Knowledge Integrated Visual Analysis system for in-depth management of Bridge Safety and Maintenance

Xiaoyu Wang[a], Wenwen Dou[a], Rashna Vatcha[c], Wanqiu Liu[b], Shen-En Chen[b], Seok-Won Lee[c], Remco Chang[a], William Ribarksy[a]

[a]Visualization Center, University of North Carolina at Charlotte, Charlotte, USA
[b]Civil Engineer Department, University of North Carolina at Charlotte, Charlotte, USA
[c]Software and Information System, University of North Carolina at Charlotte, Charlotte, USA

ABSTRACT

Infrastructure safety affects millions of U.S citizens in many ways. Among all the infrastructures, the bridge plays a significant role in providing substantial economy and public safety. Nearly 600,000 bridges across the U.S are mandated to be inspected every twenty-four months. Although these inspections could generate great amount of rich data for bridge engineers to make critical maintenance decisions, processing these data has become challenging due to the limits from those traditional bridge management systems. In collaboration with North Carolina Department of Transportation (NCDOT) and other regional DOT collaborators, we present our knowledge integrated visual analytics bridge management system. Our system aims to provide bridge engineers a highly interactive data exploration environment as well as knowledge pools for corresponding bridge information. By integrating the knowledge structure with visualization system, our system could provide comprehensive understandings of the bridge assets and enables bridge engineers to investigate potential bridge safety issues and make maintenance decisions.

Keywords: Bridge Inspection, Public Safety, Ontological Knowledge Structures, Visual Analytics

1. INTRODUCTION

When the I-35W Minneapolis River Bridge collapsed 13 years ahead of it designed lifetime, in August 2007,[1] thousands of people were devastated. This catastrophe caused hundreds of casualties and millions of financial loses. Although the ultimate cause for this calamity is a design flaw, it alerts us that we could not take the bridge safety for granted. According to Federal Highway Administration National Bridge Inspections Standards Regulation (NBIS),[2] all state wide Department of Transportation are required to inspect bridges in their jurisdiction based on a twenty-four month period. Using these collected bridge information, engineers would then analyze and score each bridge with an overall sufficiency rating, which will later be considered in their maintenance decisions.

Since these highly frequent and detailed inspections have generated a great amount of rich reports and preparatory data, it becomes more and more challenging for bridge engineers to analyze and process these data with traditional bridge management systems. Due to the growing data size, bridge engineers are facing challenges to effectively navigate through their data and to locate useful information. Because of this inconvenient investigation process, potentially, bridge mangers could only get partial understandings about the situation; hence it becomes difficult for them to make accurate maintenance decisions. More importantly, an accurate decision also requires the bridge engineers to follow standard procedures with certain domain knowledge. Although provided with official guidance, due to its complexity, it is still not easy for bridge engineers to completely follow those rules. Accidentally skipping some procedures may potentially lead to incomplete analysis of the bridges that affects the maintenance decisions. With all these issues emerging, traditional paper and spreadsheet-based bridge management systems are no longer sufficient in handling these complex assessment tasks.

Further author information: (Send correspondence to Xiaoyu Wang.)
Xiaoyu Wang: E-mail: xwang25@uncc.edu, Telephone: 1 704 687 8641

Throughout the years, USDOT has funded several universities and research institutions to search for a more effective and efficient way to perform bridge management.[3] In our collaboration with NCDOT and other regional DOTs, we present them our knowledge integrated visual analytics bridge management system to facilitate bridge engineers to efficiently maintain their bridge assets.

There are two main contributions in our system. First, our system provides a highly interactive data exploration environment that enables bridge engineers to interactively navigate through their large preparatory data and effectively locate the information they are interested in. Second, our system incorporates an ontological knowledge structure to preserve and provide bridge inspection information. By integrating these two components, our system provides bridge engineers comprehensive understandings of the potential bridge safety issues and facilitates their decision making processes.

In the remainder of this paper, we give an overview of related work in Section 2. In Section 3, we present details of our system, followed by presenting and discussing examples in Section 4. We provide our conclusion and future work in Section 5.

