Pattern Identification- A Foundation for Research in the Emphasis of Design Patterns in Systems Engineering and Knowledge Capture

Abstract

Pattern Language describes the morphology and functionality of a system in the absence of design particulars. Harnessing this capability will provide the Systems Engineering discipline a means of managing the development of increasingly complex systems with increasingly distributed design teams while capturing and retaining knowledge for future generations. Pattern Language is a syntax for describing, and structurally relating, design patterns. Design patterns contextually describe the application of domain knowledge in the engineered solution to the force balance problem. The parallels between pattern recognition and application, as a fundamental stage of human learning, and pattern observation within a complex system, suggests pattern language may be a valuable tool in the capture and dissemination of knowledge. Pattern application has enjoyed considerable study over the last several decades, however much of this work has focused on the replication of design particulars. This work returns to the roots of Pattern Language and explores the utility of patterns as an architectural description and guide, and knowledge capture method, for complex system development beginning with the identification of a time proven design pattern.

1. Introduction

The discipline of Systems Engineering lacks a formative method for developing and documenting an actionable, conceptual system architecture. Although significant development in methods and models for analyzing and characterizing engineered systems has occurred, the domain continues to rely on experienced practitioners for the development of architectural constructs in a burgeoning system. Lacking an actionable architecture documentation method, the Systems Engineering community has relied on specification documents to manage the design process, which has created legions of 'book managers' with little to no knowledge of the overarching system architecture, and increasingly costly system development activities when large or distributed design teams are used (1) (2). This work establishes the foundation for a study of the emphasis of Pattern Language in system design as a method for forming, documenting, and communicating the abstracted system architecture concept, guiding the engineering design process, and capturing knowledge from heuristic system architecture processes.

Grounded in structuralist theory, Systems Engineering relies on the use of specification documents to constrain and guide system element design, especially in large or distributed project team environments. Specification documents result from a structural decomposition of the system into system elements (subsystems) and interfaces through which elements interact. (3) Design teams engineer solutions that abide by the interface and element specification documentation, and Systems Thinkers use dynamic processes to infer and analyze relationships between the elements (4). Systems engineering acknowledges the importance of structure and relationships in system architecture, yet offers little guidance for the heuristic abstraction of a system architecture.

Pattern Language describes system architecture, and structure, based on relationships operating within and without the system. Relationships describe a state of connectedness in terms of opposing forces that require balance by the system. (5) By identifying interacting forces, and the abstraction level where the force resolution occurs, the architect documents an actionable architectural concept of the system. The design team develops engineering solutions that balance the interacting forces, identifying new forces created by the solution for potential resolution by the system. In this manner, the design team maintains an abstracted view of the architectural concept, and is able to assess the impact of the chosen design solution on the resulting system, throughout the design process.

As the Pattern Language describes relationships within and without the system, and grows with the developing system to characterize forces created and resolved by the system, the language reflects and stores domain knowledge. Domain knowledge exists in both explicit and tacit form within the Pattern Language. Resolving interacting forces requires explicit domain knowledge, while the heuristic translation of relationships into unresolved forces requires tacit knowledge. Therefore, Pattern Language offers an insightful vehicle capable of capturing knowledge for past and present system designs.

2. Pattern Recognition

Pattern language provides a simple set of rules, unencumbered by detail, which encourages creative problem solving by the designer (5) (6) (7) (8). The solution to each design problem becomes a pattern within the pattern language. Patterns that survive the test of time warrant capture to prevent the loss of domain knowledge acquired during pattern development. This work identifies ones such design pattern and describes a methodology for further research in the emphasis of design patterns in systems engineering and knowledge capture.

Lithium Ion batteries are prevalent in modern society and can be found in devices ranging from consumer electronics to the automobile. The incredible energy and power density realized with modern lithium ion chemistry is accompanied by a staggering risk, particularly one of catastrophic battery failure. (9) (10) NASA has responded to this risk by developing a design pattern that tolerates a single cell failure within a battery assembled from commonly available lithium-ion cells without catastrophic battery failure or system consequence. (11) (12) The design pattern achieves this feat by using design features to prevent a cell failure from propagating through the battery, and removing spark and flame from products vented from the battery housing. While a number of researchers have developed non-propagating battery designs (13), no *de facto* design approach yet exists (14).

The battery design pattern resulted from sequential battery development projects, each chartered to replace an existing battery without affecting the receiving system. The batteries identified in this study were required to demonstrate compliance with human space flight requirements, and include four designs referred to as Battery A, Battery B, Battery C, and Battery D. Each battery satisfy the high energy criteria of NASA's Battery Safety Requirements for Human Space Flight (15) with energy in excess of 80Wh, and only Battery D remains outside of the ISS habitable environment. Each of the batteries identified in this work utilize a commercially available electrochemical cell in the 18650 format, arranged to provide the power and energy required by the intended load within a structural housing designed to interface with the receiving system. Each battery presented a unique design challenge that influenced the developing propagation resistant design pattern, and each has deployed, or been prepared for deployment, in human spaceflight application. Table 1 summarizes the batteries used in this study.

