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Identifying and Documenting Expert Knowledge, A Practical Study of Design Patterns

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Abstract. Globalization, powered by digitization, is increasing technology growth and knowledge transfer rates to levels not seen in the previous 3500 years, obscuring absolute truth and accelerating rates of innovation and production. Competing, or remaining competitive, in this global marketplace requires a learning organization adopt a method of capture, retention, and reuse for demonstrated tacit knowledge to accelerate the development of increasingly complex systems of high quality at a reasonable cost. The architectural theory of Patterns and Pattern Language is a validated methodology for mining tacit domain knowledge from a proven system. This work applies architectural theory to a multi-year development experiment and captures exposed knowledge as a design pattern in a model based systems engineering tool, demonstrating applicability of digital engineering initiatives in the description and reuse of expert design knowledge. By creating and archiving model based expressions of expert knowledge, a learning organization can improve practical decision making and avoid uninformed concept phase decision making.

Keywords. Patterns, Pattern Mining, Pattern Language, Energy Storage, Thermal Runaway, Systems Engineering

Introduction

Recent trends in globalization has led to accelerated technology growth and knowledge transfer rates at levels not seen in the previous 3500 years, accelerating innovation and production rates [1] and creating an increasingly competitive marketplace. However, technology development projects often suffer from rework [2], delaying product release and requiring an additional 30 to 65 percent design time [3]. Decisions made during the concept phase are the most costly causes of rework [4] and are unrecoverable with more than 95 percent confidence [5], reinforcing the need for accurate and effective conceptual design decisions. Research in framework development enabling knowledge reuse to improve concept phase design decision making has been proposed as a means of reducing this costly cause of rework [2]. This effort demonstrates such a framework by applying architectural theory to extract tacit knowledge from a proven design for retention and reuse during the concept development phase of the project lifecycle.

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In the project lifecycle, the concept phase is where stakeholder needs, goals, and objectives are translated into design requirements [6]. Performed recursively, the concept development process logically decomposes stakeholder expectation into functional requirements, operational behaviors, and data/time flows for assessing tentative design approaches based on engineering analysis and trade study [6]. A logical expression describes the "what" interrogative of a system [6] [7]. Educating a systems engineer to perform the task of translating need to design has proven challenging [8] leaving organizations to foster mentorship and experiential training opportunity to grow the necessary experience [9]. This work demonstrates a methodology that accelerates knowledge acquisition from a proven system in the form of a design pattern.

A technology development activity that reduced the catastrophic failure propagation risk in three multi-cell lithium ion batteries provides the basis of study. Beginning with a design having nearly a decade of successful human spaceflight experience [10], the experiment used a design-build-test approach to incrementally develop knowledge of battery and electrochemical cell failure, mechanisms of energy transport during failure, and construction methods and materials that interrupt and manage failure energy without disrupting nominal energy storage, power delivery, volume, and mass constraints. By sequentially developing three batteries, prior solutions were reused, modified, or replaced based on observation and volumetric, mass, or external heat transfer challenges presented with each new design. Although energy density and external thermal transport restrictions increased with each new design, device performance and development time and cost improved with each iteration. Each of the three batteries of this activity are deployed in low earth orbit, and provide a basis for knowledge capture.

This paper is organzied into the following sections. Section 1 and 2 introduce architectural theory and the experimental subject, respectively. Section 3 details the pattern mining methodology, and Section 4 illustrates the mined knowledge as model fragments in a digitial engineering application. Section 5 concludes the work with a discussion on the reusability of exposed knowledge in guiding future development efforts.

1. Architectural Theory

Enterprise Architecture provides an ontology for a discussion of architecture [7] [11] by providing a schema for describing a system or enterprise according to differing perspectives [12]. The architectural perspective is concerned with aesthetics including the abstract notions of proportion, function, and behavior [13]. Architecture provides the means of translating need into system design based on the creativity and experience of the performing architect [6]. Operating at the intersection of art and science [9] [14], the experienced engineer transcends process to conceive a system that works, is robust, efficient, and minimizes unintended consequences [8]. If concept phase reasoning and accuracy is to be improved, the cognitive load of the performing engineer must be reduced by access to expert knowledge that transcends personal experience.