2. RELATED WORK

2.1 The Ontological Knowledge Structure

Ontology is a conceptualization of domain knowledge which comprises concepts, properties and their relationships. A Problem Domain Ontology (PDO) enables solving a complex problem where the underlying domain concepts have high interdependencies with each other by building up a problem scenario based on concepts, properties and features defined in the Ontology[4].[5]

One of the research opportunities in our project is to represent the explicit knowledge presented by the DOT representatives and also capturing the implicit knowledge that bridge engineers gain from their experience and represent it in a machine-understandable form.

2.2 The Bridge Data

Briefly after the Silver Bridge collapsed into the Ohio River, that resulted in 46 death, in Dec. 15, 1967, the U.S. Department of Transportation(USDOT) was ordered to by congress to establish a regime for bridge inspection. The National Bridge Inspection Standards went into effect in 1971 but were limited to bridges on the federal highway system. In 1980, the inspection rules were extended to all public bridges more than 20 feet long.[2] Since then, regional DOTs across the U.S. are required to inspect bridges within their jurisdiction on a 24 month frequency. All their bridge reports and inspected data are collected by the Federal Highway Administration (FHWA) and stored in the National Bridge Inventory database (NBI). The NBI contains information on all bridges and tunnels in the United States that have roads passing above or below. It monitors nearly 600,000 bridges, including Interstate Highways, U.S. highways, State and county roads, as well as publicly-accessible bridges on Federal lands.

The NBI is developed as a unified database for bridges that includes the identification information, bridge types and specifications, operational conditions, and bridge data including geometric data, functional description, inspection data, etc. Identification information addresses the bridge location uniquely and classifies the type of the routes carried out on and/or under the structure and locates the bridge within the spatial location. Bridge type and specifications classify the type of the bridge. This part provides defined standard categories for classification of the bridges. It also identifies the material of the bridge components, deck and deck surface. Operational conditions provide information about the age of the structure as well as construction year, rehabilitation year, type of services and traffic carried over and/or under the structure number of the lanes over and/or under the bridges, average daily traffic, average daily truck traffic and information regarding to bypass, detours. Furthermore, the bridge inventory contains information regarding to inspection data, ratings assigned by engineers and appraisal results.

2.3 The Bridge Management Systems

Although several bridge management systems (BMSs) are built on this tremendous amount of data, bridge engineers are still facing difficulties in navigating through information and locating the ones that they need to pay attention to. In general, these BMSs are typically built using the spreadsheets approach. For example, the most widely adopted PONTIS[6] system uses an excel alike interface. To access the data, bridge managers need to follow the BMS's rules on data exploration. They may need to manually set filtering parameters just in order to access certain ranges of bridge assets information. In addition, using these BMSs, bridge engineers are limited in reviewing the correlations among those bridges, which could indicate the changes and patterns for the bridges that are useful to prioritize the maintenance tasks.

Therefore, to facilitate the bridge engineers decision making processes, we present our interactive visual analytics system that enables them to freely and efficiently explore their bridge data. In addition, by using advanced visualization tools, our system presents bridge engineers those implicit correlations among different bridges.

2.4 The Communication Model between visualization and knowledge structure

In our previous work,[7] we analyzed the functional relationship between visualization and ontological knowledge structure and present our communication model that could further integrate these two components together.[7] By examining visualization and the ontological knowledge structure separately, we found a complementary functional relationship between these two, as shown in the Venn diagram (Figure1(A)), in which orange and blue circles represent functions of visualization and ontological structure, respectively.

Both visualization and the ontological knowledge structure share the similar functions on selecting information, in the forms of visual data brushing and textual data queries respectively. At the same time, each of them has their own unique characteristics: visualization is good at supporting the exploratory reasoning process, while ontological knowledge structure focuses more on assisting the user in creating and storing concepts. A concept is a set of domain knowledge and procedures that has been or will be created by domain experts.