Table 1 - Summary of Batteries Used in Pattern Development

Battery	A	B	C	D
Application Type	Accessory	Portable	Vehicle	Life Support
Cell Failure Energy	47 (16)	47 (16)	75 (17)	47 (16)
Energy	0.5 kWh	0.1 kWh	1.2 kWh	0.7 kWh
Discharge Capability	0.1C	2C	3C	0.1C
Design Challenge	Impact Resistant	Mission Replaceable	Water Exposure, Mass Efficient	Low Heat, High Reliability

Battery development occurred chronologically from Battery A to Battery D. As battery design development began prior to the shift in safety requirements, the initial version of Battery A was subjected to a single cell thermal runaway to assess the risk of catastrophic cell failure. The result of a single cell over-temperature event within the Battery A resulted in catastrophic failure as shown in Figure 1, which continued for more than 30 minutes as the failure propagated throughout the 45-cell design. (18) The severity of the event, especially if the event were to occur in the confined, and oxygen-enriched, atmosphere of a human-occupied spacecraft, is untenable.

Figure 1 - Catastrophic Failure of the Initial Battery A Design (18)

In this study, development refers to the transformative process of converting an idea into a fleet ready for deployment. The development process includes requirement generation, engineering design and analysis, manufacturing and production, and verification and validation testing. The engineering design phase is the focus of this study. Engineering design is an act of human creativity combining the application of domain and tacit knowledge in the form of engineering and cognitive psychology (19) (20). Prior to this sequence of battery developments, design team domain knowledge consisted of the physical and electrical properties of the commercial lithium-ion cell, the circuits required to enable battery function, and the effects of material selection and structural loading on metallic structures. Pre-existing tacit knowledge was limited to design patterns that yield a low rate of manufacturing or assembly error, and an understanding of the fit, form, and function of the spaceflight hardware. Design, as referenced in this study, describes the creative engineering required to select and transform construction materials into design elements that accommodate components such as switches, connectors, and lithium-ion cells. A successful design must accomplish mission objectives, be usable by the ground and on-orbit crew, and accommodate assembly by trained operators. The terms design and development describe the art, and the result, of an engineering activity, respectively.

3. Results

Designing a lithium ion battery to tolerate catastrophic cell failure without complete destruction or risk of adjoining system damage required developing an understanding of the cell failure mechanism (16) (21) and the effect of the failed cell on the battery assembly. Beginning with domain knowledge in energy transfer mechanisms, an incremental design, build, and test sequence resulted in a deeper understanding of the relationships between a failed cell and the battery design. Each sequential battery development built on the knowledge gained during the prior activity as described in NASA Report TI-14-00942 (11). The data collected for this study includes development time for each battery and a measure of the resulting design detail. Battery development time is made of two components, a proof of concept phase where new relationships are identified and resolved, and a flight phase where the demonstrated concept is transformed into a fleet ready for deployment. Project management metrics provided the time values used in this study including phase start and stop dates.

Figure 2 demonstrates the observed reduction in development time for sequential battery development activities when performed by a single project team. The development time shown in Figure 2 includes the time required to design a propagation resistant concept, and the time required to complete flight battery development for three of the four batteries previously listed in Table 1. The development time reduction with sequential battery development corresponds to the intersection of cognitive psychology and the art of engineering in the identification and application of previously proven material and component arrangement patterns (20).

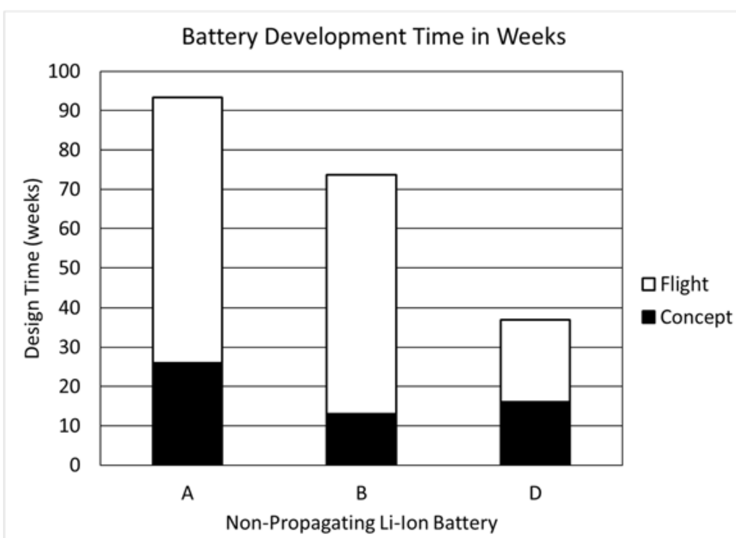

Figure 2 - Development Time for Three Non-Propagating Lithium Ion Battery Designs

The flight development time shown in Figure 2 decreases with each successive activity, while the concept development time appears independent of battery sequence. This observation results from a lack of insight into the detail of the concept design.

Table 2 illustrates the relative increase in design detail with each successive development. Inspection reveals the effect of unique design constraints associated with each battery, and the development of an increasingly detailed, and more successful, battery design. Adjacent cell temperature measured during the cell failure event provides a relative measure of design success.

