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INTEGRATED REMOTE SENSING AND VISUALIZATION (IRSV) SYSTEM FOR TRANSPORTATION INFRASTRUCTURE OPERATIONS AND MANAGEMENT

-PHASE ONE-

VOLUME 4

Use of Knowledge Integrated Visual Analytics System in Supporting Bridge Management

By

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16. Abstract

The goals of integration should be: “Supporting domain oriented data analysis through the use of knowledge augmented visual analytics system.” In this project, we focus on:

- Providing interactive data exploration for bridge managements.
- Supporting domain oriented data analysis, including geospatial analysis, temporal analysis and structural analysis.
- Enabling knowledge creation and storage through the use of interactive visual analytics system;

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Executive Summary

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4.1. Introduction

Bridges are an important component of the U.S. transportation system, and maintaining their structural integrity is crucial to the safety of millions of people. However, bridges deteriorate over the course of their designed life cycles. The steel corrodes, the concrete spalls, and the stone cracks. Without proper maintenance, these deteriorations may cause severe damages that might lead to potential catastrophes.

In theory, bridge engineers can predict the service life of bridges based on computing each bridge's deterioration rate and establish a suitable maintenance plan (Demetrios et al. 2006). However, since the presumed service conditions of a bridge may change, the bridge's deterioration rate often varies from its theoretical expectations. In practice, it has been observed that deterioration rates of similar bridges can vary significantly due to their local weather environments, traffic patterns, etc (Demetrios et al. 2006). Therefore, to ensure the integrity of a bridge and to prevent severe deteriorations, it is very important to establish regular inspections and to provide necessary bridge maintenances (Brinckerhoff et al. 2003 and Moore et al. 2001).

Given the importance of bridges, one would hope that most bridges are maintained in a timely manner. However, according to the 2009 American Society of Civil Engineers report, currently more than 26 percent of the nation's 599,766 bridges are either structurally deficient or functionally obsolete (ACSE 2009). Furthermore, given the limited budget and other resources, not all of the bridges can be maintained immediately. In order to utilize the limited budget and resource effectively, most bridge managers develop their own strategies to prioritize and determine the order in which bridges should be maintained.

While these strategies have largely balanced the limited resources with the upkeep of bridges across the country, the collapse of the I-35 Bridge in Minneapolis during August 2007 serves as a devastating reminder that the complexity of bridge management still demands novel techniques and proper tools to interpret and understand bridge data. Therefore, soon after the tragedy, members of our university formed a research partnership with the USDOT, the North Carolina State Department of Transportation (NCDOT), and the American Association of State Highway and Transportation Officials (AASHTO) to investigate novel approaches in assisting the bridge management process.

One of our first actions under this research partnership was to conduct a nation-wide survey (Corey (2008)) to understand the usage of current BMSs and to identify potential areas of improvement. 35 out of 50 state DOTs responded to our survey, and the result indicates that the current bridge management systems are often insufficient in supporting bridge analysis. As reported by several state DOTs, the current BMSs are very efficient at data storage, but they are not as effective in providing efficient data explorations and analysis. In addition, some state DOTs further indicated that these BMSs are rigid in structure and cannot be easily adapted to support individual bridge manager's routines.

Based on their feedback, we identified three types of bridge analyses that are often essential in bridge manager's decision-making process, namely, structural analysis, temporal analysis and geospatial analysis. While the use of these three analysis processes and their usage patterns may vary in each bridge manager's workflow, we have found these analysis steps to be necessary for bridge managers to analyze the bridge data, understand the severity of deteriorations, and to make further maintenance decisions.

Using these three analysis processes as foundation, we designed and developed an interactive, exploratory visual analytics system for analyzing bridge data. Our system encodes the three processes as a group of four coordinated visualizations and allows the bridge manager to choose different combinations of visualizations and to customize them to fit into their own analysis workflow. Our system is designed to assist bridge managers in depicting three essential analytical facets: Geospatial, Temporal, and Structural Analysis. For each facet, our system utilizes different types of interactive visualization views to represent the corresponding information. Instead of fixing the content for each view, our system also allows bridge managers to interactively select data dimensions and create appropriate views on the fly. Our system will then automatically coordinate these views and present the bridge managers a highly interactive visual data exploration environment.

In addition, our system incorporates an ontological knowledge structure to preserve and provide bridge inspection information. Our system presents user an interactive interface to access to the pre-defined inference rules. Through the use and integration of these rules with visualizations, we provide bridge managers a cohesive exploration and examination environment to perform in-depth bridge managements.

To evaluate the system, we conducted expert evaluations with bridge managers from NCDOT and found that most managers believed our system to be useful and complimentary to their existing analysis processes. We further identified ways in which our system could be quickly incorporated into their daily routines.