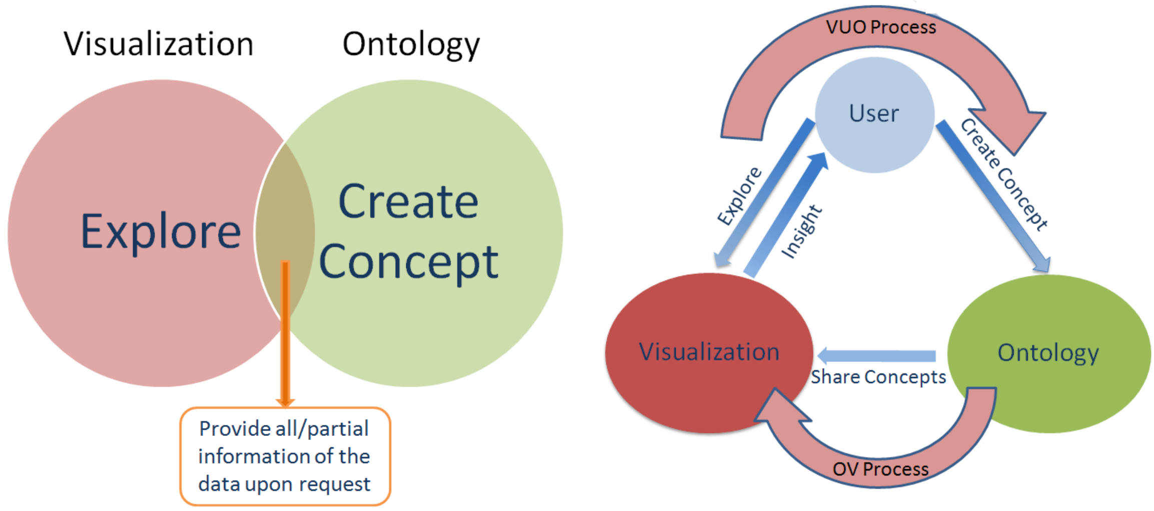

Figure 1. (A): The Venn Diagram between Ontology and Visualization; (B): The Communication Model

With the understanding of this complementary relationship, we derived a communication model that would integrate these two components. As shown in Figure1 (B), our communication model is consisted of three important parts: the user, the visualization and the ontological knowledge structure. Using a well-designed concept sharing mechanism, we establish connections among each component. Our communication model contains two major processes, the Visualization-to-User-to-Ontology (VUO) Process and the Ontology-to-Visualization (OV) Process. The VUO process is mainly used for the user to create concepts to the ontological knowledge structure, through interacting with visualization. In this process, the created concepts could either be based on a user's experience or the discoveries from visualization. The OV process is dedicated for the ontological knowledge structure to insert and share concepts with the visualization. This process would guide the visualization to represent more task-relevant information to the user.

Our communication model serves as the fundamental system design principle that leads us to build our knowledge integrated visual analytics system.

3. SYSTEM DESIGN

Based on the communication model,[7] we provide the bridge engineers a knowledge integrated visual analytics system that provides a comprehensive visual environment for them to investigate potential bridge safety issues and to make corresponding maintenance decisions. Shown in Figure 2, our system contains two major components, the visualization system that provides a highly interactive exploration environment; and the ontological knowledge structure that preserves and provides corresponding bridge inspections domain information. The integration of these two is not only flexible in nature for data exploration but also enables the creation and sharing domain information.

We are currently working with a subset of NBI data collected around Mecklenburg County, Charlotte, between year 2000 and 2006. This database contains 62 dimensions and several hundred incidents, most of which are linked with the original inspection reports. In addition to the original data, we collected extensive bridge information from varies sources, including high resolution fly-over imageries, remote sensing data, and 3D LIDAR data. By integrating these additional data, our system is capable of showing bridge managers comprehensive information about their bridge assets.

