Elicitation, Computational Representation, and Analysis of Mission and System Requirements

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11 authors, including:

Nafiseh Masoudi
Clemson University

Joshua Ortiz
University of Texas at Dallas

Dane Acena
Clemson University

Joshua David Summers
University of Texas at Dallas

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Elicitation, Computational Representation, and Analysis of Mission and System Requirements

Nafiseh Masoudi and Rahul Rai Clemson University Int'l Center for Automotive Research

Joshua Ortiz and Meredith Sutton Clemson University

Vinayak Khade Clemson University Int'l Center for Automotive Research

Dane Acena and Guo Freeman Clemson University

Joshua Summers University Of Texas at Dallas

David Gorsich, Denise Rizzo, and Jonathon Smereka United States Army DEVCOM Ground Vehicle Systems Center

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Abstract

Strategies for evaluating the impact of mission requirements on the design of mission-specific vehicles are needed to enable project managers to assess potential benefits and associated costs of changes in requirements. Top-level requirements that cause significant cascaded difficulties on lower-level requirements should be identified and presented to decision-makers. This paper aims to introduce formal methods and computational tools to enable the analysis and allocation of mission requirements. Initial results for three interrelated research problems are discussed: (1) understanding the current practices of interrelationships between requirements. the requirements elicitation and change management processes using a case study approach; (2) requirement elicitation using gamification strategies; and (3) computational representation of the technical requirements and identification The case study approach involves interviewing the stakeholders that participate in the requirements generation process to collect data on the current practices of requirements elicitation. Systematic requirements generation strategies, change management processes, limitations, and areas for improvement are the outcomes of this study. A gamification strategy is also deployed to study requirements elicitation and change management processes by incentivizing the users based on their performance on a set of metrics. Two surveys, one with and the other without gamification, are designed to study the impact of gamification methods on requirements elicitation. Lastly, text analytics tools are developed to extract requirements from textual descriptions and identify their inter-relationships to be stored in the requirement graph representation.

Introduction

The Virtual Prototyping of Ground Systems (ViPR-GS) Center at Clemson University has the vision to research innovative methods and tools for virtual and agile physical prototyping of the next generation of off-road autonomous ground vehicle systems. The overarching goal of this center is to introduce new modeling and simulation capabilities, software tools, and methods to support the research and development mandate within the Ground Vehicle Systems Center (GVSC).

The objective of the virtual prototyping and digital engineering initiative within the ViPR-GS center is to develop a framework of models, methods, and tools, providing the ability to explore large numbers of system concepts holistically in a virtual environment. It is envisioned that by developing computational tools for concept exploration, large numbers of virtual prototypes can be analyzed to understand the impact of system-level requirements on mission capabilities. Using systematic flow-down from system-level requirements and targets to final allocation to software/hardware implementations, the impact of new technologies on system architectures can be explored early in the conceptual design phase itself. Therefore, the role of mission and system requirements is critical in the overall modeling, concept exploration, and design of advanced systems such as autonomous off-road vehicles.

The efforts outlined in this paper aim to shed light on the understanding of the current requirements elicitation and change management processes and identify the challenges/limitations of the current practices. First, a case study approach

is followed where students, educators, and military practitioners are interviewed regarding their approaches to requirements elicitation and management. The data collected from these interviews result in drawing process models descriptive of the current practices in both military (GVSC) and academia (Clemson University). Further, knowledge gaps are identified, and recommendations are provided to improve the current state of requirements management.

The understanding of the current practices guides our efforts in developing innovative tools and methods for requirements elicitation, representation, and analysis. As such, in the second part of this research, we design a survey study to evaluate the effectiveness of gamification environments (as an innovative tool) on the requirements elicitation process. The advantage of gamification over the traditional requirement elicitation process is that it promotes the motivation and participation of users and designers; hence, it can keep the stakeholders engaged during the requirement elicitation process.

Lastly, following the case study results and the criticality of requirements change management, we attempt to model the relationship among design requirements and computationally represent those relationship using network trees. The understanding of such relationships will aid designers and engineers in observing the effects of one requirement on the others and make or modify decisions accordingly. Three types of relationships are the primary areas of our focus in this study: keyword, semantic, and contextual relations. After quantifying these relationships, they can be represented using network trees and graph theory principles can be applied for further analysis.

In what follows, the details of each research problem, along with our approach and preliminary results, are presented. Conclusions and main findings are also outlined.

Case Study: Current Practices of Requirements Engineering Process

A case study is conducted to understand the current practices of requirements elicitation and change management. A case study is a useful research tool that allows for real-time observation of ongoing events that cannot be adequately replicated in a laboratory setting [1, 2].

The case study used in this research explored the requirements process, including requirements elicitation, requirements change management phases, and challenges and limitations of the practiced process. The case study was conducted through interviews with two populations working on two distinct projects. The first project involved military vehicle design and included the associated requirement engineers and scientists, whereas the second was a graduate-level vehicle prototyping project that included both the students conducting the design work and the faculty advisors responsible for guiding and supervising the project. Interviews were conducted with the practitioners from these projects in a semi-structured manner, allowing the flow of information to be maintained through the flexible ordering of questions. The interviews were conducted virtually through video-conferencing software, which was critical as the interviews were conducted between 2019 and 2021, during the COVID-19 pandemic, which limited access to in-person contact with individuals. Further details of the interview protocol are shown in Table 1.

