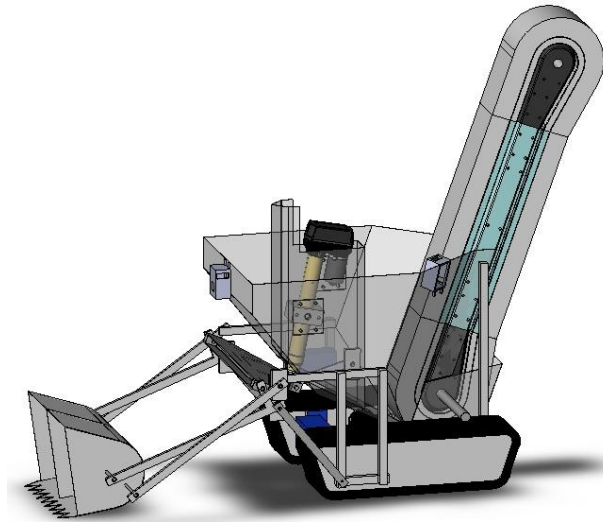
Figure 6:
Solidworks model of final design for
ARTEMIS Prime

Figure 7:
Final physical form of ARTEMIS Prime
(moment before competition attempt)

The ultimate functional goal of the device was to deposit excavated lunar regolith simulant into the provided collector. This depended upon a conveyor successfully depositing regolith into the collector, which depended upon the scoop successfully excavating simulant and storing it in the hopper—not to mention the hopper successfully facilitating all of this; this depended upon the tracks transporting the system to and from the dig site. Thus, this ultimate functional goal depended upon proper function of every sub-system—including the control system—which is important to recognize in analyzing this system's reliability.

At the competition itself the device encountered several functional issues that were not

encountered during testing at WKU, resulting in two failed competition attempts. Since the majority of these issues related to the electrical / communication system, the mechanical components still lack testing / experience operating on the simulated lunar surface. The reliability of several of the device's components—in particular those included in the control system—were called into question based upon observation at the competition. Issues with the deposit sub-system also introduced ambiguity into the conveyor and conveyor motor reliabilities. In attempt to gather as much information as possible concerning the other sub-systems, the team observed the issues—or lack thereof—that other teams with similar sub-systems experienced. For example, teams employing tracks experienced problems with the regolith simulant incapacitating their tracks; observations such as this contributed to the assessment of the reliability of the overall system.

As stated previously, reliability refers to the probability of a device (subsystem, component, etc.) performing adequately for the intended competition duration and under the operating conditions expected [1, p. 3]. Reliability assessment calls for definitions of adequate performance, intended operation time, and anticipated operating conditions. Each was defined within competition guidelines. The device was to traverse the simulated lunar surface, to be capable of digging and depositing at least 10 kg of lunar regolith simulant, and to meet all of the criteria defined in the official rules. The device was to operate through testing, practice at the competition site, and during the competition in a dusty, simulated lunar environment. The team planned to ensure / enhance the reliability of its lunar excavation device in a number of ways, including designing custom fabricated components with a high factor of safety, derating

purchased components, and purchasing major components of two of the sub-systems from companies specializing in their design and manufacture. This also allowed the team to focus upon the system as a whole and upon the components/subsystems demanding more customization.

Testing for Reliability

The uniqueness of this system posed challenges in assessing its reliability. This system, rather than being one of many identical mass-produced systems, is entirely unique. Testing this device in order to aid in assessing its reliability would involve utilizing a sample size of 1 discovery testing method. In the case of this system, only one unit is available for testing due to the nature of the competition—more reflective of research and development than large-scale production. Certain limitations exist concerning reliability testing of single mechanical systems. The first concerns the actual testing of the device. The test designer and facilitator must recognize that testing must be done without anticipated failure—unless the failing component(s) are readily available for replacement, which is not necessarily the case here. [3, p. VII-24] Thus margin testing—a test in which the presence of a safety margin (or factor of safety) is verified [3, p. VII-23]—is often used. The order of the tests must also be designed so that those with the highest risk are performed last (so that testing can be completed efficiently). The second concern involves that of utilizing the results. The results obtained from the testing of a single device are certainly helpful in predicting the behavior of the rest of the population (or other devices that might be built in the future). However, the behavior of the tested

device may represent any output from the best to the worst; there is no way to know with one unit. [3, p. VII-24] In this form of testing, it is best to first verify the operation / functionality of the device and then to verify the design / margins of safety.

The functionality of the major purchased components of the system—the tracks, the conveyor, the motors, the linear actuator, the motor controllers, and the controller board—were each initially verified independently of the rest of the system before being implemented in order to discover any immediate issues. As the system was integrated, the three major functions—drive, dig, and deposit—were each tested in order to ensure that the desired motion was achieved—particularly in the case of the dig function. After this the tracks were tested in sand to verify their functionality on such a surface, and the safety margins of the scoop sub-system components were tested with weights simulating the mass of sand that would need to be lifted in each scoopful. The margin of safety associated with the conveyor motor (and with the conveyor scoops) was tested by manually filling the hopper with sand and observing the ability of the conveyor to unload the hopper. Then the entire device was tested in the sandbox driving (empty and full of sand), lifting scoops full of sand, and unloading the hopper full of excavated sand. However, the inability to test on lunar regolith simulant—due to a combination of availability and cost—was a major validation impediment. This pre-competition testing was also limited significantly by the absence of a functioning control system until days before leaving for the competition. On-site practice / testing was limited even more severely due to the absence of a functioning control system, eliminating the chance to operate / test the device on the playing surface prior to competition (and ultimately preventing activity during the competition attempts). One important feature that our

testing regime lacked was a system of manual switches for each of the device components that could have been used in debugging the mechanics of the device while the code to control the device was being written.

CHAPTER 2

ANALYSES

As mentioned previously, this system—ARTEMIS Prime—is unique in the sense that it represents a sample size of one and must be tested differently than items that are mass produced. This system also incorporates unique functional relationships, attributed largely to the human reliability inherent in this system. Human reliability is considered in situations in which people—in this case the operator of the device—can affect the operation of the devices. Human factors can include the probability of correct operation or maintenance, ability to detect and respond to failure conditions, and ergonomic or other factors influencing behavior / response. Human error probabilities are difficult to quantify as they are typically highly dependent upon training, experience, supervision, and motivational factors. [1, p. 169] Even the use of human factors in this study is unique; in some cases the presence of a human factor increases reliability as the operator of this system can react to unexpected—and thus un-planned-for—situations and those beyond the capabilities of a machine. Other unique applications were utilized in instances where the success of the device was enhanced but not strictly dependent upon the presence and/or proper function of a component. The occurrence of these will be highlighted throughout the discussion of each analysis.

This project incorporates two specific reliability analysis / prediction techniques.