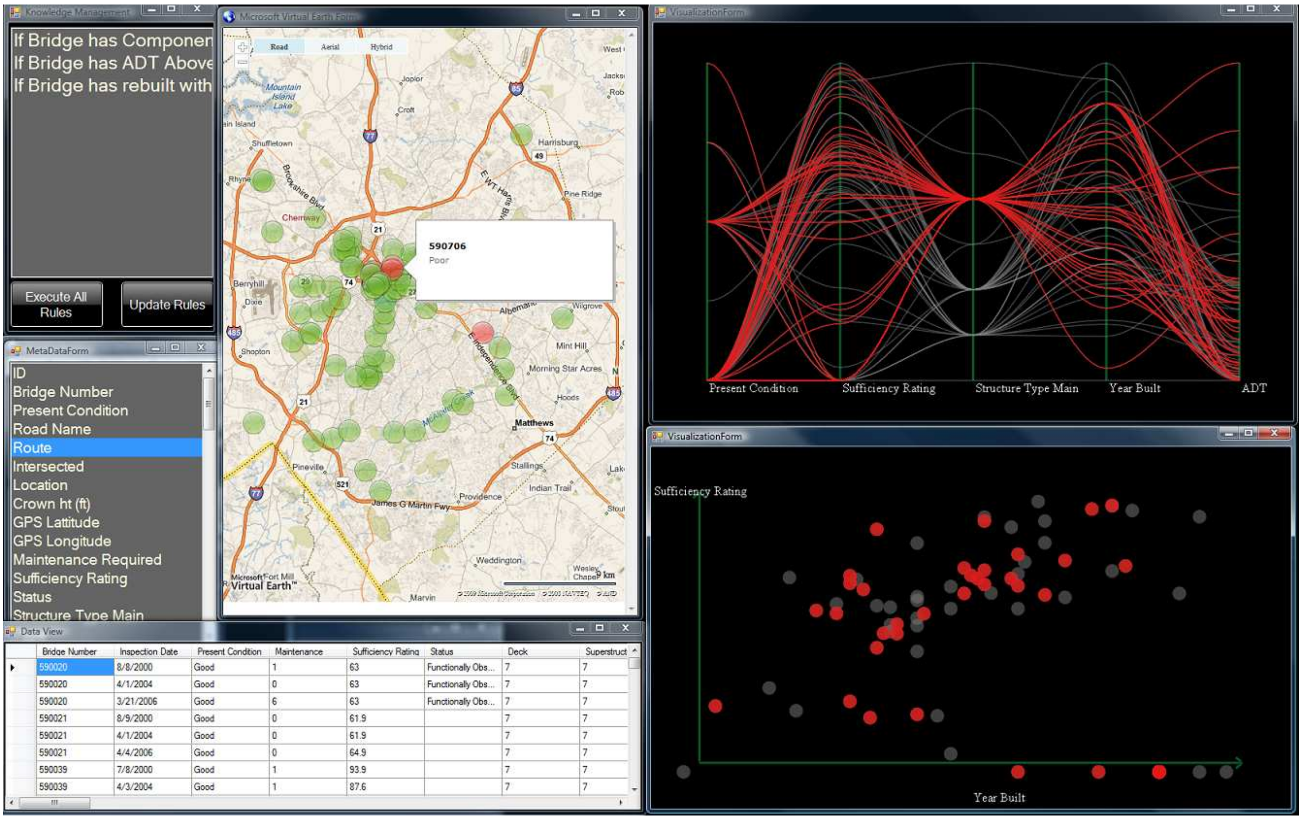

Figure 2. System Overview: (A) Upper Right: The Parallel Coordinate View; (B) Bottom Right: The Scatter Plot View; (C) Middle: The Microsoft Virtual Earth View (D) Upper Left: The Knowledge Information Panel

3.1 The Visualization Component

Based on our discussions with NCDOT, we designed our interactive visual analytics system, as shown in Figure 2 to assist bridge managers on depicting data from three aspects: Geospatial, Relational and Details bridge information. By utilizing each aspect, our system helps the bridge engineers to review their bridge assets from multiple view points.

Our system utilizes Microsoft Virtual Earth,[8] as shown in Figure 2(C), to support an interactive geospatial analysis. The Parallel Coordinate visualization[9](Figure 2(A)) and the Scatter Plot visualization(Figure 2(B)) are used to reveal relational information among bridges as well as identifying outliers. Lastly, the details view incorporates different data sources and provide bridge managers the analysis on a per-asset level. By coordinating these visualization views, our system could provide the bridge engineers with thorough understandings about their bridge assets, hence facilitating them to effectively make accurate maintenance decisions.

In order to allow engineers to freely explore bridge information and discover new trends and relationships, our system adopts a show-on-demand (SOD) multi-window approach that allow the user to generate visualization windows on-the-fly based on their selections of bridge attributes. All these SOD windows could help the users to gather and depict bridge information in a highly coordinated manner such that interaction with one of these windows immediately affects the views of other windows. This SOD multi-window approach is flexible in nature and allows engineers to inject knowledge of any information at any time. As more information is given to our system, the system reveals more precise trends and patterns, allowing engineers to reduce irrelevant information and focus on the desired incidents.