The architectural theory of Patterns and Pattern Language offer such a methodology [15]. A pattern is a heuristic, or mental shortcut, responsible for human cognition [16], learning [17] [18], and problem solving [19]. Alexander [20] applied the concept of patterns to describe the aesthetic qualities in observed human dwellings

[21]. Alexander defined a Pattern as a three-part rule for expressing a relation between a specific context, a problem, and a solution, and a Pattern Language as a network of related patterns [22]. A pattern describes relationships resolved within an operational system and therefore contains implicit knowledge known by the solution provider [22]. The architectural theory of Patterns provides a means of exposing this knowledge.

2. Experimental System

The three devices of this system use commercial lithium ion technology to convert electrical to chemical energy for storage and use during Extravehicular Activity as a part of NASA's human spaceflight program. Designed to accommodate different energy, mass, and volume constraints, the three batteries of this study use novel packaging methods and construction materials to prevent a single cell catastrophic failure from propagating throughout the multicell battery or releasing spark and flame from the battery housing without the aid of an external system. Referred to as thermal runaway, cell failure occurs when an internal short circuit results in rapid heat accumulation due to uncontrolled discharge of stored energy resulting in the thermolytic decomposition of organic cell construction materials and the generation of cell body heat and combustion products, or ejecta, in the internal envrionment of the battery [23] [24] [25]. Unmitigated, the transfer of energy between failed and exemplar cells or an external system can lead to failure propagation and increased risk of system, user, and envrionmental damage [26]. The batteries developed by this experiment are deployed in low earth orbit.

Based on a heritage design approach [10], each battery uses a structural capture plate to secure the terminal ends of the cylindrical electrochemcial cell, forming a rigid module with a known cell separation distance. Current collection elements connect secured cells in parallel and provide connection points for serialization by an electrical harness. A metallic shroud secures the module and harness and provides external system interfaces, structural support for the module during transport, handling, and use, and ventilation features to enable pressure exchange with the surrounding environment. Preventing propagation required managing heat flux between cells and interrupting current inrush from parallel connected cells. A combination of insulating and conducting materials in the interstitial module volume allows modulated transfer of cell heat to the thermal mass of the cell module. A fusible parallel bus element separates failed cell from the bus network, preserving basic battery functionality for the remainder of the mission. Orienting the intrinsic cell vent and using structure features to direct the flow of ejected materials within the battery volume reduces flow stream temperature and mass before exposure to the thermally conductive wire mesh filter element of the housing vent.

3. Pattern Mining Methodology

The three step pattern mining process begins with a list of pattern candidates, progresses through candidate refinement, and ends with a holistic description of the observed design. Using the method of Leitner [27], an initial list of pattern candidates is generated using intrinsic design knowledge. Each candidate is assigned a hierarchial category based on the architecture, design, and solution perspectives of the Enterprise

Architecture ontology [7] [12]. Graphically arranging the candidates according to the hieracrchy related candidates are connected using straight and non-directional lines to create a network diagram. Candidates are refined by arranging and redefining solution and design candidates to prevent crossing relationship lines and connections between candidates at the same hierarchial level. During this phase, the practitioner will begin to identify logical aspects of the design by redefining design candidates using higher abstraction level descriptions. Refining architectural candidates requires inspecting highly related design candidates and expressing the functionality achieved by these candidates using action words. Completing this final stage leaves the pattern mining practitioner with a conceptual abstraction of the design as shown in Figure 1 [28].