Eleven interview participants were elicited from professional networks using the "snowball method," in which the initial set of interviewees were asked to identify other potential candidates for interviews. Details about individual interviewees can be found in Table 2. For anonymity, fictitious names are assigned to each interviewee. All names are single gender, assigned to prevent identification and bias in the analysis. Those with names starting with "C" are from the graduate-level prototyping project, including faculty supervising student progress and the student designers actually conducting the design. On the other hand, those with names starting with "G" are from the military vehicle design group.

TABLE 1 Details of the interview protocol.

Topic	Requirements Process Study
Purpose of research study	Understanding
Purpose of interview	Core
Context of study	Automotive
Organization studied	Design
Relationship between interviewee and interviewer	No prior relationship
Interviewer type	Individual
Interview location	Video conferencing
Interview type	Semi-structured
Number of interviews	11
Duration	~60 minutes

TABLE 2 Interview participants information.

Name	Production Volume	Organization	Role
Charlotte	Low	Academic	Faculty Advisor
Carmen	Low	Academic	Faculty Advisor
Catherine	Low	Academic	Faculty Advisor
Claire	Low	Academic	Student Designer
Carol	Low	Academic	Student Designer
Candace	Low	Academic	Student Designer
Colleen	Low	Academic	Student Designer
Gwen	Medium	Military	Requirements Engineer
Georgia	Medium	Military	Chief Scientist
Greta	Medium	Military	Requirements Engineer
Grace	Medium	Military	Requirements Engineer

Requirements Change Management and Overall Processes

A requirement change (RC) is defined as the addition of a new requirement to a requirement set or the modification or removal of an existing requirement [3, 4, 5]. Changes can be prompted by customer requests and misunderstanding of initial requirement or by discovering that a particular requirement lies outside of the overall project scope [3, 6, 7]. Other change triggers can include the discovery of new requirements, reductions in project scope, revisions to improve testability, and changes to the product environment [8, 9, 10].

Requirement change management (RCM) refers to the approach to managing change propagation in requirement sets. The process through which this management is done varies; different researchers decompose the process into various stages of differing lengths. A comprehensive ten-step process was proposed, intended for use among distributed teams across multiple sites [11]. The ten steps are shown in Table 3.

The RCM interview questions were developed based on the discussed process model. Questions regarding requirement elicitation and development were also included. Additionally, questions were added about any limitations or areas for improvement in the current processes. Data from the interviews were used for two types of analyses. The first analysis method focused on generating process models that described the overall requirements process as well as the requirement change management process.

From each of the RCM interviews, a distinct process model was developed. Participant responses were mapped to the ten stages (Table 3) and were coded as either an explicit mention, implicit mention, or no mention. An explicit mention of a process stage means that the interviewee specifically discussed part or all of the stage by name. In contrast, an implicit mention means that the individual may have discussed the stage as part of another stage or in a way that was not immediately apparent to be a distinct stage but was later revealed with analysis. The process models for all participants were then compiled for easier comparison and analysis of trends, as shown in Table 3.

From the summary table, major trends can be determined. For instance, three stages were mentioned by all interviewees: (1) identification of the need, (2) development of the revision, and (3) implementation of the change. Identification of the need and development of the revision were predominantly implied to be included in the process, while the implementation of the change was the only stage explicitly discussed by all interviewees. Other stages were more uncommon: initiation of the change request and issuing change orders were both only mentioned by only two out of the eleven interviewees. One stage was not mentioned, either explicitly or implicitly: verification of the assessed impact. Additionally, from Table 3, it is understood that the military designers presented the most complete process models. They discussed the majority of stages in the process model and mentioned these stages mostly explicitly, demonstrating a clear understanding and strong ownership of the process. The overall requirements process differed between military and academic designers. The academic and military requirement process models are shown in Figure 1 and Figure 2, respectively.

Thematic Analysis

In addition to the process models, thematic analysis was conducted on the interview data. A theme captures an aspect of the data and represents a typically recurring pattern or trend. However, the frequency with which the theme appears in the data set does not inherently indicate the relative importance of the theme [12]. Interview data, which included handwritten notes and generated transcripts when available, was combed through in detail to identify key quotes and phrases. These quotes from the interviews were then assigned codes. The codes and the associated speakers were recorded in a Microsoft Excel spreadsheet and were color-coded and

TABLE 3 Requirements change management process summary.

Interviewee	Identify need	Initiate change request	Identify approach to change request	Develop revision	Assess revision impact	Review and approve revision	Issue change order	Implement change	Verify assessed impact	Document change
Charlotte	I		I	I		I		E		
Carmen	I	E	E	I		E		E		E
Catherine	I		I	I	I	E		E		
Claire	I		I	I		I		E		
Carol	I	I	I	I		I		E		I
Candace	I		I	I	E	I		E		E
Colleen	I		I	I		E		E		I
Gwen	E		E	E	E	E	E	E		E
Georgia	E		E	E	I	E		E		
Greta	E		E	I	I	E		E		E
Grace	E		E	I	I	E	I	E		E
TOTAL I	7	1	6	9	4	4	1	0	0	2
TOTAL E	4	1	5	2	2	7	1	11	0	5
TOTAL(E+I)	11	2	11	11	6	11	2	11	0	7

FIGURE 1 General requirements process for designers in academia.