The first technique that will be presented is a design for reliability analysis technique known as a Failure Mode, Effects, and Criticality Analysis (FMECA). The FMECA is a reliability evaluation and design review tool that investigates potential failure modes—the symptom of a failure (not its cause) [3, p. V-12]—within a system or sub-system in order to determine the effect of each failure upon system performance and personnel safety. The FMECA is considered to be a "bottom-up" approach, starting with a specific failure and tracing up to its effect upon a system. The FMECA is useful in identifying potential design problem areas, including failures that cause other components to fail—secondary failure events—and identification of single points of failure—items / functions whose failure would result in system failure and for which no redundancy or alternative operational procedures exist [3, p. II-55]. A FMECA report will highlight areas requiring corrective action, will rank the associated failures according to metrics such as severity and risk priority, and will recommend action to improve the system's reliability. [4, p. 198]

The second technique that will be presented is a reliability prediction technique known as a Reliability Block Diagram (RBD). An (RBD) is a tool that can be used to model a system and to determine the reliability of said system. Such a model provides a picture of the functional interdependencies within a system in the form of a framework into which component and/or functional reliability estimates can be incorporated [4, p. 156]. Such a model [1] allows for easy visual identification of single points of failure and weaknesses within a system, [2] demonstrates component and/or functional relationships within a system, [3] provides a mechanism for quantifying such relationships—being particularly helpful for complex ones—and [4] allows for summarization of the various factors

contributing to system a system's reliability [4, p. 156]. The RBD and the FMECA work together in that each can provide clarity to the other. Failures with the highest risk priority ranking according to the FMECA should roughly correspond to the items / functions / events most significantly lowering the overall reliability value in the RBD. A model such as this helps to guide design (and redesign) decisions by illustrating in a quantifiable manner the reliability of a system and the items affecting it most.

Failure Mode, Effects, and Criticality Analysis

As mentioned previously, a Failure Mode, Effects, and Criticality Analysis (FMECA) is a tool that investigates potential failure modes within a system or sub-system in order to determine the effect of each failure upon system performance and personnel safety. The FMECA tracks failures to their consequences in the system in terms of the physical potential results of a particular failure, the probability that said failure will occur, the severity of the failure should it occur, and the probability of detecting the failure. Another version of this analysis technique is the FMEA, which omits the criticality portion of the analysis. [3, p. V-8]

This FMECA worksheet set takes the form of a series of spreadsheets in Microsoft Excel in which various quantitative and qualitative observations and judgments are recorded about the system's potential failures. A worksheet exists for each functional sub-system—drive, dig, and deposit—each of which includes those aspects of the control system which affect its performance. Each worksheet is organized by component. In some cases, a component is a single moving part. In others it is a group of several moving

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parts that—in terms of potential failure modes—are so interdependent that for, the purpose of this analysis, they are considered to be a single component. Components are then broken down in terms of their associated potential failure modes. For each potential failure mode, potential effects of failure are listed; failure mechanisms—causes of failure—associated with each are also listed. The next two columns list the current controls in place for preventing and for detecting each failure, respectively. Entries in these five columns experience some overlap; for example, one failure mode may have three effects, four failure mechanisms, and two controls each of failure prevention and detection. Each combination of these five items has been assigned an Assessment Number for distinction and reference.

The next five columns represent the risk assessment associated with each failure. The first three columns of these are values ranging from 1 to 10 that describe the probability of occurrence for a failure (P), the severity should said failure occur (S), and the probability of detecting the failure prior to use in its intended setting (D), respectively [3, p. V-10]. In order to conduct a valid assessment of each of these, controls must exist to ensure consistency with each type of ranking between components and functional sub-systems. For this study, the author created a set of indices—one each for probability of occurrence, severity, and probability of detection, specifically applicable to this system and its goals—which provides ranking values and descriptions of each value's meaning. Appendix C contains these Risk Assessment Indices.

The next column represents the Risk Priority Number (RPN) for each assessment number; $RPN = (P)(S)(D)$. [3, p. V-10] The next value represents the Probability Value (PV) associated with each assessment number. This is another aspect of this

analysis which is unique. The author has defined this term as PV = (P)(D), excluding the severity of the failure, as a quantitative measure to distinguish items which are most likely cause problems within the system. Some failures may be described with a very high severity but be relatively unlikely to occur and/or escape detection, resulting is a sort of false indication of priority. Using the PV along with the RPN, the author has been better able to draw quantitative conclusions regarding the system. Additionally, the RPN and PV entries for all assessment numbers associated with a particular component have been each added together in order to identify components requiring the most attention.

The following three columns represent corrective actions—those recommended and those taken, respectively—and the person or sub-team responsible for implementation. Since the FMECA involves iterative design, upon recognition of pressing design issues / flaws, modifications and other actions were implemented—as time and resources allowed—for improvement. Following corrective actions and operation at the Lunabotics competition, the device was re-assessed in terms of P, S, and D; the resultant RPN and PV entries were then compared to the initial RPN and PV entries in order to assess improvement. One should note that some revised RPN and PV entries were higher (worse) than their associated initial entries due to problems experienced at the competition. Therefore, revised PRN and PV entries indicate items requiring attention during redesign.

Reliability Block Diagram

As mentioned previously, a Reliability Block Diagram (RBD) is a tool that can be used to model and find the overall reliability of a system. An RBD is typically constructed based

upon functional system requirements and the components, systems, and/or functions satisfying said requirements. Data is typically input to an RBD in various forms, including reliability predictions, test data, field data, and customer requirements and use profiles [4, p. 156]. The detail to which a system is analyzed can be as great as accounting for duty cycles, service life limitations, wear-out, environmental factors, software, and human reliability [4, p. 156].

An RBD is often constructed in either hardware form or functional form. Component block diagrams are useful for incorporating reliability test data and prediction methods and for analyzing the relationships between those components; success probabilities for each component are determined and combined according to the structure of the diagram. Functional block diagrams use useful for better understanding (complex) systems [3, p. VI-6].

The two most basic and simple RBD modeling relationships are series and parallel, which are analogous to series and parallel circuits in electrical wiring schemes. The series model is used in instances where components (or functions) are single points of failure. If the failure of a component results in the failure of the entire system, that component is in series with the rest of the system [1, p. 124]. The parallel model is used when only one of a pair (or group) of components must function in order for the system to function. The parallel model can take any of the basic forms of active redundancy, standby redundancy, and m-out-of-n redundancy [1, pp. 124-126]. The former two are both incorporated into the model developed for this study and will be explained later in terms of their specific application in the analysis.

The RBD constructed for this study is a hybrid of the component and functional block diagram approaches. Generally, the top level of the analysis represents the major functional subsystems comprising the overall device while the lower levels of the analysis contain the various components comprising that subsystem. Though this approach may be less common, instances where events can cause failures as well as components demand the inclusion of blocks for said events [1, p. 124]. Within the lower levels of the analysis are scattered various functional blocks as were deemed appropriate that are themselves often comprised of components and/or human reliability estimations. The analysis mechanism itself has taken the form of a Microsoft Excel workbook comprised of a top level worksheet representing the basic functional subsystems of the overall system with succeeding worksheet representing the different branches and levels of the overall system. When a component or functional bock within a level is itself comprised of components, a new—lower—level is created to model the components of the parent block. The workbook is equipped with a mechanism for easy navigation of the model.