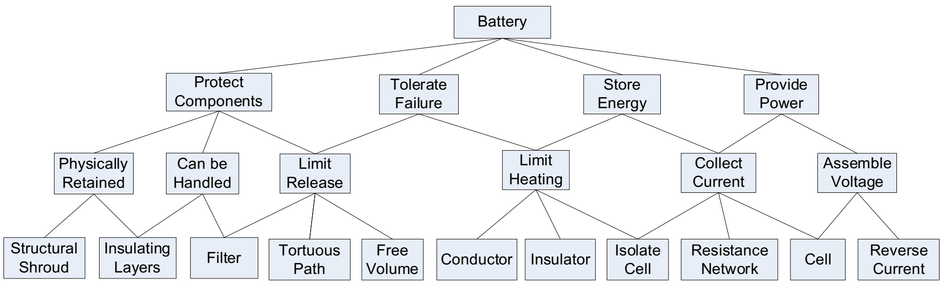

Figure 1. Design Pattern for the Experimental System.

Figure 1 is a logical description of the battery that expresses tacit knowledge in the form of the relationships between solution, design, and architecture. The development experiment incorporated failure tolerance into the heritage design, resulting in new functionality, design, and solutions. For example, the battery tolerates thermal runaway by limiting the transfer of heat and materials resulting from cell failure. A combination of insulating, conducting, and electrical cell isolation limit heat transfer, while free volume, tortuous flow path, and filter limits the release of materials from the battery. Incorporating the new functionality required modifying heritage designs, handling and current collection, to incorporate filter and cell electrical isolation solutions.

4. Expressing Mined Knowledge

Transferring the pattern to a systems engineering tool enables relationship quantification and archival and reuse of mined knowledge. Modeled using SysML [29], the internal block diagram (IBD) of Figure 2 provides a logical view of how physical properties interrelate to perform the tolerate failure functionality of Figure 1. For example, the relationship between tolerate failure and limit heating and limit release of Figure 1 are logicial expressions of the current and heat, and ejecta and flow linkages in the physical expression of Figure 2, respectively.

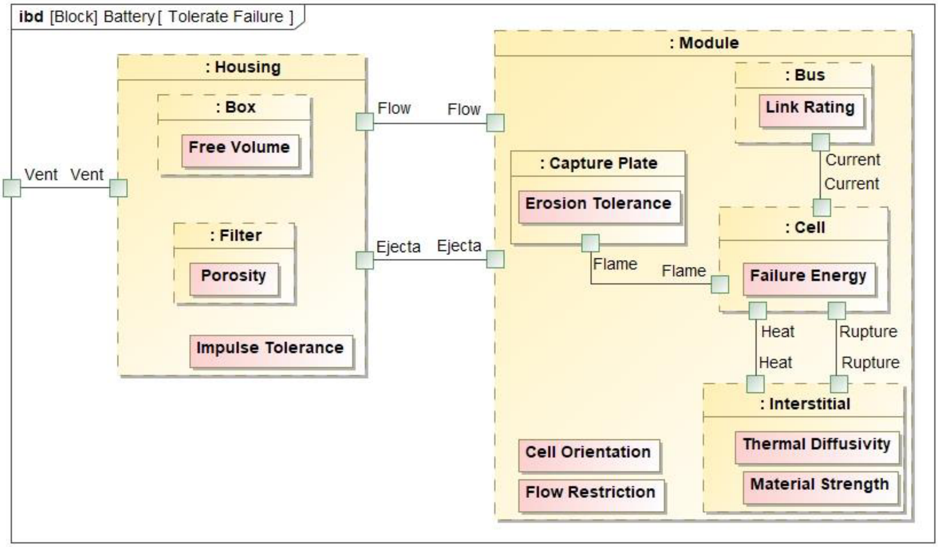

Figure 2. Enabling Tolerate Failure Functionality.

4.1. Failure Tolerant Design

The tolerate failure function of Figure 1 is performed by limit release and limit heating designs as shown in the block defintion diagram (BDD) of Figure 3. The behavior of limit release and limit heating designs are shown in the activity diagram of Figure 4.