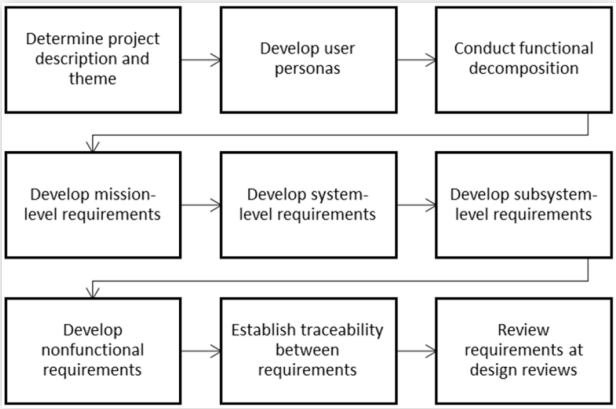
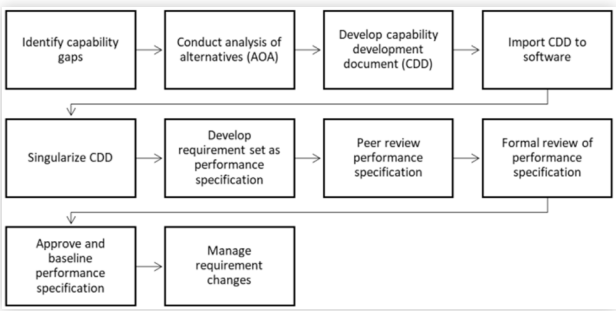


FIGURE 2 General requirements process for designers in military.



grouped to form initial themes, per the approach specified by Bree and Gallagher [13]. An inductive approach was used in which no themes were predetermined before the analysis process began, thus allowing the analysis to be driven by the data rather than forcing the data to conform to a predetermined coding scheme. These themes were then revised and refined into overarching themes and more detailed subthemes. Connections between the resulting themes and subthemes were explored and recorded in a thematic map, per the approach of [14], shown in Figure 3. Three main themes are identified - requirement generation, requirement management, and issues with the current approach - with an additional eight subthemes. The interviewee groups that addressed these subthemes are illustrated by color tags: yellow designates faculty advisors, red designates military designers, and green denotes student designers. This color-coding scheme reveals a disconnect between the faculty and students in the academic design group. The faculty were focused on high-level project management and student instruction. Thus, the topics of requirement writing, requirement management, and more general information management were of more importance than a discussion on the challenges with the current approach. Conversely, the student interviewees seem to be most interested and focused on the challenges of the current approach with little focus on documentation. The military designers discussed all issues equally.

Survey Study: Effectiveness of Gamification on Requirements Elicitation

The objective of this task is to leverage the existing gamification approaches to identify the inter-relationship between mission definitions and technology infusion. Often, the success or failure of a project is dependent on practices related to requirements. Incomplete, ambiguous, and missing requirements lead to an increase in rework, overall project cost, delays in the timeline, and ultimately to project failure [15, 16, 17]. Thus, it is important to collect requirements in an efficient way. Common elicitation techniques such as questionnaires, interviews, prototyping, and focus groups [16, 18] may fail to

FIGURE 3 Thematic analysis.

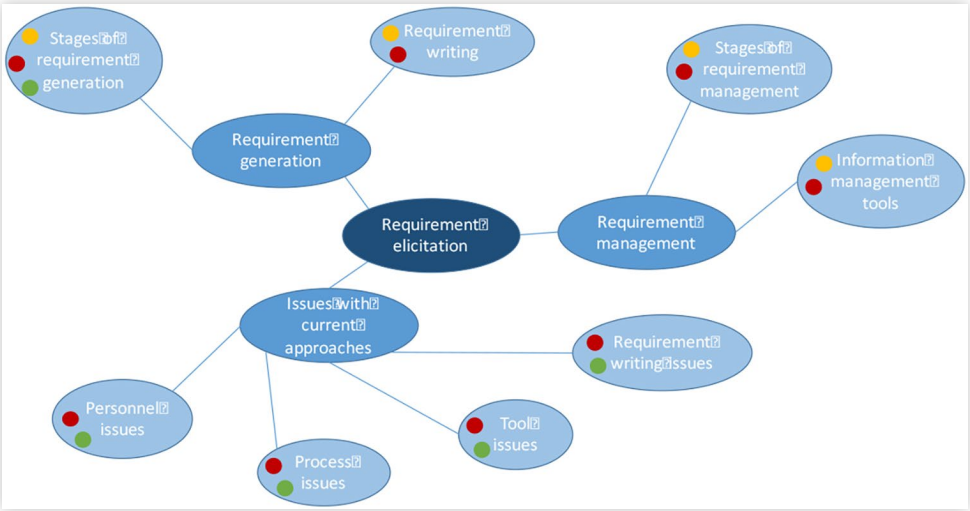


TABLE 4 Game design elements for the gamified survey.