The first worksheet of the workbook—the top level page—is entitled "ARTEMIS Prime"; this level contains four blocks. The value beneath each block refers to the reliability calculation from that specific subsystem level and branch. Each of the four blocks in this worksheet contains a link to the worksheet containing a model of the associated function / sub-system within the overall system. By following the link, one can view the subsystem worksheet—for example the "Dig" sheet. This worksheet contains both linked blocks and terminating blocks—ones not representing a sub(-sub)-component. There is also a link to return to   the top level. Each worksheet in the

workbook contains links to the levels immediately below and above as well as a link to the top level. Some linked blocks lead to worksheets that demonstrate the reliability prediction method used for that component / function rather than a deeper level of the model.

The system analyzed for this study is at its core a series system—being comprised almost entirely of single points of failure; therefore, each component must be highly reliable in order to ensure success during competition.

For a series of two components functions, events, etc, with reliabilities R_1 and R_2, the total reliability, R_T, is determined from the following equation:

$$R_T = R_1 \cdot R_2 \tag{Eq. 1}$$

In general, for a series of n, the following equation models the reliability [1, p. 124]

$$R_T = \prod_{i=1}^{n} R_i \tag{Eq. 2}$$

where R_i is the reliability of the ith component. The great lack of redundancy in this system is due in part to the design restrictions placed upon it by the customer— competition rules and technical specifications. The reliability for most items was estimated based upon observed performance and/or calculated safety factors. (If a component has a factor of safety much greater than 1, it is considered to have a reliability of 1 (100%)). However, if reliability data was available, the component was modeled accordingly. (The specific method used for each component for which this was done will be detailed later.)

Despite the overall series nature of the system, some blocks (components,

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functions, etc.) were modeled using various forms of redundancy—specifically active and standby redundancy. Demonstration of both forms of redundancy can be seen in the modeling of determination of collected simulant volume. (This exists in the "Dig" function model regarding the "'Full' Indication" block (and model) and the "Hopper Partially Full" block.) The instance of active redundancy modeling is in the "'Full' Indication" block—the determination of whether or not the collection hopper is full of collected simulant. Two methods exist by which this indication can be achieved: [1] by observing consistency in collection trials and using this observation to predict the number of scoopfuls that constitutes a full hopper and [2] by operator observation via onboard camera. Successful indication of a full hopper can include one or both of these methods; therefore, this model is one of active redundancy. Active redundancy exists in a system where satisfactory operation occurs if any number of the components in redundancy functions properly and is modeled by the following equation: [1, p. 125]

$$R_T = 1 - \prod_{i=1}^{n} (1 - R_i) \qquad \text{(Eq. 3)}$$

where R_i is the reliability of the ith unit and n the number of units in parallel.

However, it is important to note that the "full" indication itself is not strictly necessary. The system can still operate and successfully collect lunar regolith simulant even with a smaller volume of simulant is collected. The first attempt at modeling this was to consider a block representing a keynote component—in this case using the scoop subsystem in coordination with the drive function to move obstacles. However, upon researching this modeling method, its inapplicability to this situation quickly became apparent, as keynote—or keystone— components are typically used in

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application of Bayes' theorem to simplify complex configurations [5, p. 87]. Following

research into other modeling methods, standby redundancy was determined to be the

most appropriate for this application. (Standby redundancy refers to a system in which

one unit—the standby unit—does not operate unless it is switched "on" in the case of

failure of the active unit [1, p. 126].) Using this method, the active block represents the

preferred method and the standby block, the alternative method.

In this case, the "full" indication is considered the active option and the option in which

the hopper is only partially full is considered the standby option. In order to model the

standby redundancy here, a system with perfect switching and components with unequal

failure rates was considered, according to the following equation [3, p. VI-16].

$$R_{(t)} = e^{-\lambda_1 t} + \frac{\lambda_1}{\lambda_2 - \lambda_1} \left(e^{-\lambda_1 t} - e^{-\lambda_2 t} \right)$$ (Eq. 4)

where λ_1 represents the failure rate of active unit, λ_2 represents the failure rate of the

standby unit, and t represents the total time of operation (in hours). Since

$$R_i = e^{-\lambda_i t} ,$$ (Eq. 5)

assuming an exponential distribution [4, p. 39], the following equation was used in the

model.

$$R_{(t)} = R_1 + \frac{\lambda_1}{\lambda_2 - \lambda_1} (R_1 - R_2)$$ (Eq. 6)

The failure rates for each of the components was determined by solving Equation 5 for

λ, assuming a cumulative operation time, t, and using the estimated reliability from each

block, respectively. (This method was implemented for each case in which

standby redundancy—with perfect switching and unequal component failure rates—was applied.) After doing this, all of the components of Equation 6 were known, and said model equation could be implemented.

For this model, it is important to note that—in cases where reliability data was unattainable and physical stress / fatigue analysis was inapplicable—component reliabilities are based upon observations of either the component itself or a similar component / system. Therefore, as the performance of the system and its components was observed, the values changed. Since this set of models / analyses are to be used for redesign—a second iteration of the system—ARTEMIS Prime can be considered the test article.

Appendix E contains detailed descriptions of each of the blocks and sub-models within the RBD.

CHAPTER 3

RESULTS

Failure Mode, Effects, and Criticality Analysis

The results of a FMECA are typically quantified using a Risk Priority Number (RPN), which incorporates probability of occurrence and detection of the failure as well as the severity of the failure. Along with the RPN, this analysis makes use of a Probability Value (PV) that incorporates only the probabilities of occurrence and detection in order to determine the items most likely to cause problems (regardless of severity). The highest—both initial and revised—RPN and PV terms are discussed in this section in order to indicate those items requiring most attention during redesign.

Drive: In the "Drive" FMECA worksheet, the highest initial overall RPN's belong to the track treads—relating to regolith simulant becoming lodged in the joints of the treads—the electrical system (highest contributors being wiring issues, problems with the program code and the RS80D motor controller) and to the scoop (in this case being used to move obstacles, relating most to insufficient practice and camera malfunction concerns). The RPN of the track motor was also relatively high due to potential overload and fatigue and the severe consequences of inability to complete a competition attempt. The highest initial PV's belong to the electrical system, to the scoop, and to the track

motors—each for the same concerns as with the RPN's. Here, the RPN's and PV's indicated the same weaknesses in the design. (One should note that potential consequences concerning with the treads were not fully realized until competition and were therefore not addressed prior to competition.)

After observing issues other teams' experienced with their track treads, measures were taken to prevent issues with regolith impeding track performance. These modifications have not been tested. The highest revised RPN's and PV's belong to the track treads, to the electrical system, to the scoop, and to the track motors. Confidence in the reliable performance of the CSD controller board diminished after issues encountered at competition, making it a higher contributor to the RPN's and PV's in the electrical system concerning the drive function. One should note that the RPN's (initial and revised) for the battery are less indicative of its performance than the PV's since, although failure severity is high, the battery is unlikely to experience failure. The battery failures are indicated as an issue in each FMECA according to the RPN's, but according to the PV's they present no real pressing concerns.

Dig: For the "Dig" function, in addition to the (initial) electrical RPN (with similar issues to those mentioned in the "Drive" function section), the initial RPN of the turning mechanism is also high, due mainly to unstable turning, loss of bushings, and loss of connection pins. Scoop lifting (linear actuator) involved uncertainty due to complex calculations and unknowns associated with operational conditions and therefore had a high initial RPN. Scoop lifting (lifting arms) experienced high RPN's due to potential overload, which was difficult to accurately predict due to stress concentration unknowns. The same components experienced high PV's; however, the greatest contributor

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was unstable connections (for both the turning and the lifting arms). Here again, the PV helped to provide a clearer picture of the issues—in this case those associated with the lifting and turning mechanisms.