3.1.1 The Geospatial View

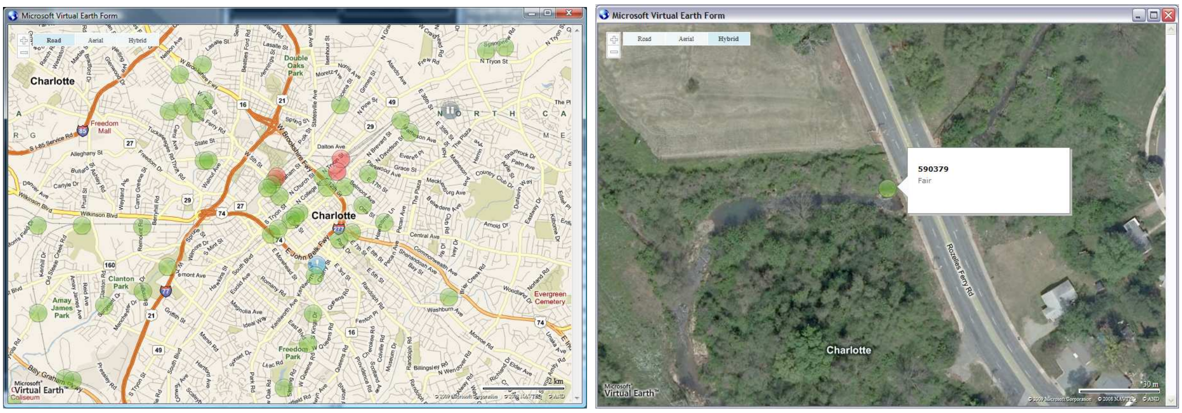

Figure 3. Left: (A) The Microsoft Virtual Earth View. Currently looking at the Downtown Charlotte Area. The Green Icons indicate bridges in good condition, while the Red icons indicate Poor condition Right: (B) The Detail views about a bridge over water

Our visualization system uses Microsoft Virtual Earth[8]to help bridge engineers in analyzing the geospatial aspect of their data. By placing the bridges on this interactive geospatial map, bridge engineers could efficiently select regions of their jurisdictions and examine the bridges within those regions. In addition, since all the bridges are categorized using different icons, bridge managers could easily see the distribution patterns. For example, as shown in the Figure 3(A), the bridge engineers could immediately see that near the downtown area of Charlotte, there are more bridges in poor conditions(Red icons) than other regions in Charlotte, most of which are in good condition(green icons).

3.1.2 The Relational View

Our system uses two types of advanced visualizations to help bridge engineers understand the relationships among their assets. The Parallel Coordinate visualization (PCV)[9] depicts correlations among different bridge attributes, and the scatter plot visualization (SPV) shows the relationships between bridges. In PCV(Figure 4(A)) , each curved line represents an individual bridge with their attributes mapped to the vertical axes; in the

SPV, the bridges are mapped to the dots and their distributions are based on their values on the two selected attributes.

Using these views, bridge managers could easily identify outliers as well as general trends. For example, in the SPV(Figure 4(B)) , the bridge managers could easily find which bridge is scored with the lowest sufficiency rating as well as what is the general pattern between the ”sufficiency rating” values and the years that the bridges were built.