Game design element	Affected motivation ([22]; [23]; [21])
Points	Order, Status
Badges	Order, Power
Leaderboard	Power, Order, Status
Activity feed	Power, Order, Status
Avatar	Power, Independence, Status
Quests	Curiosity, Power

keep stakeholders engaged in the process, and often, stakeholder involvement is insufficient. Common elicitation techniques such as questionnaires, interviews, prototyping, and focus groups [16, 18] may fail to keep stakeholders engaged in the process and often stakeholder involvement is insufficient. In recent years, the application of gamification to improve the motivation and participation of users has drawn attention. Gamification is defined [19] as the use of game design elements (such as points, badges, leaderboards, etc.) in a non-game context. Several studies have already shown the positive impact of using gamification, stating an increase in engagement, collaboration, and communication among users and team members [15, 20]. Some commonly used game design elements as discussed in studies [15, 20, 21] include points, leaderboards, badges, achievements, rewards/challenges, levels and progression, profile and avatar, activity feeds, timer, storytelling, and feedback. In the context of requirements engineering, the most common game elements are points, leaderboards, and badges.

As part of the second study, we have designed a survey study using two online platforms: Pointagram (gamified) and MS Forms (non-gamified), with the aim of studying the impact of gamification on the requirements elicitation process. The game design elements used for the gamified survey are listed in Table 4.

The survey questions are developed based on the findings of the case studies and are centered around asking the participants to provide the requirement type (mission or system), requirement description, and relation to the pre-defined mission scenarios, and the functional objectives of requirements (when available).

For the gamified survey, each user has to create an account on Pointagram, after which they will have access to a personal dashboard. On this dashboard (Figure 4), users can access active competitions (2), view their badges (3), see the achievements of their peers, and post questions or start discussions

FIGURE 4 Pointagram interface, dashboard (1-3) and quests (4).

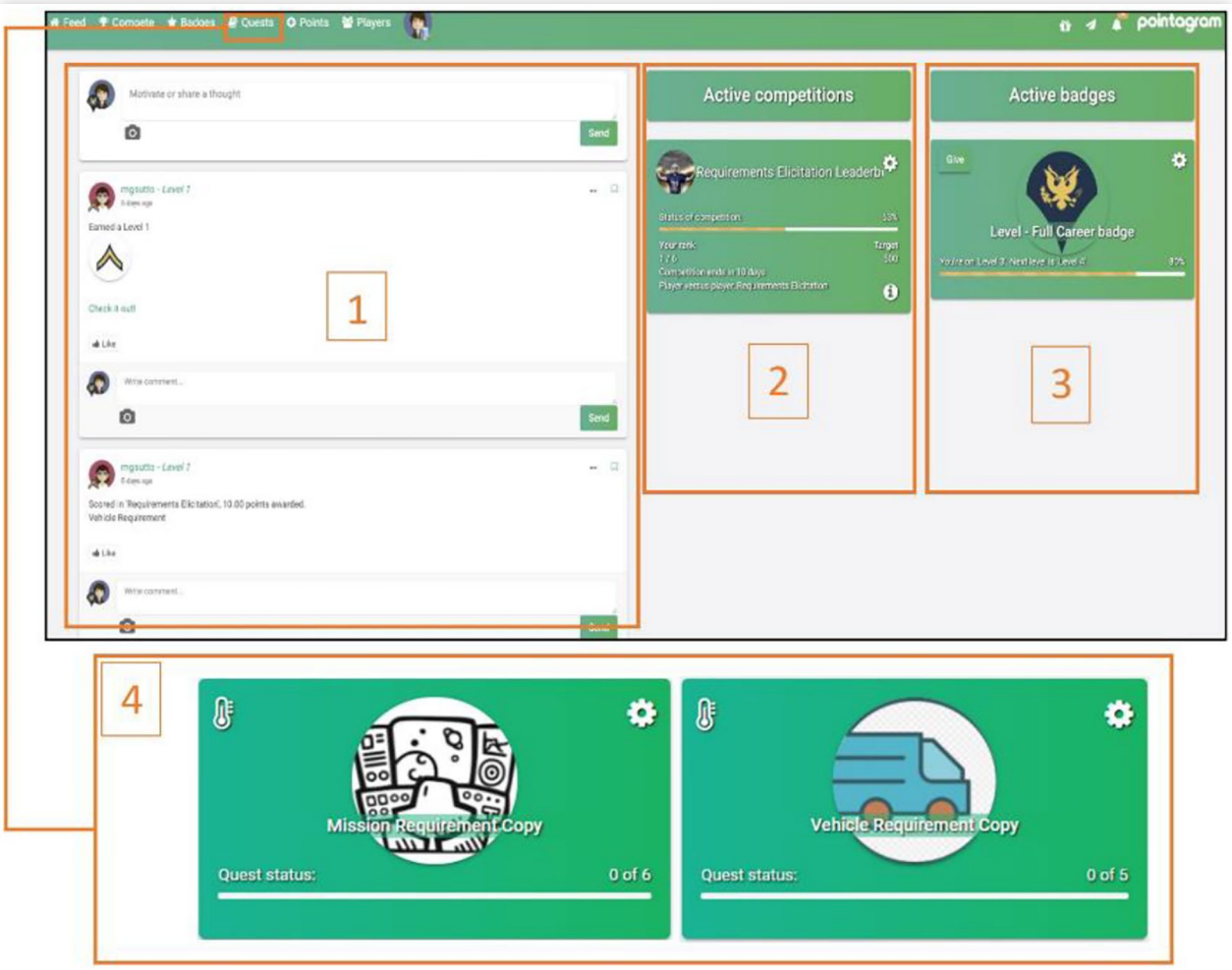
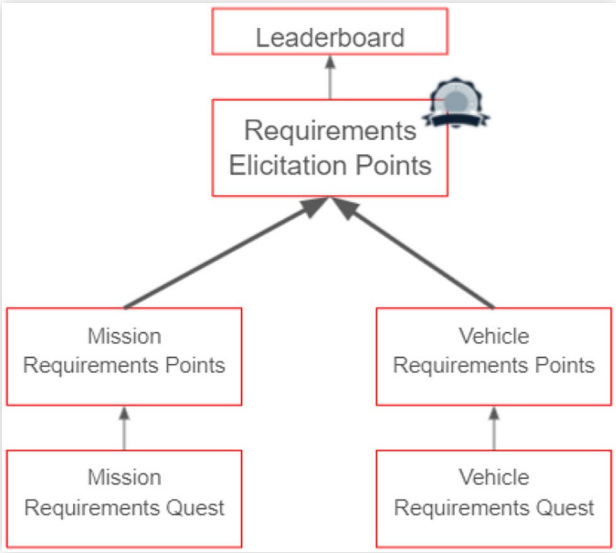


