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Towards Sustainable Infrastructure Management: Knowledge-based Service-oriented Computing Framework for Visual Analytics

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ABSTRACT

Infrastructure management (and its associated processes) is complex to understand, perform and thus, hard to make efficient and effective informed decisions. The management involves a multi-faceted operation that requires the most robust data fusion, visualization and decision making. In order to protect and build sustainable critical assets, we present our on-going multi-disciplinary large-scale project that establishes the *Integrated Remote Sensing and Visualization (IRSV)* system with a focus on supporting bridge structure inspection and management. This project involves specific expertise from civil engineers, computer scientists, geographers, and real-world practitioners from industry, local and federal government agencies.

IRSV is being designed to accommodate the essential needs from the following aspects: 1) Better understanding and enforcement of complex inspection process that can bridge the gap between evidence gathering and decision making through the implementation of ontological knowledge engineering system; 2) Aggregation, representation and fusion of complex multi-layered heterogeneous data (i.e. infrared imaging, aerial photos and ground-mounted LIDAR etc.) with domain application knowledge to support machine understandable recommendation system; 3) Robust visualization techniques with large-scale analytical and interactive visualizations that support users' decision making; and 4) Integration of these needs through the flexible Service-oriented Architecture (SOA) framework to compose and provide services on-demand.

IRSV is expected to serve as a management and data visualization tool for construction deliverable assurance and infrastructure monitoring both periodically (annually, monthly, even daily if needed) as well as after extreme events.

Keywords: Infrastructure Management, Remote Sensing, Visual Analytics, Ontological Engineering, Service-oriented Architecture

1. INTRODUCTION

Critical infrastructure management and its associated inspection processes, to assure the protection of assets, include tremendous amount of efforts due to the complexity in making decisions. A normal inspection process for a specific domain would only involve checking for limited attributes e.g. for the domain as a normal bridge

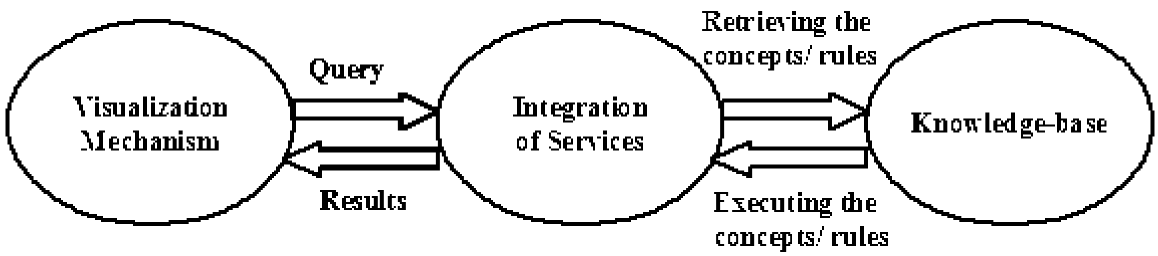


Figure 1. Framework of IRSV for Bridge Management System

inspection only corrosion, age-related cracking or structural analysis are checked. However, there are large number of attributes in a domain, that need to be considered by the human experts for making complex decisions in a limited time period, with limited resources, and under different administrative policies.

In this paper, the domain is bridge management systems which requires complex transportation infrastructure asset management and construction monitoring. For this purpose, the Commercial Remote Sensing - System Integration (CRS-SI) is used by Department of Transportation (DoT) as the current application. The goal of the project is to extend the current application via the development of a platform that allows validation of CRS-SI data. This will enhance current procedures of our public partners from the State and City DoT.

The DoT evaluates its assets on a periodic basis, and based on the results of this evaluation process, decides if a particular asset requires additional attention in terms of maintenance, repair or replacement. This evaluation process is specific for every asset. Bridges are one such asset, and the process for evaluation of their physical condition is called the Bridge Inspection Process (BIP). It is performed by the bridge inspectors who have gone through the experience and training and have developed a deep understanding of the way bridges behave when exposed to various environmental and man-made stresses, and the kind of damage they sustain in the process. The scope of a BIP also encompasses the process of assessment of damage and allocation of funds to minimize damage to the structural integrity of the asset in the future.

The fact that the bridge inspection process is guided by the inspector makes the outcome of the process subjective, as every expert has his own take on the domain of bridge inspection. It also becomes very tedious and difficult for the bridge inspectors to make an informed decision because of the large volumes of bridge inspection data involved and the lack of tools to visualize and analyze this data.