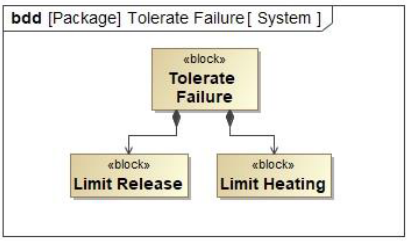

Figure 3. Tolerate Failure BDD.

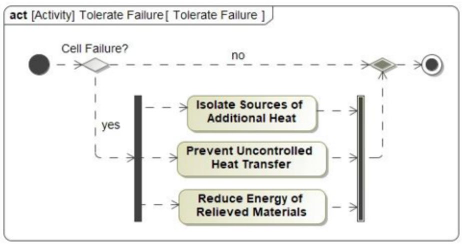

Figure 4. Tolerate Failure Activity Diagram.

Figure 4 shows that the design responds to cell failure by the parallel and concurrent activities of isolating additional heat sources, preventing uncontrolled heat transfer between cells, and reducing the energy of relieved materials before release to the external system. The parametric diagram of Figure 5 defines the relationship between the interacting designs and serves as an energy balance for the system during cell failure.

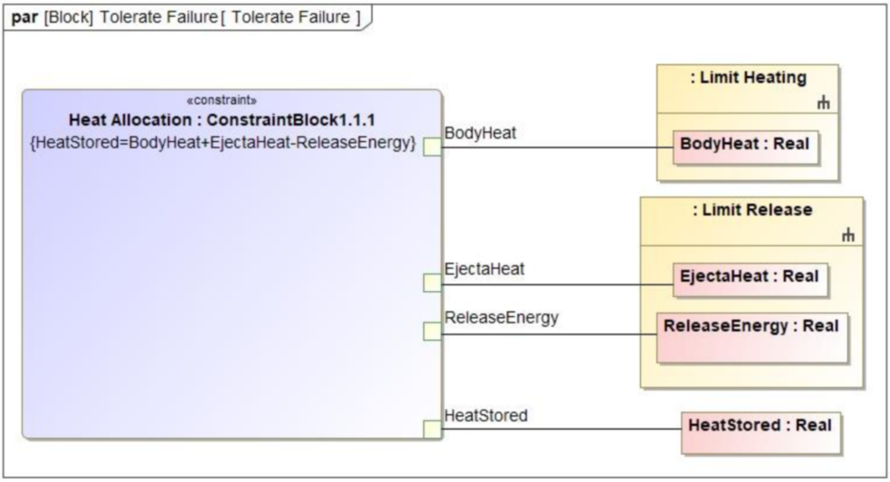

Figure 5. Tolerate Failure Parametric Diagram.

Figure 5 illustrates the relationship between limit heating and limit release design as heat stored in response to cell failure. Heat stored is a value property of the tolerate failure design and is a useful measure for assessing boundary effects such as the temperature of surfaces exposed to the external system. The rake icon indicates that each design has an internal structure explored in the following sections.

4.2. Limit Heating Design

The BDD of Figure 6 shows the structure of limit heating design. Composed of failure energy, thermal management, and electrical heating, the behavior of the design is shown in the activity diagram of Figure 7. Failure energy addresses temperature and erosion tolerance of construction materials and is not shown. Thermal management is accomplished by insulating and conducting behaviors that enable heat dispersion across cells in the battery module. Electrical heating is performed by a resistive element that fails under high discharge conditions, reducing input into the failure and parallel cell ohmic heating.

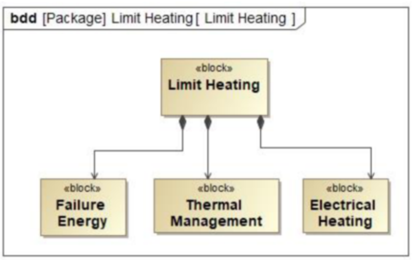

Figure 6. Limit Heating BDD.