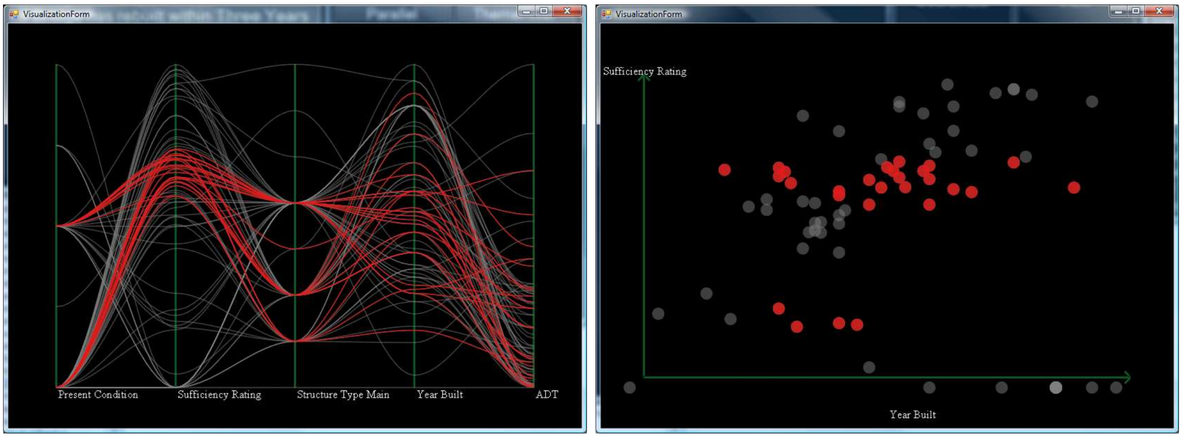

Figure 4. (A): The Parallel Coordinate View with several items highlighted in red; (B): The Scatter Plot View with several items highlighted

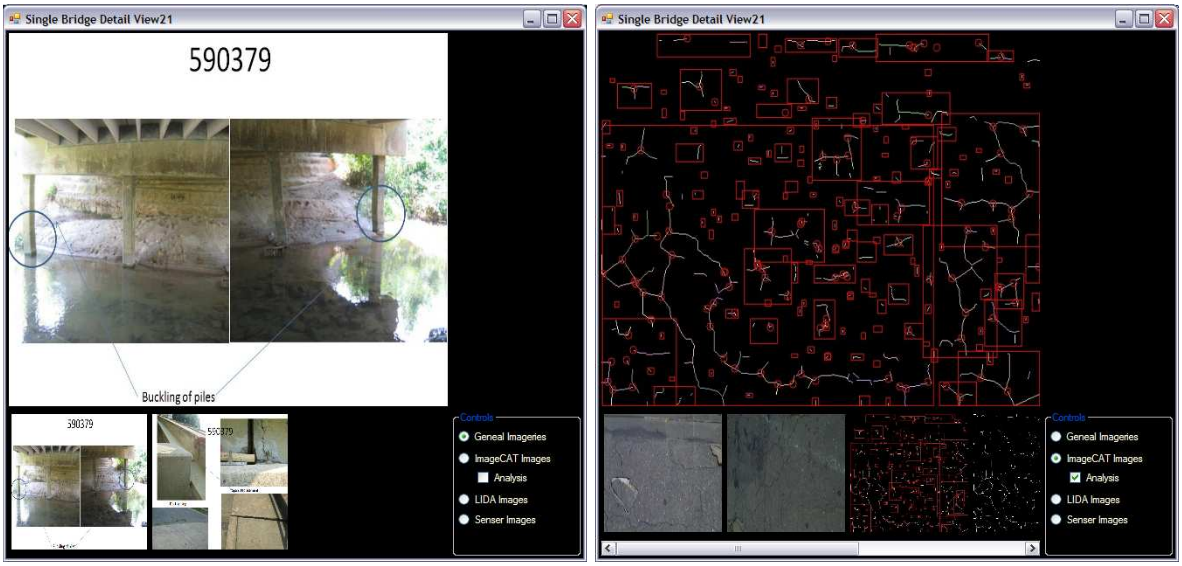

Figure 5. Left: (A)The Details collected from field inspection. We could easily see the supporting structure for this bridge is severely bent. Right: (B) The Analysis Results from ImageCAT Inc.[10]

3.1.3 The Details View

The Details view is designed to integrate all collected bridge data together and present bridge engineers a detailed drill-down view about their assets. For example, as shown in Figure6(B), the Details panel shows the field inspection results and individual cracks that have been detected and reported. In addition, with the extensive data source we collected, such as the results from pavement analysis tool ImageCAT[10](Figure 5(B)), the detail view could help the bridge engineers to analyze the bridge asset with external analysis tools. With all this information, it is easier for bridge engineers to interactively review each bridge and gain comprehensive understandings of their bridge assets, that could lead to making accurate maintenance decisions.

3.2 The Ontological Knowledge Component

Through repeated interactions with bridge engineers and other domain experts, it was determined that the domain of bridge inspection is based on a very complex body of knowledge with many internal interdependencies. To make the correct decision, a bridge engineer has to understand all the factors contributing to his/her decision making process. Given the vast number of variables involved, bridge engineer can be easily overwhelmed.