Therefore, it is essential to develop a computing framework called as *Integrated Remote Sensing and Visualization* (IRSV), that can support the human experts by providing knowledge assisted tools with following benefits:

- **Knowledge-base:** Captures explicit definition of languages reflected in the process, and the relationships among the attributes and their semantic understanding in different level of abstractions. It creates and promotes common understanding among different subject matter experts and uniform way of processing complex processes.
- **Integration of services**: Provides necessary ways of presenting and collecting evidences of data from various types of large database that includes reports, images, analysis results, and the human interactions. The service framework is flexible and scalable to the changes of the process; and its definition and implementation.
- **Visualization mechanism:** Enables human experts to explore and discover meaningful and useful knowledge through various kinds of visualization algorithms and toolkits.

Figure 1 shows the interaction between the knowledge-base and visualization mechanism through service oriented architecture. An IRSV system is built upon an ontological knowledge representation system that interfaces to Geographical Information System (GIS)-based platform, existing CRS-SI technologies, satellite imaging, visual inspection guidelines and large-scale data visualization. The system will also provide real-time structural information, structural loss estimation, and post-event damage assessment through the visual analytical interfaces. It aims to provide the right information at the right time to the bridge inspectors to help them make the most informed decision regarding bridge maintenance/repair.

2. OUR APPROACH: INTEGRATED REMOTE SENSING AND VISUALIZATION

Our approach will enable flexible and scalable integration by using a Service-Oriented Architecture (SOA) framework[1,2,3] which promotes the encapsulation of individual software solution functionality as "system services". A repository of these services will be exposed to other system components through a service interface, which will function as a cohesive and coordinated point of integration for all system services.

Another important aspect of this approach is the ability to map business requirements to individual system services, also referred to as process composition. Business requirements can be met by sequences of activities that describe business processes. Incorporating business process representations into the problem domain ontology[4,5] will enable the IRSV system to respond more effectively to business requirements, e.g., inspection requirements and activities.

The primary objective of this project is to use of the SOA paradigm and an ontological engineering approach to build the prototype IRSV system that combines the various bridge inspection data and domain knowledge based on the frame-based knowledge representation and a goal-driven modeling technique. Using the SOA paradigm and an ontological engineering approach, the IRSV system will provide a common platform for heterogeneous system components to share bridge data and knowledge under a base framework that will be flexible, scalable and adaptable.

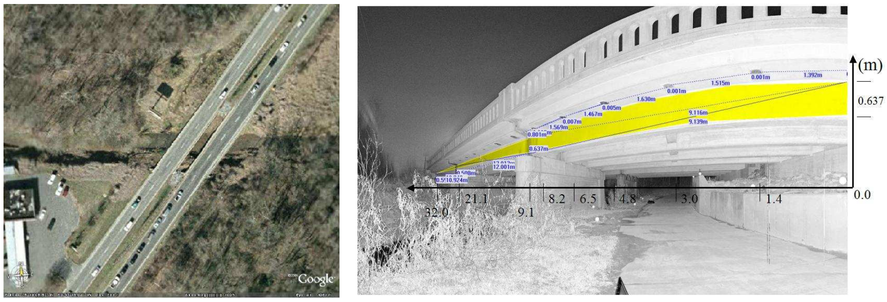
2.1 A real-world scenario

The Bridge Inspection Process for a bridge begins with Bridge Inspectors reviewing the previous Bridge Inspection Reports for the bridge and planning its inspection and evaluation.

Figure 2 describes the scenario for bridge number 590147. According to the inspection record of year 2006, Bridge 590147 is in Fair condition and the sufficiency rating is low. This is an aged bridge which was built in 1938 and carrying 21000 traffic per day (according to 2004 statistics) on the route US 29. Although not classified as structural deficient bridge, the bridge structure has been found many problems like abutment cap erosion, guardrail cracking, spalling at girder end and so on. Based on this initial analysis, bridge inspectors issues a prompt action report, forcing NCDoT to act on the findings of the visual inspection. The inspection report and other relevant data collected from the bridge site were to be used as a proof to justify any future course of action with regards to issuing orders to repair this bridge. NCDoT personnel, to confirm the findings of the visual inspection visits the inspection site to note down the recommendation and verbal measurement of the damage detected.