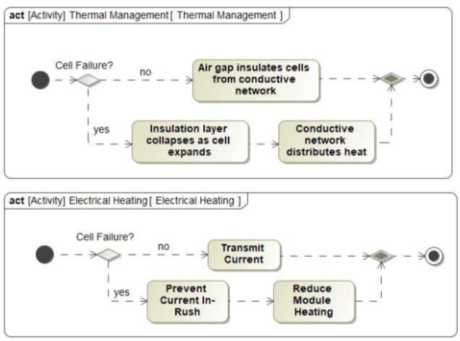

Figure 7. Limit Heating Design Activities.

Figure 7 illustrates the role Figure 1 solutions serve in limit heating design. For example, thermal management combines insulating and conducting materials to transport heat from a failed cell while slowing the rate of heat transfer to exemplar cells. The design elliminates two sources of heat input by preventing the influx of electrical energy into the failure event and reducing parallel cell discharge heating.

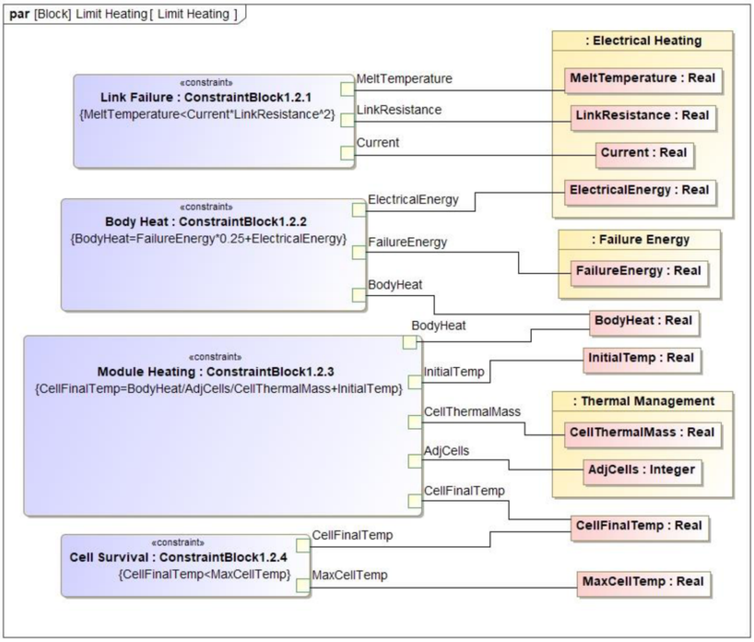

Figure 8. Limit Heating Parametric Diagram.

The parametric diagram of Figure 8 quantifies relationships operating in limit heating design. Value properties are typed as real except for the adjacent cell interger. An experimentally derived ratio of body to ejecta heat distribution is included and time dependent properties are neglected as the failure event is shortlived [30]. The link failure constraint represents electrical heating of the fusible element. Body heat is the failure energy remaining in the failed cell which is then weighed against initial module temperature and the thermal capacity of connected cells in the module heating constraint. Cell survival compares predicted cell temperature to an experimentally determined survivability limit. Table 1 compares the effect of adjacent cell quantity on final cell temperature for a failure energy input of 43500 J and cell thermal mass of 45 J/°C [24].

Table 1. Instance Table for Limit Heating assuming 25% of total heat is distributed equally to adjacent cells

Instance	Adjacent Cell Quantity	Initial Cell Temperature (°C)	Final Cell Temperature (°C)
1	1	25	265
2	2	25	145
3	3	25	105
4	6	25	65
5	3	35	115
6	3	15	95
7	70	25	28

The cell quantity values of Table 1 reflect cell position in a multi-cell battery. For example, a completely surrounded cell has six neighboring cells, a corner cell has no more than three, and cells arranged in a single layer will have no more than two. The table shows the expected relationship between thermal mass and temperature reduction. The instance table also shows that batteries with cell quantities of less than 3 require near ideal insulating materials or active cooling to prevent neighboring cell temperatures from exceeding ~120°C [23] at operational temperatures of approximately 35°C.