4.1.1 Bridge domain characterization

Before the 1960s, there was no nation-wide bridge safety inspection and maintenance regulation in the US. Bridge safety issues, although previously discussed and researched among state and local government agencies responsible for bridges, first attracted a broad public interest after the collapse of the Silver Bridge at Point Pleasant, West Virginia (46 people were killed) in 1967 (Brinckerhoff 1993). In 1968, a national bridge inspection standard was required to be established by action taken by the U.S. Congress. Bridge inspection authorization was added to the “Federal Highway Act of 1968” (FHWA 2002). The National Bridge Inventory (NBI) system was reauthorized in the “Federal Highway Act of 1970” as the basis for funding for the Special Bridge Replacement Program (SBRP) (Czepiel 1995).

Briefly after the Silver Bridge collapsed into the Ohio River, that resulted in 46 deaths, 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. 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.

In 1971, the Federal Highway Administration (FHWA) Bridge Inspector's Training Manual, the American Association of State Highway Officials (AASHO) Manual for Maintenance Inspection of Bridges, and the FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges were developed to form the National Bridge Inspection Standards (NBIS). It is the minimum standard for the inspection of the nation's highway bridges

Bridge maintenance workflow is a process of deciding the severity, trending, relevance, and benefits of maintenance work on a specific bridge as well as a network of bridges. According to AASHTO's asset management guidelines (AASHTO 2003), the first step in this process is to gather relevant data about a particular bridge, including its known damages, previous maintenance histories, and typical deterioration patterns. Bridge managers will then start analyzing the obtained information, identifying the needs for maintenance and coming up with proper maintenance plans.

4.1.2 Bridge Maintenance Process

According to bridge managers from NCDOT, it is common for a bridge manager to be responsible for hundreds of bridges. Since federal guideline dictates that bridges are inspected on a biennially basis, approximately 50% of the bridges are inspected in a given year. However, in that same year, only a portion of the bridges, approximately 20% - 25%, would require any maintenance attention. Even fewer bridges (around 10%) may actually receive maintenance work. Given the complexity of these inspection results, compounded with external constraints on budget and resources, a bridge manager needs to have complete understanding of all bridges under his jurisdiction when making maintenance decisions.

It is therefore necessary to have a BMS that monitors and analyzes the conditions of bridges in a way that allows a bridge manager to maintain an overview of all bridges and yet retain the capability to inspect detailed information of a particular bridge. Currently, there are a few available BMSs, such as Pontis (Robert 2003) and BRIDGIT (Hawk 1998) that promise analytical capabilities. However, there exist many limitations and issues with these BMSs (some of which will be described in detail in the following section), many bridge managers, including a few from NCDOT, still rely on using simple spreadsheets such as Microsoft Excel to perform their analyses.

4.1.3 Visualization System in Transportation

US and state DOTs have had a long history of adopting visualizations. As summarized in a recent survey by R.G. Hughes (Hughes 2008), transportation visualizations can be generally categorized into two groups: (1) 3D visualizations that support design simulation and planning and (2) geographic information visualization that helps with data analysis and managing.

There is an extensive literature devoted to the use of visualization to support transportation simulation and planning. For example, both VISSIM (Visual Solution Inc. 2008 and CORSIM (University of Florida 2006) are widely used to visualize traffic simulations and microscopic traffic controls. In addition, 3D visualizations have been adopted to depict transportation designs and maintenance processes, such as NC3D (Newland Company 2009), a 3D visualization tool for designing high-speed railroads.

The field of geospatial visualization is a well-established area of research, especially in the field of Geographical Information Systems (GIS). Commercial GIS systems have also been developed to specifically help depict transportation data, such as GeoTrAMS (Intergraph Corp 2005), which is designed to manage train and rail assets, and TransCAD which focus on road management.

4.1.4 Visual Analytics System

On the other hand, the use of visualization to perform data analysis and management is still in a preliminary stage. Although some simulation-based highway management systems have been developed by Plainsant et al. 1998, the main thread in this research focuses on depicting and extending knowledge from the geospatial nature of transportation information. Geospatial visualization is a well-established area of research, especially in the field of Geographical Information Systems (GIS). Examples of such systems include GeoVista by Takatsuka et al. (2002) and GeoTime by Kapler et al. (2004). Additionally, commercialized GIS systems have been developed to specifically help depicting transportation data, such as GeoTrAMS (Intergraph Corp 2005), which is specifically designed to manage the train transit and rail assets, and TransCAD (Capliper Corp. 2009), which focuses on road management. To our best knowledge, the only system intended to manage transportation data from both geospatial and multi-variable aspects was developed by Wongsuphssawat et al. (2009) to perform data analysis of federal highway incidents.