Figure 2(b) shows the LIDAR scans of the affected areas of the substructure for damage detection and defect reasoning purpose. Satellite images were procured to determine if the excessive growth of vegetation, stress and traffic impacts of the bridge were influential in contributing to the damage defect which is shown in Figure 2(a). Satellite data can be used to quantify the impacts of the initial disruption on local economics and businesses, as well as its continued impact on the region during the recovery period.

Based on all relevant visual and analytical data (location, highway system, Sufficiency rating, status, type of superstructure, structure length, etc) obtained from data sources such as Bridge Maintenance Units, Inspection Reports, National Bridge Inventory, etc, NCDoT personnel have to determine if damage to the bridge warrants immediate attention and repairs. If this is the case, then the extent of the damage and cost of repairs have to be determined, which might even include measures to limit the influence of vegetation and the stress and traffic impacts on the structural integrity of the bridge. Due to the current condition of the bridge and the recommendations, it needs to be replaced or rehabilitated and it is already on the state 2006-2012 TIP (Transportation Improvement Program) list.



(a) Satellite Image (b) LIDAR Image

Figure 2. Bridge 590147

By introducing Ontology-based Semantic Matching, IRSV will enable bridge inspectors to correlate data from previous Inspection Reports and deduce patterns, if any, in this data. For example, the Domain Knowledge Representation will help bridge inspectors in establishing relationships between the characteristics of a bridge (sufficiency ratings, year of build, condition, etc) over a period of time for which inspection reports exist. These relations will highlight any and all damage the bridge might have suffered over a period of time and the cumulative effect of this damage on the structural integrity of the bridge. Also with the help of knowledge structure, the bridge inspectors will have the capability of establishing rules inferred from ontology. With the help of this example we can follow the similar pattern to determine the number of bridges which fall under these factors.

With the help of knowledge structure, we can correlate such defects shown in the scenario and further determine other bridges which are affected due to these defects. There are nearly more than 200 bridges in North Carolina and sometimes it is difficult for bridge inspectors to keep the track of all the bridges that needs attention. Also the process shown in the scenario tends to be very time consuming for all the bridges in states to be inspected regularly. Therefore, IRSV will benefit from the rules inferred from the knowledge structure that will infer all the bridges based on the defects like abutment cap erosion, guardrail cracking, sufficiency deficient and spalling at girder end. In conclusion, as described in the scenario, we can follow the similar pattern to determine the number of bridges which can fall under these factors. By generating this pattern based approach with the help of knowledge structure, bridge inspectors will benefit with the list of bridges that also needs to be replaced or rehabilitated. Also with the help of LIDAR and satellite images and rating analysis by AMPIS and civil engineers, knowledge structure can help bridge inspectors in making decision by associating the defects with the particular bridge. Further with the help of service oriented architecture framework (described more in detail in section 2.3), knowledge structure will be passed as services to the visualization module to leverage the results in the form of visual analytics.

2.2 Ontological representation of the process

One of the challenging research issues in this project is to gather various types of "evidences" that support the decision making in the bridge inspection process. The evidences can be textual documents, photo images, sensor images, or geospatial notations etc. Through repeated interactions with bridge inspectors and other domain experts, it was determined that the domain of bridge inspection is based on a very complex body of knowledge which has many internal interdependencies among each other. In order to make the correct decision, a bridge inspector has to understand all the factors contributing to his/her decision making process, and given the vast number of variables involved, bridge inspector can be easily overwhelmed. In addition to the bridge inspection guidelines, bridge inspectors' experience and intensive training were valuable resources. Therefore, it was imperative to capture the inherent knowledge collected by bridge inspectors in their line of work during the domain modeling phase.