To solve this problem, we take an ontology-driven domain knowledge modeling approach[4].[11] The use of this goal-driven approach is to model the understanding process that underlies the semantics of data and the way the process is implemented in the proto-type system. The domain knowledge of bridge inspection process is captured and modeled by using the ontological engineering toolkit (GenOM). GenOM[?] provides functionalities to browse, access, query and reason about complex bridge inspection process. GenOM can also benefit bridge engineers by establishing rules inferred from the knowledge structure. Rules are statements in the form of an if-then (antecedent-consequent) sentence that describes the logical inferences that can be drawn from an assertion in a particular form. Rules can be formed by building a problem scenario based on the concepts, properties and features defined in the ontology, and then respond to the what-if inquires about the behavior of a system by matching various initial conditions and different circumstances with the rules in the domain model.

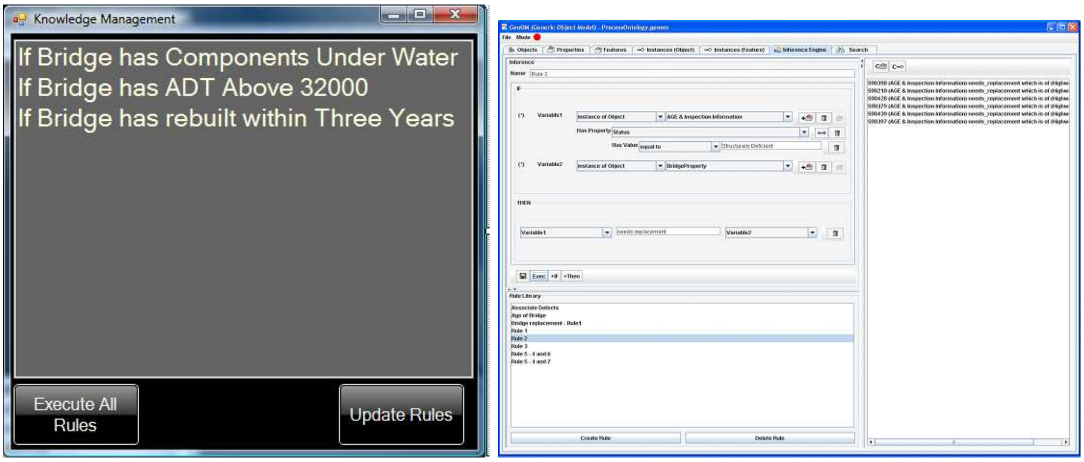

Figure 6. Left: (A)The Ontological Knowledge Interface. Currently showing three suggestions for bridge managers to follow; Right: (B) The GenOM Backend interface

3.3 Communicating Visualization with the Ontological Knowledge Structure

While visual components could assist engineers on exploring collected data, the aforementioned external ontological knowledge structure, on the other hand, could provide more specific concepts of bridges. We use the server-client approach to establish a strong communication with the ontological knowledge structure. The visualization component is the client that will request and pull information from the server side, through a web-service interface.

In the visualization system, we provide an interactive interface for the bridge engineers to access the ontology knowledge pools. The ontology provides the bridge engineers with the information that they may take into consideration during their decision making processes. For example, the ontology may suggest the bridge mangers to pay more attentions to bridges that have structures underwater for longer than 10 years, as shown in Figure 6. By selecting this suggestion, the bridge engineers would immediately see changes in the visualization views and therefore starts further investigate on those bridges for water corrosion.

By communicating information between the visualization component and the knowledge component, our system can now provide bridge engineers not only the ability to freely explore their preparatory data, but also to guide them through their decision making processes with standard procedures.

4. SCENARIO

In this section, a bridge engineer is trying to understand the distribution pattern of bridges that are built on top of any water. He starts the system by selecting the corresponding knowledge from the ontology knowledge interface. By doing so, the system will automatically retrieve information of all the bridges that are built over water and update this information in all the visualizations that the bridge engineer is currently viewing(the Geospatial view and Scatter Plot View). Immediately, the distribution pattern is shown to the bridge engineer. As shown in Figure 3(B), a bridge that is above water is highlighted as opaque icons.

From here, he begins to examine bridges with considerable low sufficiency ratings by filtering and selecting them on the Scatter Plot view and further bring up details views to understand the cause for those low ratings. As shown in the detail view (Figure 5(A)), the bridge manage could see that the supporting structure is severely bent and in bad condition. Finding this immediately draws his attention and could be used to determine future maintenance schedule.