FIGURE 5 Points accumulation structure.



to collaborate with others (1). The questions to capture requirements are asked in the form of quests (a set of quests for mission requirements and a different set for system requirements). On completion of each quest, users are awarded a pre-defined number of points. The points are separately tracked for mission requirements and system requirements ("Mission Requirement Points" and "Vehicle Requirement Points"). The accumulated points are counted as "Requirements Elicitation Points," which indicate the user's place on the Leaderboard (see Figure 5).

The next step of our study is to run the surveys with participants who are senior Mechanical Engineering undergraduate students enrolled in a capstone design project to gauge the efficacy of the gamification- based requirement elicitation process. The participants will be grouped into two teams, and each team will take either the plain or the gamified survey. Data will be collected to evaluate the effectiveness of gamification in requirements elicitation using metrics such as the number and structure of the generated requirements. Figure 6 shows the overall structure of the gamification study followed in our research.

Modeling of Relationships Between Requirements

In engineering design, requirements are used to describe a given design problem. As the design efforts progress toward a solution, those requirements evolve to describe not only the original problem but also each subordinate problem that arises as a result of design decisions that are made, namely, subsystems and components of the overarching product ([24, 25, 26]). Some have surmised that understanding the relationships between requirements can provide an insight that can hasten development and improve the final product [27, 28, 29]. This requires an effective method for determining what relationships exist among requirements and representing them in a manner that allows for relationships analysis.

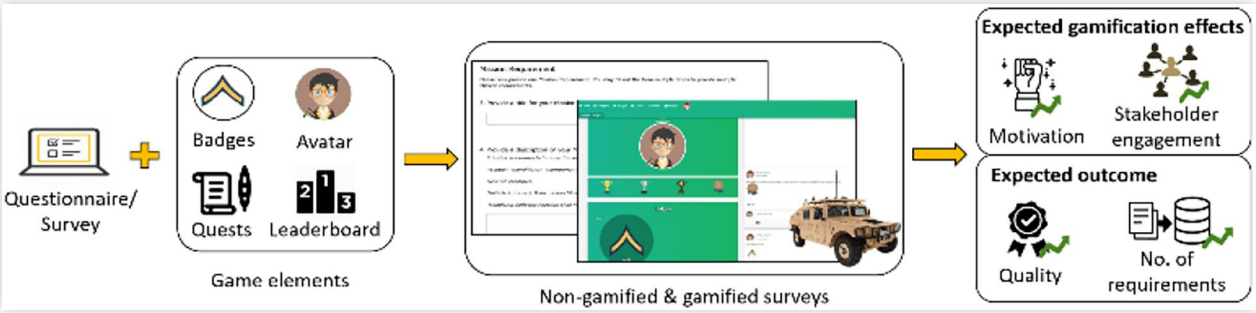
Once the relationships have been extracted and characterized, they must be modeled in a useful manner. Here, network graphs have been chosen as one such representation. Each type of relationship forms its own network. These individual graphs can be combined in a variety of ways to discern information from the complex relations and patterns that arise. In each case, the vertices denote requirements, and edges show the connections between them with weights indicating the significance of the links. These graphs form the building blocks upon which reasoning may be performed.

Identifying and Quantifying Relationships

The first phase of relationship modeling is to recognize the connections within a set of requirements and assign to each one a degree of significance that is agnostic to the nature of the relation. This process can be broadly described by three distinct stages: identification, quantification, and scaling.