DoT databases contain a large multitude of heterogeneous data with complex correlations. To effectively process this data, it is necessary to represent it in a machine understandable and processable form. This can be accomplished using the concept of meta-knowledge to represent the semantics of this large data repository. But meta-knowledge representation in a database is complex and not efficient when compared to a standard database schema used to store information.[6] To solve this knowledge representation problem, we take an ontology-driven

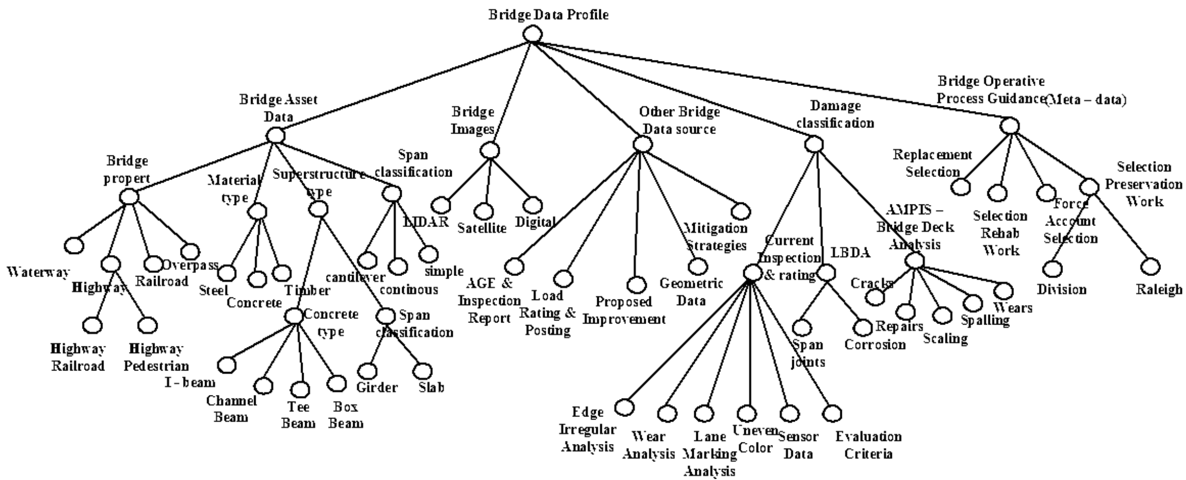


Figure 3. Ontological Knowledge Structure for Bridge Management

domain knowledge modeling approach.[7,8] 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. Ontology is a conceptualization of domain knowledge which comprises concepts, properties and their relationships. A Problem Domain Ontology (PDO) enables to solve 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[4,7] After collection of domain information pertaining to the bridge inspection process as well as the knowledge from the domain experts from the State and City DoT, this domain knowledge is represented by ontology-driven domain knowledge modeling approach. We have used Generic Object Modeling (GenOM) toolkit[9] to capture, represent and model this domain knowledge. GenOM provides functionalities to browse, access, query and reason about complex bridge inspection process. Figure 3 represents the knowledge structure of bridge management.

2.3 Service-oriented architecture and knowledge service

The current software development process employed in realizing the IRSV system has multiple research teams working on independent software solutions which include heterogeneous data, operational and functional requirements. For the IRSV system to effectively leverage the needs and functionalities of each software solution, it is very important to build a system architecture that facilitates the interoperability among different software systems, and provide a scalable and adaptable solution to challenging systems integration.

We have adopted SOA paradigm to support bridge inspection process by developing a system based on a knowledge-based approach that provides a scalable and adaptable platform support solution for all system components to share the common knowledge and rules to promote the common understanding among the stakeholders. This architecture would comprise of business services each of which is an aggregation of relevant functionalities of each of the individual software solutions.

Using the SOA paradigm and an ontological engineering framework, the IRSV system will provide a common platform to integrate heterogeneous system components to share bridge data and domain knowledge. For example, one of the modules in the IRSV system is the Visualization (VIS) module which requires knowledge service, a composite of the object, properties and instances from GenOM, the ontology engine. The ontology adapter provides very specific functionality of interfacing with and extracting knowledge from external data structures/sources.

A knowledge service was developed to expose the functionality or the composition of specific functionalities of individual software component as a service. This knowledge service is responsible for representing domain knowledge in a machine understandable manner. The frame-based knowledge representation enables to create meta-knowledge from various types of data such as the sensor data, inspection data, images, geo-spatial data. A knowledge service provides not only the access to relevant set of data but also the help to understand the nature and correlations among the data set.

The purpose of this knowledge service is to provide a mechanism to other component modules in the IRSV system to infer knowledge from these data sources, which in this case are the ontology and databases, without having to understand the underlying intricacies of the data structures in which they are stored.