Table 2 – Non-Propagating Lithium Ion Battery Design Detail

Mechanism	**A**	**B**	**C**	**D**
Propagation is the result of energy transfer	*Volume limited, planar pack, vent oriented towards housing wall*	*Internal volume, cells in a bundle, external electrical configuration*	*Energy dense, high voltage, heat transfer interface, water exposure*	*Energy dense, sensitive location, isothermal, high reliability*
Energy is transferred through conduction to nearest neighbor	Separate and protect cells	Separate and protect cells	Insulate cells, protect insulation, thermal ground plane, exchange heat	Protect and insulate cells, improved thermal ground plane, isothermal
Energy is transferred as current circulating between cells	Fusible cell-to-cell connection	Fusible cell-to-cell connection	Fusible cell-to-cell connection	Fusible cell-to-cell connection
Energy is transferred by exposure to cell ejecta	High temperature construction materials, external vent expansion	High temperature construction materials, internal vent expansion	High temperature construction materials, internal vent expansion	High temperature construction materials, internal vent expansion
Eliminate spark/flame	Reinforced external shroud	Baffle and screen assembly	Baffle, screen, and semi-permeable barrier	Baffle, screen, and semi-permeable barrier
Adjacent Cell Temperature	120 °C	110 °C	95 °C	80 °C

4. Analysis

Alexander (5) stated, "Patterns are observed, not created" in his treatise on design patterns. The reduction in development time and decrease in adjacent cell temperature observations for increasingly detailed battery designs indicates the presence, and realization, of a new design pattern. Patterns describe relationships, and provide rules for transforming those relationships. (5) (6) (8) For example, a design challenge, or problem, occurs when forces acting within the design are unresolved, and the solution that resolves the reacting forces is a design pattern. A pattern provides a morphological and functional description of the solution although detail clarity may be missing (5). Considering only a bundle of cells used in LREBA, a design pattern written in the format recommended by Alexander (5) describes the effect of the development summarized in

Table 2:

Prior to Concept Development:

REPLACEABLE

RETAINED

EXTENDED WIRES

CONNECTED COMPONENTS

INACCESIBLE SURFACES

CELLS TOUCHING ONE ANOTHER

CLEAN, FREE OF DEBRIS

After Concept Development:

REPLACEABLE

RETAINED

EXTENDED WIRES

SUSPENDED COMPONENTS

FUSIBLE INTERCONNECTS

INACCESSIBLE SURFACES

AIRY ARRANGEMENT

HEAT RESISTANT LAYERS

CELLS SEPARATED

REINFORCED VENT OPENINGS

CLEAN, FREE OF DEBRIS

The example patterns are morphologically complete, but additional patterns are required to resolve forces acting within the bundle. For example, a CELL pattern is required to balance SUSPENDED and VENT forces. Similarly, electrical circuitry and structural patterns are required to resolve WIRE, VENT, and RETAINED forces. Thus, patterns interact with other patterns to form a Pattern Language, the development of which is beyond the scope of this initial work.

A comparison of design approach for each energy transfer mechanism with corresponding battery build illustrates the progression of knowledge development. For example, the screen assembly remained largely unchanged after initial development, yet the method for accommodating conductive energy transfer evolved significantly. Beginning with insulation via separation, the method progressed through use of a material insulator and a low-rate thermal ground plane and external heat rejection, to end with a predominantly conductive and isothermal design. The corresponding change in adjacent cell temperature during this transition is notable leading the design team to recognize a Gestalt; an arrangement of an insulating layer and a conductive medium, which when combined, resulted in a significant reduction in adjacent cell heating during induced cell failure. However, when viewing the pattern without context or the remaining patterns in the language, the necessity of each item remains out of reach.

5. Conclusion

This work identifies a design pattern and establishes the foundation for research in pattern emphasis in system design and knowledge capture. The inverse relationship between development time and design detail for sequential battery development activities validates the presence of a design pattern. A sample pattern describes the effect of the first development on a single aspect of battery design. The resulting pattern provides an incomplete morphological and functional description of the battery architecture, but illustrates the development of new domain knowledge. The following research questions provide a methodology for further study in the emphasis of patterns in system engineering and knowledge capture:

Hypothesis: Pattern Language provides a deep understanding of a system architecture:

- Does relationship mapping provide a documented architectural concept abstraction?
- Is the transformation of relationships to forces a heuristic process?
- Does Pattern Language provide insight into the structure of the system?

Hypothesis: Pattern Language offers insight into management of the design process:

- Does force resolution provide a measure of design progression?
- Does creation of a new or duplicate force indicate over-design?
- Does Pattern Language encourage reuse of existing patterns (force balancing solutions)?
- Does pattern use encourage new solutions and new technology?

Hypothesis: Pattern Language captures and transfers knowledge:

- What are the indicators for time-proven patterns in existing systems?
- Does design team performance reflect the creation of a design pattern?
- Does pattern language discern between explicit and tacit knowledge?
- Does knowledge transfer by pattern language require tacit knowledge?
- Can pattern language detect knowledge bias or misconception?

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