Identification is the process of identifying the phenomena that give rise to the relationship in question. For example, if a relationship based on keywords is being sought, then keywords for the set of requirements must be identified and linked in a particular way to each requirement. There may be multiple methods for extracting similar information from a set of requirements. To continue with the keyword example,

FIGURE 6 The overall workflow of the gamification study.



the choice of words to use or whether to consider their order of appearance are examples of this. Each identification method is likely to produce a unique set of relationships. Therefore, it is important that the method of identification be carefully chosen and documented so that the results may be interpreted and used appropriately.

Quantification is closely related to identification and, in some instances, may take place simultaneously. However, it is a separate element and may be implemented differently, even given a similar identification process. As the name implies, quantification involves the assignment of a value to the phenomena discovered during identification. For the example of finding keywords in the requirements, counting the frequency of occurrence would be one method of quantifying the relationship, but a binary value could be used instead. Another means of quantifying a relationship might be the use of a distance function.

Typically, scaling will also be necessary so that results from one relationship can be compared or combined with those from another to prevent one from dominating the analysis or from being artificially ignored. Here, efforts have been made to bound all relational quantities between 0 and 1 and to make a value of 1 synonymous with the maximum possible similarity for a given relationship. Doing so will allow for identifying redundant or identical relationships since a value of 1 has the same significance in every category.

Keyword Relations The method of establishing keyword relations was adapted from [30] and employed the latent semantic analysis (LSA) algorithm [31].

A set of words must first be chosen from among the requirements to evaluate keyword relation. These can be obtained in any manner the engineer chooses, provided that each word appears in at least one requirement. A common method is simply to identify and filter out stop-words, which can be ignored without loss of meaning. Any remaining words after filtering may be considered important enough to be used as keywords. However, one could also manually identify individual words or use a software extraction package.

Once keywords have been identified, LSA is performed by establishing a matrix X having a row for each keyword and a column for each requirement in the set. Then the elements of the matrix are assigned values such that element i, j is the number of times the ith keyword appears in the jth requirement. A singular value decomposition (SVD) is then performed on matrix X. Any matrix X can be decomposed into the matrix product of its left singular vectors U, a diagonal matrix Σ having its singular values on the diagonal, and the transpose of its right singular vectors V.

$$X = U\Sigma V^T \tag{1}$$

The right singular vectors V of the decomposition encode information pertaining to the columns of X, the requirements [30]. This allows each requirement to be represented as a point in a semantic space, where each row of V gives the coordinates of a point in the space that represents a particular requirement. The Euclidean distances between points in this latent space are inversely analogous to the strength of the relationships between the corresponding requirements. The radial basis function

$$K\left(\vec{a},\vec{b}\right) = \exp\left(-\frac{\left\|\vec{a}-\vec{b}\right\|^2}{2\sigma^2}\right) \tag{2}$$

is used to assign values to those strengths by bounding them between 0 and 1 and inverting the correlation between distance and relationship strength, K=1 implies that two statements contain the exact same frequencies for all keywords. In this equation, σ is the scaling parameter and a and b are any two vectors. Calculating K pairwise for the set of requirements results in a square matrix A_1, with dimensions equal to the number of requirements in the set. Then a complete network graph is constructed with A_1 as its adjacency matrix, in which the edges are weighted according to the radial basis value of the distance between them in the latent space.

Semantic Relations Semantic relationships indicate how similar two requirements are in their meaning. Here, Sentence-BERT is used to analyze the semantic similarity between requirements through sentence embeddings, but other tools also exist which may be used instead. Sentence-BERT is a natural language processing (NLP) technique that uses specialized neural networks to encode entire sentences as numerical vectors based on their semantic meanings [32]. The semantic similarity of two sentences can be quantified from these vectors by their cosine similarity

$$\mathrm{Sim}\left(\vec{a},\vec{b}\right) = \frac{\vec{a}\cdot\vec{b}}{\left|\vec{a}\right|\left|\vec{b}\right|} \tag{3}$$

This function is performed pairwise on the set of requirements to obtain matrix A_2. No further processing is necessary since the range of the cosine similarity function is already scaled appropriately. The graph network can then be generated using A_2 as its weighted adjacency matrix.

Contextual Relations Contextual relationships indicate the relative location of two requirements in the source document. The process for establishing contextual relations differs significantly from the previous two in that additional information is needed apart from the requirements themselves before connections can be established. In order to identify where relationships exist between requirements in the same document, their locations must be established. This, in turn, necessitates the structure of the document to be identified against which localization can be defined. Distance, in this regard, could be measured by the number of pages, sentences, words, or characters between requirements. However, each of these neglects the relationships intended by the document authors when creating the chapters, sections, and subsections. A document tree can be used wherein these entities are represented by nodes in the tree to incorporate such information into the relationships. Since it is the relationship between requirements that is of interest and not that of document sections, it is desirable to capture both the relative "depth" of the requirements as well as the graph distance. In terms of the document structure, depth refers to the hierarchy of sections and subsections, while distance would be the number of sections between two requirements. The root node of the tree is the document itself, which is the highest level of its own

structure. The following equation is proposed to incorporate both aspects of location when calculating the strength of the relationship.

$$\mathrm{Rel}(A,B)=\sqrt{\mathrm{d}(A,B)^2+\left(\mathrm{depth}(A)-\mathrm{depth}(B)\right)^2} \qquad (4)$$

Where the distance function d(A, B) returns shortest path -- the minimum number of edges -- between two nodes A and B; and depth(A) refers to the distance from A to the root node of the tree.