For a knowledge service to be truly effective, it has to not only talk in an acceptable language, but also interpret and answer requests for knowledge from other tools in a transparent way. In other words, other modules do not have to understand the ontology to request information from it. The process of transforming the request for knowledge to a query that can be run on the ontology to request information has to be seamless and transparent. Thus the knowledge services encompass methods calls and underlying logic to perform this transformation to map a request to the actual data in the ontology.

The knowledge service provides information regarding three different areas of the inspection process:

1. The sensor data collected for every bridge
2. Inspection data accumulated for every bridge
3. Information pertaining to bridge inspection processes

Because the ontology encompasses knowledge from different aspects of the bridge inspection domain, the knowledge service comprises of system services that have been composed to query different parts of the ontology. For example, the ontology contains knowledge about types of defects that can possibly affect a bridge. Bridge defect knowledge is a part of the ontology that could be leveraged by bridge inspectors in analyzing bridge inspection related artifacts and to make recommendations for repair/replacement. Exposing this part of the ontology as a service would hence provide a channel to expose vital bridge defect information to other parts of the tool that might need it. To use the bridge defect service, any tools or module within the IRSV system can subscribe to this service, and use one of its provided methods.

As shown in Figure 4, each system service in the knowledge module has a set of functions. Some of these functions are used to test connectivity and availability of service. These functions are essential since we do not support dynamic service discovery in the current version of the IRSV prototype.

In Figure 4, the database adapters are designed to query a database with a set of parameters that can be translated into a SQL query. The ontology adapter is more complicated in their functionality and design. This complexity comes from the fact that web service communications by default do not support complex user defined data types.

To provide a scalable and adaptable platform support solution for all other system components to share the common knowledge and the common understanding, we have developed and host a web service shown in Figure 4. The basic approach of service oriented architecture is to:

1. Support the interoperability, scalability and adaptability to facilitate heterogeneous data requirements, operational requirements and the overlapping functionalities
2. Compose meaningful set of services that support other system components needs.
3. Knowledge services can mediate between the various system components and the process services.

By hosting a web service in the knowledge module, other modules can access the services and share the common knowledge and common understanding. With the help of SOA concept, one of the modules of IRSV system, visualization module can successfully invoke the list of rules implemented based on knowledge structure and execute those rules in the platform of visual analytics engine.

We implemented a server which is composed of various services and those services are invoked by the client using IRSV prototype user interface. On the server side where the services are implemented, each service contains the business logic that invoked the object, property, features or rules from the GenOM. After the services are

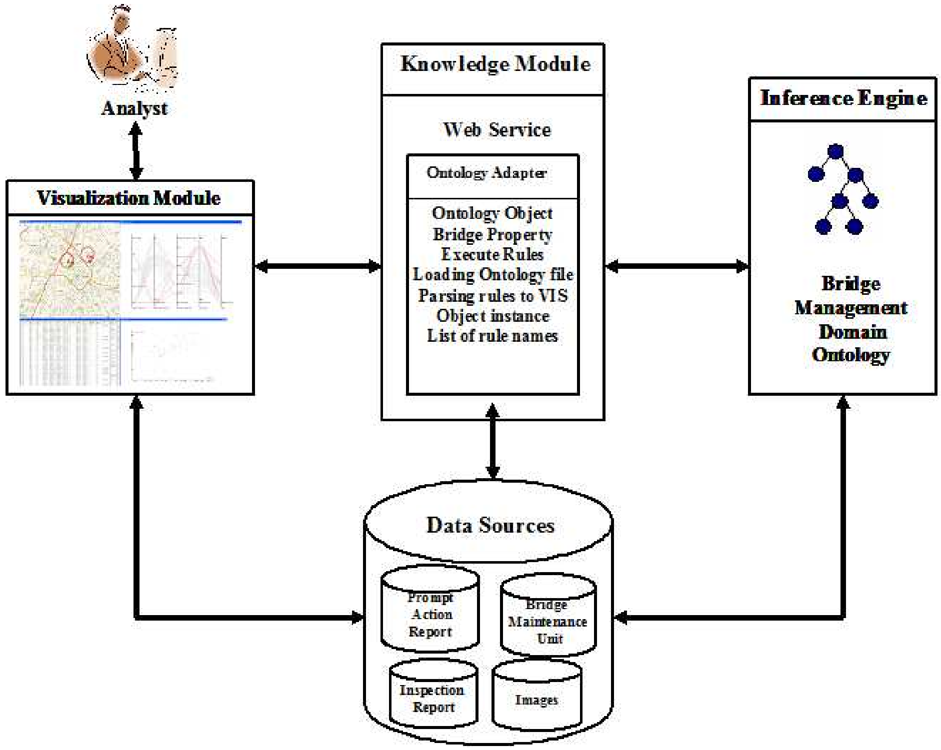


Figure 4. Communication Channel among Data Sources, Knowledge Module, and Visualization Module in IRSV