Device testing confirmed linear actuator choice and lifting / turning arm design, and code revisions and rewiring increased confidence in the control system; however, issues with the CSD controller board and Sabertooth motor controllers experienced at competition diminished confidence in the control system. High revised RPN's and PV's include the electrical system.

Deposit: For the "Deposit" function, the highest initial RPN's belong to the electrical system (due to wiring and code issues) and to the conveyor motor (due to conveyor overload or atypical loading and to insufficient voltage supply to the conveyor motor). Highest initial PV items include the electrical system (wiring, code, motor controller, and CSD controller board), the conveyor motor (same as for RPN's), the hopper (deformation due to overload and inability to direct simulant to conveyor due to hopper floor angle), and the supports (due to overload).

A number of yet unexplained issues occurred at the competition resulting in increased RPN's and PV's for the control system, the conveyor motor, and the conveyor itself—relating to diminished rigidity due to weight-reduction modifications made to the conveyor chain structure prior to competition, leaving it untested.

FMECA Overall: In general most issues that occurred concerned the control system. During testing a fully properly functioning electrical system was never demonstrated. Additional control system issues (including communication, which is not explicitly noted

in any of the FMECA worksheets) manifested themselves at competition, increasing the number of unknowns associated with the control system. The RPN's and PV's in the FMECA worksheets reflect this statement. Other items requiring attention according to the FMECA worksheets are the tracks (particularly the sprocket-tread interface), the lifting and turning arms (concerning their unstable motion), the conveyor (concerning the rigidity of the chain structure and potentially the conveyor motor functionality), and the hopper (concerning effective direction of the regolith to the conveyor).

Reliability Block Diagram

The results of an RBD are quantified reliability probabilities for individual items, subsystems, and the overall system. By reducing the model for each functional subsystem to a series system, the highest contributors to the "unreliability" of the system can be identified. If this is done at each level for problem items, a fairly inclusive list of problem items for the system can be generated. This list and the items / failures noted from the FMECA worksheets should correlate. From these two, decisions can be made as to where to focus redesign efforts.

Drive: Excepting the control system, the "Drive" subsystem affects the reliability of the overall system most, with a reliability of only 0.471 (47.1%). Within the drive system, the two greatest contributors to unreliability are the tracks and the device location function / event. Affecting the tracks most are environmental factors that manifest themselves at the tread-sprocket interface. Concerning device location, the greatest impediment appears to be visibility, suggesting that a system that does not require

visibility may need to be designed and implemented for the function of device location.

Dig: The "Dig" subsystem has the highest reliability of the functional subsystems (0.888). Contributing most to its unreliability is the scoop subsystem. The reliabilities of the components of the scoop subsystem are nearly equal and relatively high. Concerning the collected volume indication in the dig subsystem, the "full" indication is again impeded by problems with visibility. While a system with higher visibility (improved camera reliability) or no need for visibility would not necessarily improve system reliability—and would therefore not be considered a priority—it would likely enhance its success.

Deposit: The reliability of the "Deposit" subsystem is 0.692. The item contributing most to its unreliability is the conveyor. Affecting most the performance of the conveyor is the conveyor chain. The conveyor from ARTEMIS Prime will be tested extensively in order to both accurately and precisely determine the affect of conveyor chain modifications on the conveyor's ability to deposit regolith simulant before redesign is finalized.

Control: The control system contributes most to the unreliability of the system, with a reliability of 0.202. The two aspects affecting most the reliability of the control system are the communication (WiFi) and the electrical control. According to the model, the CSD controller board is the item most responsible for unreliability. The two Sabertooth motor controllers contribute second-most. The assignment of blame regarding the components within the control system is highly imprecise as the cause(s) of many of the issues were unable to be determined prior to competition.

RBD Overall: Overall, the RBD model suggests that the highest priority items for

redesign include the track tread-sprocket interface, device location system, conveyor chain, and various aspects of the control system.

CHAPTER 4

FUTURE APPLICATION

From the FMECA, the items with highest priority for further testing / redesign are the control system in general, the tracks (particularly the sprocket / tread interface), the conveyor (concerning the chain structure and potentially conveyor motor), the hopper (concerning translation of the regolith simulant to the conveyor base), and the lifting and turning arms (concerning fluidity of motion). The RBD adds to this list the device location system and suggests that an improved collected volume determination system would enhance the success of the system.

System weaknesses associated with the drive function involve lunar regolith simulant deposits in the mechanical joints of the tracks. While operation in sand has been demonstrated effectively, the fine, abrasive qualities of the simulant material immobilized that tracks. Due to the severe and complete nature of the track failure observed, the drive subsystem will undergo conceptual redesign. The team currently plans to design a drive train in which joints and other such simulant-sensitive parts will not come into contact with the playing surface (regolith simulant) at all.

The next high priority item was the conveyor. Since the exact cause of the conveyor issues experienced at competition has not been determined, additional testing of the

deposit subsystem is necessary. Despite these issues, the current team still believes the conveyor system to be an effective concept based upon performance during testing at WKU. Therefore, pending results from said testing, the current team plans to employ a very similar system, specifying a conveyor—particularly conveyor chain—more suited to the system's needs.

Next is the collection / storage hopper. ARTEMIS Prime's hopper was optimized for maximum regolith simulant storage, assuming a (less than conservative) angle required for regolith to translate freely to the base of the conveyor. This complicated design did not effectively facilitate translation of regolith simulant to the base of the conveyor. Furthermore, it lacked rigidity, which was manifested in the lifting of heavy loads with the scoop. However, the hopper concept itself was very effective once the necessary modifications were made. The next hopper iteration will employ a greater floor angle as well as enhanced rigidity.

The following three items are of lower priority as their particular "failures" do not cause the system itself to fail; however, their improvement will enhance the success of the system. The first of these is the scoop mechanism—particularly the connection points of the lifting and turning arms. The scoop mechanism concept proved successful; however, execution was a bit sloppy. In order to improve this item, potentially slight redesign and certainly more precision machining will be employed. The second and third of these are the collected volume determination system and the device location system. These systems will be redesigned conceptually, perhaps involving a type of sensing system and/or simply a more reliable onboard camera system.

In order to fully determine the plan of action for improving the control system, one must understand that the process by which the control system was developed was inherently flawed. No intermediate steps existed between control system design and (attempted) implementation of a completed control system. The control system itself involved several connection steps that had to be troubleshot simultaneously and quickly. The laptop interface (HMI) had to successfully send commands from the control station, which had to be running tested and proven code; the control station had to successfully establish wireless communication with the controller board onboard ARTEMIS Prime, which in turn had to command each of the motor controllers. When problems arose during testing, the team had to determine which of these steps was experiencing malfunction; troubleshooting a system implemented and tested in steps would have been much more straightforward and efficient. However, in the case of ARTEMIS Prime, by the time the mechanical components of the system were themselves integrated and then ready to be integrated with the control system, the competition date was fast approaching, and the system had seen no electrical implementation save battery power and physical "on/off" switches.