5. DISCUSSIONS AND FUTURE WORK

Although visualization is really powerful in supporting user a highly interactive exploration environment, it is still quite opportunistic in finding the needed information and does not guarantee repeatable and reusable results. For example, certain outliers would only occur when other information has been chosen in the same visualization. This could lead to complex processes as bridge management in the sense that if a bridge engineer need to review or explain his maintenance decisions, he might not be able to regenerate the same working environment. The ontological knowledge structure on the other hand, is great at storing reasoning elements and enabling user to reuse those elements to achieve similar results. These two become very complementary when applied together to real-world applications.

Therefore, a complex process such as a bridge management cannot solely rely on one of these two methods. We propose to integrate the visualization and knowledge structure to facilitate comprehensive decision making processes. Although there are much to be researched on, for example, how and what should be the best way to automatically improve or construct part of the ontological knowledge structure is still unclear, we are confident that integrating these two have already enabled the users to perform better on such processes.

At present, our system is still in a developing stage, where we are trying to carefully implement and integrate all the proposed components together. Currently, although the system can provide engineers reasoning paths and certain results, the aforementioned knowledge capture component is not ready yet. Therefore, one of our next steps is to provide a comprehensive knowledge capture interface that would help users to insert and improve the ontological knowledge structure.

In addition, our current system lacks a formal verification and validation component to authenticate user created knowledge. Such a component is important in the sense that it could lower the risk of knowledge duplication and confliction, and to reduce the chance of false knowledge insertion. With further discussion with ontology experts, we will try to build and integrate this component into the system.

6. CONCLUSION

In this paper, we provide a novel knowledge integrated visual analytics system that provides high efficiency in bridge management. Utilizing visualization and an ontological knowledge structure, our system enables bridge engineers to effectively examine their preparatory data and facilitate their decision making processes.

We further use a scenario to show how our system could help bridge engineers to effectively discover information and make accurate maintenance decisions. We conclude our paper by discussing the possible improvements for our system and how to extend our collaborative work.

ACKNOWLEDGMENTS

This project is supported by grant number DTOS59-07-H-0005 from the United States Department of Transportation (USDOT), Research and Innovative Technology Administration (RITA). The views, opinions, findings and conclusions reflected in this presentation or publication are the responsibility of the authors or presenters only and do not represent the official policy or position of the USDOT, RITA, or any State or other entity. The authors also would like to acknowledge the guidance and contributions of Mr. Caesar Singh, the Program Manager at USDOT; and the technical assistance of Dr. Moy Biswas of the North Carolina DOT (NCDOT), Mr. Garland Haywoord of NCDOT Division 10, and Mr. Jimmy Rhyne of Charlotte DOT.

REFERENCES

[1] Dedman, B., "Bridge collapse revealed holes in federal data," (2008).

[2] Administration, F. H., *Bridge Inspectors Reference Manual* (2006).

[3] Research and Administration, I. T., "http://www.rita.dot.gov," (2009).

[4] Lee, S. W. and Yavagal, D., "Genom user's guide v2.0," Tech. Rep. TR-NiSE-05-05, UNC Charlotte (2005).

[5] Lee S. W., M. D. and Gandhi, R., "Building decision support problem domain ontology from natural language requirements for software assurance," in [*International Journal on Software Engineering and Knowledge Engineering, Vol. 16, No.6*], 1–34, World Scientific (December 2006).

[6] AASHTO, "http://aashtoware.org/," (2009).

[7] Xiaoyu Wang, Wenwen Dou, S.-W. L. W. R. R. C., "Integrating visual analysis with ontological knowledge structure," tech. rep. (2008).

[8] Corporation, M., "Mircrosoft virtual earth http://www.microsoft.com/virtualearth/," (2009).

[9] Inselberg, A., "The plane with parallel coordinates," *The Visual Computer* **1**, 69–91 (Aug. 1985).

[10] ImageCat, I., "http://www.imagecatinc.com," (2009).

[11] Lee S. W., R.A. Gandhi, W. S. and Murty, A., "r-analytica: Requirements analytics for certification & accreditation," in [*In the Proc. of the 15th IEEE Int. Requirements Engg. Conf. (RE 07)Posters, Demos and Exhibits Session*], (October 2007).