created the WSDL file is generated on the server. With the help of WSDL file, we can establish the connection between the server and the client. On the client end, the java class serviceConnector is implemented where the methods are used to invoke the relevant services from the server and then finally displayed on the user interface with the help of java component.

Following are the brief description of each service implemented.

- **Ontology Object Service**

  getOntology: Object Service defines the concept or object created in the bridge management knowledge structure through GenOM. This service enables the consumer to retrieve objects from GenOM file. By using this web service the consumer/client can invoke objects from the Ontology/Knowledge structure of the GenOM file.

- **Bridge Property Service**

  getBridgePropertyNames: This service enables the consumer/client to invoke properties from GenOM file. With the help of this service we can retrieve properties associated with a particular object from GenOM file. For example, this service can be used if the consumer wants to view the properties of "Bridge Asset Data".

- **Execute Rules Service**

  executeRules: This service allows the user to view the instances of a specific rule that is being selected. In the service, a Rule name is passed by the client as a parameter to the service provider (Ontology/Knowledge structure of GenOM). The service provider then looks up that rule in the GenOM file and returns its instances to the consumer (IRSV Prototype). For instance, when the client passes a rule named "Age of Bridge" as a parameter to the web service via the executeRule service, all the instances of that particular rule is displayed to the consumer.

- **Loading Ontology file Service**

  getOntologyfile: This service reads the Ontology file and loads the GenOM model into memory. The Ontology file resides in the local machine of the server. With the help of this service, the consumer is able to fetch the contents of this file. For example, the list of objects, properties, instances and rules can retrieved from the Ontology file once it has been loaded.

- **Parsing Rules to VIS Service**

  RulesVIS: This service passes rules to the Visualization module in order to let them view the details of bridges they are exactly looking for. The service that is being offered here by the service provider is to let the consumer view all the rules available in Ontology/Knowledge Structure.

- **Object Instance Service**

  getGenInstances: This service fetches the instances of a specified object from the GenOM file. The service provider (GenOM file) presents the instances of the object to the client. For instance, if the consumer wants to view the instances of an object named "Material Type", the service "getGenInstances" will provide the consumer with all the instances associated with the object "Material Type".

- **List of rule names Service**

  ListOfRules: This service lists all the Rules available in the GenOM file. The service being offered here by the Ontology/Knowledge structure is of providing the Visualization module with the list of existing rules from the GenOM file.

2.4 Knowledge-based Visual Analytics

The main goal of Visual Analytics[10] is to explore and analyze the bridges of interest from different perspectives.

- The visualization system solves the scalability issue by helping bridge inspectors to see an overview of hundreds to thousands of bridges in one view.
- It is also capable to link all other systems (e.g. Database, Remote Sensing Data and AMPIS) together to provide one tightly integrated tool for the inspectors.

The Figure 5 describes various resources that are related to the use of visual analytics in problem solving activities. For example, the knowledge structure in GenOM ontology correlates the defects from the remote sensing data and with the help of GenOM inference engine, a set of rules are created. Those rules are then passed onto as a service to the visual analytics engine and they are being used to explore the trends and pattern among the bridges that are inferred in the data. More specifically, the parallel coordinate view indicates outliers that are hard to identify through spreadsheets. This view acts like, for example, the MS Windows' window management that allows users to coordinate between views. The data is not only viewed in the parallel coordinate form but also displays the rule inference engine results in the form of scatter plot view. This view shows the data distribution, correlations and indicates trends and possible outliers. Since there could be hundreds of bridges in an urban area, the geo-spatial view enables the inspectors to investigate multiple bridges at the same time. By showing the output of the rule inference engine in geo-spatial view could significantly restrict the number of bridge icons displayed and also show the ones most meaningful to the user for the given task.