In order to develop and test the electrical components simultaneously (as the mechanical system is being designed and built) with the second iteration of the lunar excavator (tentatively named ARTEMIS Double Prime), control will first be perfected via tethered control of ARTEMIS Prime and then via some sort of un-tethered control. (The control system conceptual design has not yet been finalized; therefore, based upon its form, additional steps may be implemented.) Pending a semi-complete Double Prime, tethered control testing will begin on the actual competition device, followed by un-

tethered control in preparation for competition. Mechanical and electrical development will occur simultaneously with correlated deadlines, which will be managed by a group of seniors on the team who will also be involved with the realization of said deadlines. This device completion scheme will also enhance mechanical development and troubleshooting as design weaknesses will be manifested earlier in the development with an (at least partially) functioning control system.

In addition to the process of developing and testing the control system, the testing process for the mechanical components must undergo redesign. The (limited) testing ARTEMIS Prime underwent involved benign environmental and situational conditions; they were in fact less harsh and strenuous than those at the competition. These included operation in sand, which was less abrasive and likely to immobilize the tracks, operation with complete visibility of the system at all times, operation with the control station (transmitter) in very close proximity to the excavator (receiver), and operation under ideal communication conditions where other systems were not attempting connection over the same network. The excavator also operated for shorter amounts of time (continuously) than would occur at competition. The device did not experience any semblance of dress rehearsal.

Beyond simulation of competition conditions, effective testing of the second iteration of this excavation device—expected (though not required) to last longer than the competition—should involve some form of accelerated life testing (ALT). Two generic methods for ALT include [1] testing continuously for a longer period of time than is expected (required) for use (competition) and [2] testing under higher stress levels (including harsher conditions) than anticipated [3, p. VII-16]. The first

method is relatively self-explanatory. The second—as used in this application—would potentially involve testing on a playing surface of a more abrasive and sticky substance than the lunar regolith simulant (Black Point-1 for the 2011 competition) for accelerated drive train testing, lifting more than anticipated weight with the scoop mechanism, and packing excavation material (sand or other simulant material that is used) into the hopper to test the deposit subsystem's ability to remove it.

Additional suggestions based upon observation of the system concern weight. Many if the last-minute modifications made to the system were due to the system being over the weight competition specification. In researching high-weight components—including but not limited to motors and conveyor chain—the team will make weight a more highly-considered criterion.

The application of this study has potential to extend beyond the 2011 Lunabotics Mining Competition. One goal of developing this device is that its concept and/or design be used one day in actual lunar excavation. The higher the quality of the design and performance of the system at competition the more likely this becomes. The analyses themselves could potentially serve as a template for analysis and reliability prediction of future iterations of the device.

CHAPTER 5

CONCLUSIONS

The Failure Mode, Effects, and Criticality Analysis in conjunction with the Reliability Block Diagram system model of the ARTEMIS Prime Lunar Excavator has resulted in a set of suggested modifications / improvements for the second iteration of the device— ARTEMIS Double Prime—to be entered in the 2011 Lunabotics Mining Competition. Complete redesign will take place concerning the control / communication system as well as the drive train. The collection / storage hopper will undergo detailed redesign, while the general concept for it will likely persist. The scoop mechanism will be realized using more precise machining techniques. Conveyor chain selection will be more customized for the application and design specifications / constraints. Additionally, the device location (and collected volume determination) methods will be redesigned. The design and verification processes themselves for the control system will be executed differently and in better correlation with the mechanical component design and verification processes. The testing methods for Double Prime will be revised, incorporating accelerated life testing in one or both of the two general forms discussed. The design process of the ARTEMIS Double Prime Lunar Excavator will an iterative one, as the design will be monitored via analysis techniques similar to those implemented here in order to optimize reliability.

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APPENDIX C

FMECA RISK ASSESSMENT INDICES

Table 1: Lunabot Failure Probability of Occurrence Index

Rank	Description	Criteria
1-2	Remote Probability	Testing demonstrates satisfactory performance Safety factor > 2 Very few (or no) unknowns associated with component High confidence in designer/manufacturer
3-4	Low Probability	Testing demonstrates mainly satisfactory performance OR no testing has taken place Safety factor > 1.5 Few unknowns associated with component Moderate - high confidence in designer/manufacturer
5-6	Moderate Probability	Testing demonstrates mediocre performance OR no testing has taken place Safety factor low or unknown Several unknowns associated with component Moderate confidence in designer/manufacturer
7-8	High Probability	No testing has occurred* Safety factor low or unknown** Several unknowns associated with component Low confidence in designer/manufacturer
9-10	Very High Probability	No testing has occurred* Safety factor low or unknown** Several unknowns associated with component Very Low confidence in designer/manufacturer

*Presumably, if testing indicated poor performance, changes were automatically made
**Presumably, if safety factor is <1.5, changes were made automatically

Table 2: Lunabot Failure Effect Severity Index

Rank	Criteria*
1	No risk to observers; no damage to system; little or no drop in functional mission/sub-mission efficiency
2	No risk to observers; minor damage to system; minor drop in functional mission/sub-mission efficiency
3-4	No risk to observers; minor to moderate damage to system; moderate drop in functional mission/sub-mission efficiency
5-6	No risk to observers; moderate damage to system; significant drop in functional mission/sub-mission efficiency
7-8	No risk to observers; moderate damage to system; mission loss
9-10	Potential injury to observers; severe damage to system; mission loss

*Criteria based upon desire to avoid 1) damage to system, 2) drop in efficiency of travel, excavation, retention, or deposit (mission functions), and 3) mission loss

Table 3:Lunabot Probability of Failure Detection Index

Rank	Description	Factors*
1-2	Failure almost always detected prior to competition	Failure mechanism (and mode) visibly manifested Sufficient testing conducted to test failure mechanism
3-4	Failure frequently detected prior to competition	Failure mechanism (and mode) visibly manifested Insufficient testing conducted to test failure mechanism
5-6	Failure infrequently detected prior to competition	Failure mechanism (and mode) somewhat visibly manifested Sufficient testing conducted to test failure mechanism
7-8	Failure rarely detected prior to competition	Failure mechanism (and mode) somewhat visibly manifested Insufficient testing conducted to test failure mechanism
9-10	Failure virtually impossible to detect	Failure mechanism (and mode) invisibly manifested No testing conducted to test for failure

*Note in report that factors contributing to detection are visibility of failure mechanisms (and modes), sufficiency of testing conducted, and care taken by test observers; chose the lower value when observers are unlikely to be looking for failure (taking "care")

APPENDIX D

DETAIlED FMECA WORKSHEET DESCRIPTIONS

ARTEMIS Prime FMECA Worksheets:

The FMECA for the ARTEMIS Prime Lunar Excavator utilizes three worksheets: one each for the three main functional sub-systems—"Drive", "Dig", and "Deposit". The aforementioned Risk Assessment Indices generated for this study facilitated relatively straightforward ranking. However, some items still fell outside the ranking descriptions in the indices; others simply require additional explanation for clarity. The following describes the ranking decisions made in these cases. Refer to Appendix C for the FMECA Risk Assessment Indices.