With this metric and an appropriate document structure tree, a pairwise distance matrix D can be constructed from which the third relation matrix $A_3 = K(D)$ can be constructed, which is then used to build the relationship network in the same manner as the previous two relationship types.

Example Case

The list below shows a set of 27 requirements for a vehicle. The requirements have been extracted from a requirements document, and the section number to which they pertain has been recorded for the construction of the contextual relationship graph.

1. The car shall be capable of accelerating to 100 km/h within 5 seconds. (1.)
2. The car shall have a maximum velocity of 250 km/h or more. (1.)
3. The car shall have a maximum fuel efficiency of 11 kpl or more (1.)
4. The steering system shall allow for the front wheels to turn 35 degrees from center. (1.1.)
5. The steering system shall be capable of turning the front wheels at 30 deg/sec. (1.1.)
6. The steering wheel shall have a diameter on the interval of 350 - 450 mm. (1.1.1.)
7. The power steering pump shall be capable of 900 kpa output pressure. (1.1.2.)
8. The power steering pump shall maintain output pressure at serpentine belt speeds of 5-100 m/s. (1.1.2.)
9. The power steering pump pulley shall support a belt width of 20 mm. (1.1.2.1.)
10. The drive system shall have an overall energy efficiency of 0.28 or higher. (1.2.)
11. The drive system shall produce a wheel power of 330 W or higher. (1.2.)
12. The drive system shall have an overall backlash of less than 75 deg. (1.2.)
13. The engine shall have a thermal efficiency of 0.35 or higher. (1.2.1.)
14. The engine shall consume less than 0.2 liters per minute at peak power. (1.2.1.)
15. The clutch shall be capable of holding 900 Nm torque static. (1.2.2.)
16. The clutch shall be capable of matching input to output revolutions from static output within 0.1 s under 1000 W input shaft power. (1.2.2.)
17. The clutch plate shall have a diameter on the interval 300 - 350 mm. (1.2.2.1.)
18. The transmission shall have an overall input-output backlash of 15 deg or less. (1.2.3.)
19. The transmission shall be capable of providing a minimum gear ratio of 2.66:1. (1.2.3.)
20. The transmission shall be capable of providing a maximum gear ratio of 0.43:1. (1.2.3.)
21. The idler gear shall have a helix angle of 30 degrees. (1.2.3.1.)
22. The idler gear shall be 0.4 module. (1.2.3.1.)
23. The input shaft shall have a diameter of 40 mm. (1.2.3.2.)
24. The input shaft shall have 64 splines at the clutch plate. (1.2.3.2.)
25. The input shaft material shall have a Young's modulus greater than 200 MPa. (1.2.3.2.)
26. The differential shall provide a gear ratio on the interval 3.6 - 3.75:1. (1.2.4.)
27. The differential input shaft shall have a female spline receptacle with 48 splines. (1.2.4.)

From the numbering scheme, the following tree is established upon which the contextual relationships are calculated.

Given this information, the relationship graphs for this small set of requirements can be generated according to the process described in the preceding sections. The keyword, semantic, and contextual relationships for the discussed example are shown in Figures 8 to 10, respectively.

Figures 8-10 depict the graphs for the three relationship types described in the preceding sections. In each graph, the

FIGURE 7 Tree illustrating the structure of the original requirements document. Used to calculate the contextual distances between requirements

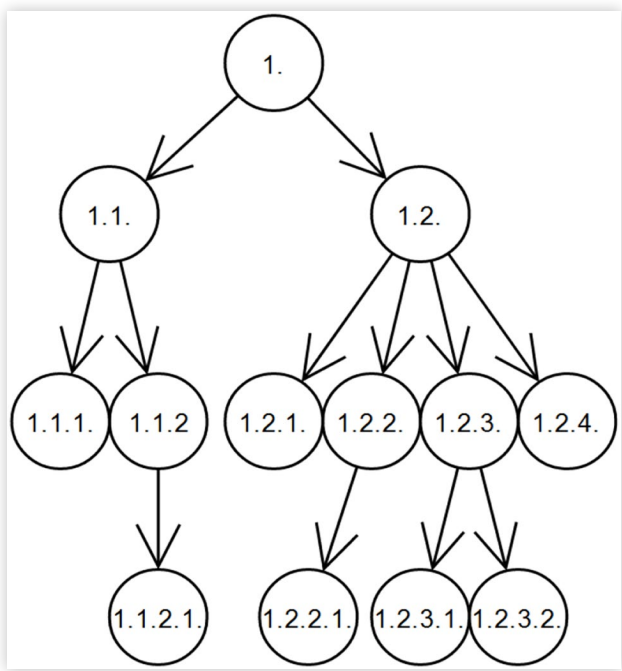


FIGURE 8 Keyword relationship graph for the example requirements. The color of the node indicates the sum of the weights for each of its edges. Higher values are lighter in color.