3. RELATED WORK

Hansen system[11] is a commercial bridge management system that stores inspection data and information about DoT assets. It delivers descriptive reports based on a subset of attributes (using crystal reports). It contains Operator and inventory ratings of individual bridges and it can be integrated into a Work Management System. It shows the repair history of each DoT asset (history of work orders and money spent on that particular asset). However, it does not support images nor PDF files; also does not contain any analytical components to support the users to perform in their analysis.

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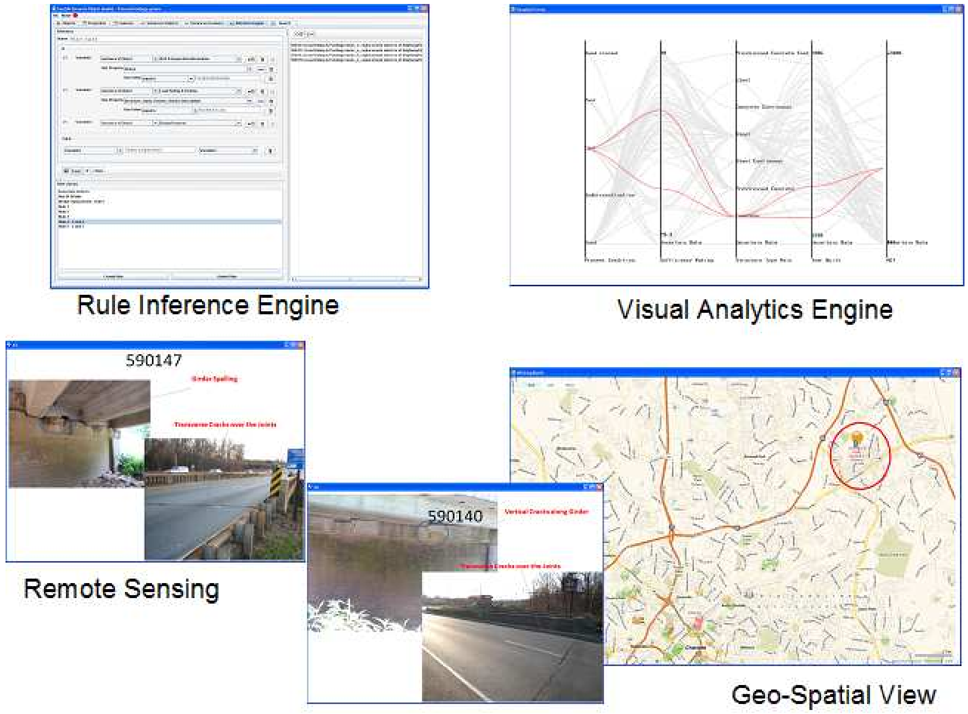

Figure 5. Knowledge assisted Visual Analytics

PONTIS[12] is a windows-based bridge management system with functionality for recording bridge inventory and inspection data, developing an optimal preservation policy, simulating conditions and generating work candidates and developing a bridge program. PONTIS is defined as the representation of a bridge as a set of structural elements and recommendation of an optimal preservation policy. Extensive functionality for program simulation is to recommend preservation and improvements, considers agency and user costs and predicts a broad range of performance measures, with the support from the Federal Highway Administration (FHWA) National Bridge Inventory (NBI) Translator. Like the Hansen system, PONTIS is also in lack of analytical components in their system that can support the users' analysis tasks.

4. CONCLUSION AND FUTURE WORK

In this paper, an integrated framework to support infrastructure management and a proto-type system called IRSV have been presented. IRSV system benefits from captured process knowledge and assessment knowledge for enhanced bridge evaluation. It provides responses to "what-if" queries from system behaviors through matching various initial conditions and circumstances based on rules in domain model. With the help of knowledge structure we can capture important knowledge and make it available for other modules. The integration framework provides an opportunity to build a system that can scale and adapt to incorporate evolving processes and technologies and in addition service framework can mediate between various system components, knowledge and process services and can provide right information at the right time

As a future work, we plan to add the following more advanced technologies to the existing proto-type.

- Automated reasoning engine for categorizing, classifying and recommending integrated data resources for more effective and efficient support to the decision making process.
- Enhance the rule engine results by further preprocessing on it with the help of meaningful algorithm, in case of ambiguity in the results.
- Automate the generation of rules by implementing Data mining techniques

We will also work with the subject matter experts to evaluate our project on how efficient and effective the use of the system with the usability study.

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