"Drive" Function:

DR-1a.1:   Concerning the detection ranking, the failure mode mechanism was visible, while the mechanism was not; therefore, the item was ranked with an average of the values representing these two conditions.

DR-1b: *See DR-1a.1 description.*

DR-1c: The high severity ranking in this case is due to the fact that a device cannot

function if the proper code is not implemented / executed

DR-1d: The severity rank is indicative of a single occurrence. Should the operator make multiple mistakes, the severity would increase; however, as the probability rank indicates, this is unlikely.

DR-2c: In this case—concerning severity—there exists no risk to observers, and no system damage resulting from the failure. However, there does exist potential for a significant drop in efficiency. The severity ranking is reflective of this combination of factors.

DR-4a: This severity rating is reflective of a situation in which—resulting from this particular failure—there exists no risk to observers, minor-to-moderate damage to the system, and little or no drop in efficiency.

DR-5b: Concerning the probability of occurrence, this failure did occur in practice; however, the team cleaned the treads periodically—specifically prior to competition—in order to lower the probability of occurrence.

DR-5c: For this item, one should note that this failure was not manifested until the competition during another team's competition attempt. (This team's device employed the same track models; this is considered valid data for ARTEMIS Prime since the latter was unable to test this functionality due to failure to execute the drive function on the competition surface due to electrical / communication issues).

DR-7a: For this item, the detection ranking is reflective of a failure that is visible but only if it is specifically sought, as it would occur in the underside of the system.

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DR-8c: Regarding the severity ranking, if the system is able to perform maneuvers during the competition attempt and to continue with the attempt, this failure should only cause damage to the device and cost time.

DR-8d: *See DR-8c description.*

DR-8e: *See DR-8c description.*

"Dig" Function:

DI-1a.1:   *See DR-1a.1 description.*

DI-1b: *See DR-1a.1 description.*

DI-1c: *See DR-1c description.*

DI-1d: *See DR-1d description.*

DI-2a: The final probability rank is based both on testing and on the fact that the factor of safety is less than 1.5.

DI-3a: The severity rank is reflective of potential mission loss.

DI-3b: The severity rank is reflective of no risk to observers, little damage to the system, and moderate drop in efficiency as a result of the failure.

DI-3c: *See DI-3b description.*

DI-3d: *See DI-3b description.*

DI-3e: *See DI-3b description.*

DI-3f: The severity rank is reflective of no risk to observers, damage to the

system, and potential mission loss as a result of the failure.

DI-3g: The severity rank for this item differs from the others for which the potential effect of failure is also "failure to turn scoop to desired position"; in items DI-3a - e, there existed potential to drop efficiency more than in this item (DI-3g)

"Deposit" Function:

DE-1d: *See DR-1d description.*

DE-1e: The probability of occurrence increased from the initial risk assessment to the revised risk assessment because the number of unknowns increased.

DE-1f: *See DE-1e description.*

DE-2a: The "atypical load conditions" refer to loading conditions for which the system was not designed. The changes mentioned in the Actions Taken entry include chain modification (removal of middle sections of the chain), removal of some moving side guides, and additional taping to ensure complete seal of the chain. There existed issues with pulling the load at competition; however, it is not certain if these were due to the modified conveyor structure or due to problems with the motor control. This affected the detection ranking, as the cause (mechanism) is difficult to identify.

DE-3: The cause and effect relationship here could be considered a "snowball effect". Increased wear would increase likelihood (and rate of occurrence) of teeth jumping, which would increase wear, etc, eventually ceasing operation of the conveyor. The revised value for probability should actually be increased. Once the belt tensioning

mechanism was improved, performance was also much improved; however, just before competition the belt was jumping teeth.

DE-4:   This probability rating reflects the fact that though this will certainly occur, the rate has been significantly decreased by preventative controls. The severity ranking for this item reflects the fact that it can happen quickly.

DE-5a: This probability rating reflects the fact that though this will certainly occur, the rate has been significantly decreased by preventative controls.

DE-5b: Modifications to chain may have given rise to atypical load conditions.

DE-5c: *See DE-5b description.*

DE-6:   *See DE-5a description.*

DE-7a: This probability rating reflects the probability of this occurring *during* competition.

DE-9c: This probability rating reflects the fact that though this will certainly occur, the rate has been significantly decreased by preventative controls. The detection ranking reflects that, while this failure would be easy to detect, the operators might not be looking for it.

DE-10a: Probability ratings reflect the unknowns associated with these components prior to testing (initial values) and then increased confidence after testing (revised values). The severity ranking indicates that this would unlikely disqualify the device as it would have been measured / weighed before this.

DE-10b: Probability ratings reflect the unknowns associated with these components

prior to testing (initial values) and then increased confidence after testing (revised values).

DE-10c: *See DE-10b description.*

DE-10d: *See DE-10b description.*

The reader should note that early application in the design cycle results in higher benefit than application after the design is finalized. [4, p. 198] However, while this system was analyzed late in the design / construction process, this analysis still provides tremendous benefit in the form of identification of points of improvement for the next iteration of the device which is very early in its design phase and will be similar to ARTEMIS Prime.

DETAILED RBD BLOCK AND SUB-MODEL DESCRIPTIONS

ARTEMIS Prime RBD Model:

The system RBD for the ARTEMIS Prime Lunar Excavator consists of four main sub-models: three main functions—"Drive", "Dig", and "Deposit"—as well as the control system. The three functions will be discussed first, beginning with the "Drive" Function.

"Drive" Function:

Tracks: The first block (in series) represents the tracks. These are modeled by connecting their component blocks in series and estimating their reliabilities based upon design specifications versus the device's required performance. Since the tracks used in this system were designed to carry a heavier load than they would encounter in this application, their components were given high reliability ratings. Since the ability of the track motors to provide enough torque to carry the system at its heaviest on regolith simulant was (and is still) unknown, the motors have been given a slightly lower reliability rating. An environmental factor block has also been introduced (into the tread-sprocket interface block) in order to account for observation of similar systems at the Lunabotics Competition. (A team with the same track system as the one described here experienced trouble in the form of regolith simulant building up in between the sprocket

teeth and causing the tracks to jump teeth rather than function properly.)

Obstacle Handling: The next set of blocks represents obstacle handing. These are modeled in standby redundancy, with the preferred (active) method of obstacle handling considered to be navigation around said obstacle(s) and the alternative (standby) method, the removal of the obstacles. The first of these blocks—the active block—represents an action—the ability to navigate around an obstacle. This is the first specific encounter with a human reliability factor. The device—in this case the tracks—may operate flawlessly, but if the operator is unable to execute the function—in this case navigate around obstacles—then the device is not successful. Since the device has never been tested (navigating around obstacles) on the lunar regolith simulant surface, this reliability value was estimated based simply upon experience testing the device on sand and observing navigational difficulties and successes. The standby block also represents an action—the ability to move obstacles. In the case that navigation around obstacles is deemed impossible or impractical, said obstacle must be removed in order to allow passage. This component was modeled using the reliability determined for the scoop subsystem (which will be described under the Dig section) multiplied by a factor to account for potential additional stress on the system and for human reliability.