4.3. Limit Release Design

The limit release design BDD, activity diagram, and parametric diagrams are shown in Figure 9, Figure 10, and Figure 11, respectively. The figures show limit release consists of failure energy, filter, tortuous path, and free volume and the behavior during failure is a parallel and concurrent process of ejecta expansion into unoccupied regions of the battery enclosure, material flow through these regions, and flame quench and large particulate capture. The design solutions relationships include flow resistance, ejecta heat, and vented energy.

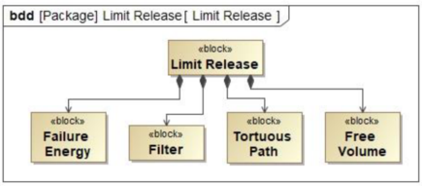

Figure 9. Limit Release BDD.

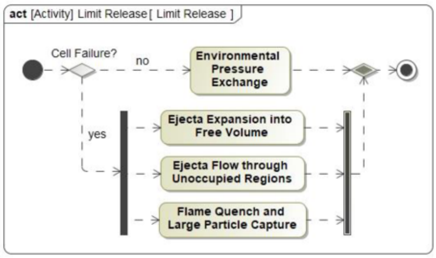

Figure 10. Limit Release Activity Diagram.

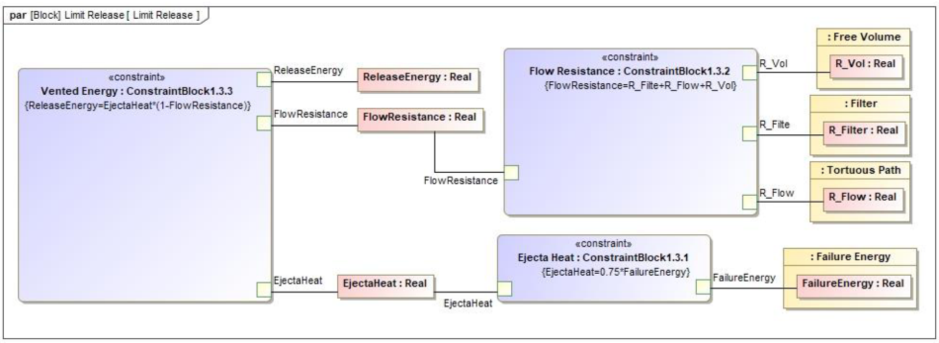

Figure 11. Limit Release Parametric Diagram.

The relationships between design measures such as filter resistance, free volume, and flow path are used to reduce ejecta energy and mass before release to the external system. The vented energy constraint shows that ejecta energy is released directly to the environment in the absence of flow restriction as is the case in an unhoused cell. Flow resistance includes internal volume for gas expansion, restrictions such as direction changes or baffles, and the filter element. Energy not released to the external system is stored in the battery as shown in the introductory energy balance of Figure 5.

5. Conclusion

The key to using patterns is to recognize that patterns are not completed designs. Instead, they represent the most common or most useful aspects of a design or operation and must then be adapted and refined for specific applications. This work introduces patterns and describes the application of architectural theory to the results of a sequential development activity using a network diagram and SysML activity, internal block, block definition, and parametric diagrams. The resulting logical description expressed expert knowledge in the form of relationships balanced by the design in an archivable, sharable, and reusable means, providing a basis for practical decision making. Future work will explore architectural expressions for relation to other patterns in a Reference Architecture [11]. Well-curated patterns represent reusable domain knowledge within the organization and should be readily available to the systems and design engineers as part of the digital engineering environment. The patterns should include documentation that recommends usage and how they can and should be adapted and refined. Patterns are not cast in stone. Starting a design with a proven approach always takes less time than starting from scratch, and when used during the concept development phase, will reduce costly rework in a development project.

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