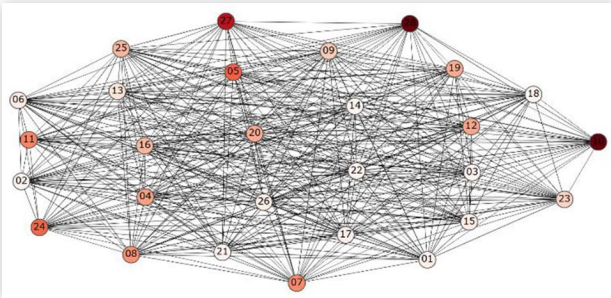


FIGURE 9 Semantic relationship graph for the example requirements. The color of the node indicates the sum of the weights for each of its edges. Higher values are lighter in color.

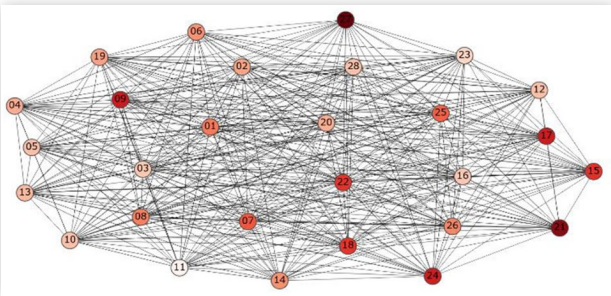
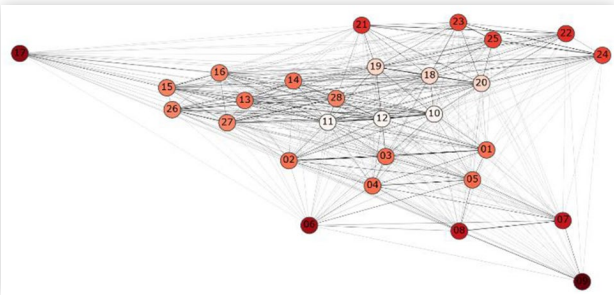


FIGURE 10 Contextual relationship graph for the example requirements. The color of the node indicates the sum of the weights for each of its edges. Higher values are lighter in color.



nodes represent requirements with numbers corresponding to their position in the list above. Connections, also called edges, between the nodes indicate that the two corresponding requirements share a relationship of that type, with darker lines showing stronger relations. The shade of each node indicates its weighted degree, which is the sum of weights for all of its connected edges. Light-colored nodes have a higher degree relative to other nodes in the graph, indicating that their relations to other requirements tend to be stronger. By default, the processes described previously produce fully connected graphs with edge weights ranging from 0 to 1. However, if a partially connected graph is desired for certain analysis, a threshold can be set in order to treat nodes with weaker relations as disconnected. This allows for the detection of cliques and cycles, which may illuminate further patterns in the data. Furthermore, graphs can be combined in various ways to infer more complex associations, such as by adding edge weights from different relationship types or by using one set of edges to mask another. Other relationship types will be captured in the future as well to more fully describe the interrelationships of requirement sets and research into the scope and quality of the insights that can be gleaned from these graphs is ongoing.

Conclusions

This paper presented approaches to (1) understand the current state of requirement elicitation and change management, (2) improve the motivation and participation of users in requirement elicitation activities following gamification technology, and (3) identify, model, and represent the relationships between requirements in a design project.

The case studies revealed some key observations and conclusions through the process models and thematic analysis. For example, it is seen that the interviewees included requirement generation as part of the overall process, as shown in the thematic map. While, at the surface level, requirement generation may not seem to be part of the RCM process, the definition of a requirement change includes adding new requirements as well as modifying or deleting existing requirements. Thus, requirement generation is a critical part of the RCM process.

Considering the thematic map and the population groups that each theme was present in, a correlation can be observed. Faculty and military largely overlapped when discussing prescriptive themes, such as the process stages and requirement writing methods. This could be attributed to ownership, as faculty and military designers primarily developed or selected the process stages and thus had sufficient understanding to discuss them in detail. In contrast, students and the military overlapped on descriptive themes, such as those describing issues with the current process. This difference can be explained by the fact that the students and military practitioners are the ones using the process day-to-day and experiencing any issues that may arise. The fact that the faculty population group did not identify many of these same issues illustrates that there is a gap between instruction and practice. This gap must be closed to improve the overall change management practice ([33]). However, to do so, communication between practitioners, researchers, and instructors must be improved. This would allow issues to be discovered in practice and communicated to incoming practitioners with methods to minimize the issues.

Also, from the process models, it can be observed that they do not include a stage to verify the results of the impact assessment after the change is implemented. The only verification and validation is conducted to ensure that the requirements are necessary and fulfilled, without significant consideration of the changes.

In addition, a formal method is proposed to mathematically model the interrelationships among requirements and represent them using network trees. Three relationships are

of interest in the context of requirements: keywords, semantics, and contextual. An example is shown with a set of requirements for which relationships are identified and represented in the form of trees. The results of this modeling and representation effort can be applied to capture the top-level requirements that cause significant cascaded difficulties on lower-level requirements.

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Contact Information

Dr. Rahul Rai
rrai@clemson.edu.

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Definitions/Abbreviations

$\boldsymbol{A_i}$ - Relation matrices

d(A, B) - Shortest path between nodes *A* and *B*

depth(A) - distance from A to the root node of the tree

D - pairwise distance matrix

K - Radial basis function

RC - Requirement change

RCM - Requirement change management

V - Singular vectors of the decomposition

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