Device Location: The next set of blocks was also modeled as standby redundancy with perfect switching and unequal component failure rates. It represents the indication to the operator that the device has reached the collection bin. The active block represents the device's indication and the standby block represents the operator's interpretation of this. The reliability of the active block is determined by a series sub-model including prediction of the successful operation of the components of this function—rocker

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sensor, bumper (to which the sensor is attached), and LED markers (which light when the sensor is tripped). Successful operation of the sensor and bumper is likely; however, it is less likely that the LED markers will be visible to the operator when they are lit. The standby block again represents human reliability—in this case the ability to discern from the overhead cameras the position of the device in relationship to the collection bin. This was estimated based upon experience and observed visibility via overhead cameras.

Supports: The next (and final) block (in series) in the Drive subsystem model represents the supports ensuring a rigid drive train. These supports were designed to have a safety factor of greater than 1; it was actually much greater than 1. Therefore, the reliability if this block is 1.

"Dig" Function:

Scoop Subsystem:

The first block in the "Dig" function represents the scoop subsystem, which is the main physical subsystem of this function. **Linear Actuator:** The first block in the scoop sub-system model represents the linear actuator. This component was derated in order to enhance its reliability. A component or subsystem can be derated by: [1] using an item in such a way that the applied stresses are below rated values or, [2] by lowering the rating of an item in one stress field in order to allow an increase in rating in another stress field [3, p. V-77]. The linear actuator used in the digging function is rated at 1500 lbs for 1 million inches of travel (approximately 700 hours of operation); by the first definition above, the device was operated a maximum of 1100 lbs for less than 10 hours.

The reliability test data obtained for this component from the manufacturer was used to predict its reliability (at the device maximum load rating of 1500 lbs). This component was modeled by the 2-Parameter Weibull distribution. The following represents the Weibull distribution as used to predict reliability [4, p. 41].

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$ (Eq. 7)

where t refers to the total operation time (in hours), η refers to mean time to failure (MTTF)—life expectancy—and β refers to a scaling factor. In this case a β value corresponding to infant mortality ($\beta < 1$)—for "burn-in" period, decreasing failure rate [4, p. III-62], in this case $\beta = 0.8$—was chosen since the linear actuator was expected to be in operation for a very short period of time compared to its life expectancy and would therefore fail due to defects rather than wear-out. The value for η was determined based on the total expected travel (1 million inches) of the linear actuator and its top speed (0.4 in/s). The total operation time (which was used for reliability prediction of all components / functions) was estimated to be 10 hours.

Linkages: The next block in the scoop sub-system model represents the linkage system used to lift and turn the scoop. This was modeled by a series model of the linkage components / events—linear actuator link component, arms, connector pins, and the bushing presence event. Each of these components (bushing included) was designed / purchased to have a safety factor greater than 1 (much greater than one in the case of the pins and bushings). In order to verify safety factors, simple stress calculations were performed on items with simple geometries. However, the geometry of some of the components—in particular the linear actuator link component and the scoop

lifting arms—was sufficiently complicated to require FEA modeling of stresses using SolidWorks Simulation. However, stress overload isn't the only mechanism by which the bushings can fail. They can also fail by shifting from their set position (even though measures have been taken to ensure that this doesn't happen). Similar to the obstacle handling and obstacle location models described in the "Drive" function, the bushings are not strictly necessary for operation of the system. However, their proper function contributes incredibly to the *successful* operation of the system. To clarify, the scoop will very likely still lift and turn should the bushings be removed; however, the scoop will likely not lift and/or turn to the necessary position without the bushings. (This function has not yet been tested.) The bushing presence event has been modeled as a standby redundancy scenario; however, it should be noted that introducing a standby redundancy event situation changed the reliability very little from the series model due to the small likelihoods that the bushings will fail and that the scoop would function properly in the event that the bushings did fail (were lost).

Scoop: The final block in the scoop sub-system model represents the scoop itself, which is modeled by another series of components / events—teeth, shell, connector pins, and another bushing presence event very similar to the one described for the linkages. The teeth, shell, pins, and bushings themselves are considered infallible due to their high safety factors (much greater than 1). The only modification made (from the linkage bushing presence event model) for the scoop bushing presence event model is the reliability prediction (slightly higher) for the scoop in the event that the bushings are lost.

Collected Volume Determination: Rising a level—back to the "Dig" function model, the next block represents the "full" indication of the hopper—a signal to stop

collecting lunar regolith simulant. This block represents a sub-level model incorporating two indication methods in active redundancy—[1] observing consistency in collection trials and using this observation to predict the number of scoopfuls that constitutes a full hopper and [2] operator observation via onboard camera. However, the "full" indication itself is not strictly necessary. The system can still operate and successfully collect lunar regolith simulant even with a smaller volume of simulant is collected. Therefore, the "full" indication itself (the preferred, or active, option) is modeled in standby redundancy with an event stating that less than the desired amount of simulant is collected.

Hopper and Supports: The next block in the "Dig" function represents the hopper; the hopper was tested, modified according to its behavior and consequent necessary improvements, and then retested to confirm its conformity to design requirements. Though it is not perfectly reliable since it has the potential to leak regolith simulant, its reliability prediction value is very high. The next block represents the supports for the hopper and scoop subsystem. As mentioned in the "Drive" function section, all supports were designed to have a safety factor much greater than 1; therefore the reliability of the supports is considered to be 1.

"Deposit" Function:

Conveyor: The first block represents the conveyor and its various components. The conveyor itself was manufactured by an external source whose design was not intended to convey small abrasive particles—including sand and lunar regolith simulant; for this reason, wear became a failure mode worth considering. The design team considered

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options such as replacing key components prior to competition in order to ensure proper function. However, initial tests of the conveyor moving sand quickly revealed that wear was not the immediate issue but sand (or regolith simulant) lodging in the many joints of the conveyor, increasing the torque necessary to turn the conveyor. In order to treat this issue the design team—after considering several options—decided to line the conveyor chain—including its moving side guides—with duct tape to create a seal. Now, the main concern was ensuring that the tape remained sufficiently adhesive; a plan was developed to replace the tape prior to the competition.

However, as constructed reached completion (and competition drew nigh), the overall system was discovered to be exceeding the weight limitations set by the competition rules. Each option for weight reduction was considered according a cost-benefit philosophy in terms of potential weight reduction versus functional penalty. Several items were altered or sacrificed. For example, competition strategy was modified to accommodate the removal of one onboard camera; sections of material were removed from components such that neither structural integrity nor regolith containment was sacrificed. The team estimated the potential weight loss from removing sections of the conveyor chain such that chain could overall maintain its shape and its functionality, finding it to be the greatest contributor to the weight loss goal; therefore, the chain was modified and then duct tape used not only to seal the chain but now to cover its bare chain. Figures 8 and 9 represent the original chain and the modified chain, respectively, each without duct tape applied.

The team was unable to test this modification prior to departure for the competition. During competition practice days, the device faced and overcame several issues;
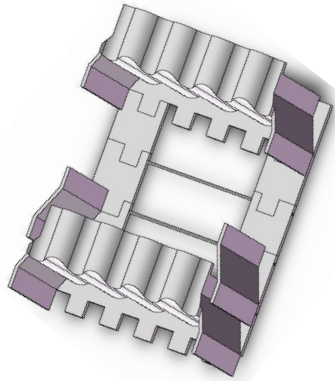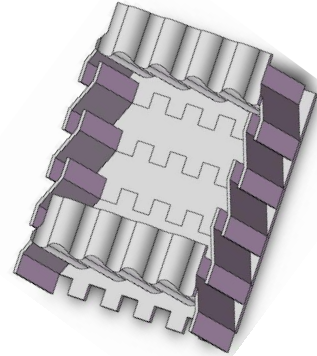
Figure 8 (Left): Unmodified chain section

Figure 9 (Right): Modified chain

however, conveyor malfunction was not one of the resolved issues. Post-competition the device has been under repair and investigation, and current evidence suggests that the conveyor malfunction was not a product of the chain modifications or malfunction of the conveyor motor. Bearing all of this in mind, the reliability of the conveyor and its associated components was considered to be relatively high, with a lower score for the chain itself since a reduction in rigidity may have contributed to the malfunction mentioned previously.

Another functional issue concerning the conveyor was the tensioning of the timing belt that transferred torque from the conveyor motor to the conveyor's drive shaft. Due to a poor tensioning method, the belt sometimes did not grip motor pulley properly—particularly when experiencing high torque. However, once an improved tensioning system was implemented, the problem was almost completely mitigated. This is reflected in the reliability rating for the "Timing Belt / Pulleys" block.

Emptied Volume Determination: The next set of blocks in the "Deposit" function model represents the indication that the regolith simulant collection / retention hopper has been emptied completely (or nearly so) by the conveyor. This is modeled virtually

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identically to the "full" indication model described in the "Dig" function section—through active redundancy where the operator attempts to establish consistency in the time taken to deposit a load of regolith while also monitoring the onboard and overhead cameras. Unfortunately, the onboard cameras did not function at competition (and were likely the cause of the malfunction that ultimately kept the device from operating at competition, which will be described later); therefore, their reliability rating is very low. Since the "empty" indication itself is not strictly necessary, it is modeled in standby redundancy with the event that the hopper is only partially emptied (standby case), which is a highly probable event, assuming proper function of the conveyor.

Hopper and Supports: The next block represents the hopper in terms of its role in the "Deposit" function. For this function, the hopper must be able to connect to the conveyor so that its contents (lunar regolith simulant) are transferred from the former to the latter while preventing simulant from leaking into the conveyor. Connecting the two components was relatively simple; however, sustaining no regolith loss to the inside of the conveyor was more difficult to achieve. The final device included a combination of a rubber flap and a foam insert (Figure 10) to seal the inside of the conveyor from the

Figure 10: Rubber flap and foam insert conveyor-to-hopper sealing mechanism. (Red ellipse indicates location where foam is inserted.)

simulant. The flap and insert had to be reset periodically; however, this solution was overall effective. The reliability rating for the hopper in this section reflects this.

The final block in the "Deposit" function model represents the supports. Again, these were designed to have a safety factor of much greater than 1; therefore, for the purpose of this analysis, they are considered infallible (reliability of 1).

Control System:

The fourth and final sub-model of ARTEMIS Prime is the control system. **HMI (Laptop):** The first block in this sub-model represents the human-machine interface (HMI) used in this system—the laptop interface. The interface was designed to execute commands upon registering a mouse click event for a specific button. This method was highly unreliable in the beginning stages of testing—being unable to register and/or relay commands most of the time; however, by the time of the competition, its reliability had improved—the command was registered / relayed nearly 100% of the time. The HMI's reliability reflects this.

WiFi Communication: The next block in the control system model represents the reliability of the communication was system's (WiFi) communication system. During testing at WKU prior to leaving for the competition, communication was fairly reliable. However, at the competition site, communication with the device was nearly impossible to achieve accept when operating under the practice and competition networks (which were reserved for the teams actually operating on the playing surface at that time); this difficulty was likely due to the number (20+) of teams attempting communication with

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their devices at the same time. There was not sufficient time on the playing surface to completely diagnose the issues the device (and operator) experienced with communication; therefore one can only speculate as to the contribution of the WiFi communication system to this. The reliability rating for this component of the control system reflects an educated estimate based upon experience and observation.

Electrical Control:

The next block represents the electrical control system, which is composed of several components in series. **Track Motor Controller[1]:** The first block—the RS80D Motor Controller—was intended to be modeled using test data from the manufacturer; unfortunately, several contacts to the manufacturer yielded no access to test data. However, research of the controller manual resulted in some insight in to the controller's expected operation. The manual states that "no warrantee of suitability or performance for any purpose [is provided] for the controller"; it also states that in some cases where the motor fails it becomes "lock[ed] in the "ON" position with no ability to stop the motor that is being controlled" [6, p. 9]. This typically occurred when the controller was left idle for 30 seconds or more. In order to eliminate device failures, the electrical design team devised a method for ensuring that the controller was constantly being sent a command of some kind (the "STOP" command when locomotion was not required). The reliability rating for this motor controller reflects the controller's reliability including our adjustments to prevent failure.

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[1] Each of the motor controllers was derated—chosen to have a higher current rating than would be reached—in order to enhance their reliability.

Scoop Motor Controller[2]: The next block represents the 2x25 Sabertooth Motor Controller used to control the linear actuator. Like the RS80D Motor Controller, the Sabertooth was intended to be modeled according to test and/or reliability data obtained from the manufacturer. The manufacturer responded to the initial request for data by requesting more information about the controller's use in this system and promised information; however the information was never received, even after several reminder e-mails. Attempts are still being made at attaining the information. In the meantime this component's reliability is based upon performance at the competition (during practice), which was successful.

Conveyor Motor Controller: The next block represents the 2x25 Sabertooth Motor Controller used to control the conveyor motor. This is the same model used to control the linear actuator for the "Dig" function. (Two separate controllers were used—one for the linear actuator and one for the conveyor motor). Pending information from the controller's manufacturer, this component's reliability is based upon performance at the competition (during practice). The conveyor motor was not controlled successfully; however, this was likely due to an issue with the controller board and not the motor controller. However, a small amount of smoke was observed issuing from this controller at one point.

Controller Board: The final block represents the controller board used for this system. It was designed and built custom for this application by Custom Design Solutions. The board was built to the electrical design team's specifications; however—as initial post-

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[2] The reliability of the Sabertooth controllers as used in this application was initially enhanced due to familiarity of the electrical engineering sub-team with this motor controller.

competition investigations suggest—at the competition when the cameras were connected to the device, they drew more current than the board was designed to accommodate, causing certain connections on the board to fail. Even though the board performed to specification, those specifications were not in line with the actual needs of the system. The reliability rating of this device reflects this discrepancy.

Power Supply and Electrical Connections: Rising a level to the control system model, the next block represents the power supply (battery). When functioning properly, the battery provided more than enough power for the system to operate during the competition; furthermore, it can be charged to ensure optimum operation. However, the week before the competition, one of the two batteries failed due to a dead cell; the spare was used for the competition. Consequently, confidence in the battery's reliability dropped significantly. The final block in this model represents the electrical connections within the system. The reliability of these components is difficult to evaluate. The team experienced very little trouble that could be specifically and directly attributed to faulty electrical connections; however, there were instances when unexplained occurrences could have been the result of such. The associated reliability rating reflects this.