Given the complexity of bridge data, only depicting from the geospatial point of view would sometimes limit a bridge manager's understanding. Our system, however, presents this data using not only geospatial and multi-variable aspects, but also supports analysis of temporal trends.

4.1.5 Data Used in Current Project

The following two tables contain data we used in developing our visual analytics system:

Table 4.1. AMBIS Project Test Case Bridges, Mecklenburg County, NC

Bridge Number	Owner	Status (Assessed by DOTs)	NBIS Sufficiency Rating	Condition (Assessed by DOTs)	Bridge Type
590179	NCDOT	Fair	72.3	*	Concrete
590255	CDOT	Fair	77.7	Obsolete	Steel
590140	NCDOT	Fair	77.5	Obsolete	RC Girder
590147	NCDOT	Fair	47.5	Deficient	RC Girder
590084	NCDOT	Poor	82.1	Obsolete	PCC Cored Slab
590239	NCDOT	Fair	78.2	*	Steel
590059	NCDOT	Poor	11.8	Deficient	Steel Plank
590161	NCDOT	Fair	63.7	Obsolete	Steel
590165	NCDOT	Poor	48.2	Deficient	Steel
590177	NCDOT	Fair	29.1	Deficient	Steel
590296	NCDOT	Fair	94.7	*	Prestressed Concrete
590376	CDOT	Fair	84.83	Deficient	Steel
590379	CDOT	Fair	29.3	Deficient	Prestressed Concrete
590511	NCDOT	Good	80.4	*	RC Deck
590512	NCDOT	Good	80.4	*	RC Deck
590038	NCDOT	Fair	30.4	Deficient	RC Deck
590049	NCDOT	Fair	48.4	Deficient	RC Deck
590108	NCDOT	Fair	100	Deficient	RC Deck
590176	NCDOT	Fair	70.3	Obsolete	RC Deck
590700	CDOT	Poor		RR Bridge	Steel
590702	CDOT	Good		RR Bridge	Steel

590704	CDOT	Fair		RR Bridge	Concrete
640024	NCDOT	Poor	30.1	Deficient	Concrete

***** Note: Bridges not showing condition are described as neither Deficient nor Obsolete

Table 4.2 Calculation and Comparison of Various Sufficiency Ratings for Test Case Bridges

Bridge Number	NBIS Sufficiency Rating (Calculated by DOTs)	BSCI Aerial Photo Rating (Deck Rating)	AMBIS Rating (Deck Rating)	LiDAR Damage Rating (Structure)	Average between BSCI and AMBIS (Deck)	IRSV Sufficiency Rating (Avg. of Deck and Structure)
590179	72.3	99.0	45.7	62.2	72.8	67.5
590255	77.7	47.5	96.9	57.8	72.2	65.0
590140	77.5	91.0	99.1	90.0	95.1	92.6
590147	47.5	99.0	99.1	55.9	99.0	77.45
590084	82.1	99.0	98.2	-	-	
590239	78.2	78.9	86.6	-	-	
590059	11.8	-	-	-	-	
590161	63.7	26.2	56.9	-	-	
590165	48.2	48.7	88.1	-	-	
590177	29.1	38.9	65.6	-	-	
590296	94.7	-	-	-	-	
590376	84.83					
590379	29.3	62.0	82.8	-	-	

590511	80.4	93.4	-	-	-	
590512	80.4	97.9	-	-	-	
590038	30.4	76.0	56.3	-	-	
590049	48.4	49.2	77.6	-	-	
590108	100	77.5	85.1	-	-	
590176	70.3	-	98.7	-	-	
590700	Poor	-	RR Bridge	-	-	
590702	Good	-	RR Bridge	78.2	78.2	
590704	Fair	-	RR Bridge	56.1	56.1	
640024	Poor	30.1	Wilmington	38.8	38.8	

These initial IRSV calculations (for three bridges) are conducted based on the following:

1) Image analysis rating of bridge decks is the average of BSCI and AMBIS ratings;
2) IRSV Sufficiency Rating is calculated by averaging superstructure LiDAR ratings and with average # 1 - BSCI and AMBIS;
3) Actual IRSV Sufficiency Rating should include reliability and environmental factors, however, currently we are using equal weights (1.0) for the three factors that make up the IRSV Sufficiency Ratings.

4.2 Background and Literature Review

4.2.1 Introduction

Current federal bridge inspection procedure, developed about 30 years ago, is largely based on visual inspection and does not include remote sensing data (NCDOT 2005, AASHTO 2005). AASHTO bridge management software, PONTIS, does not include commercial remote sensing-spatial information (CRS-SI) capabilities.

As a result, a common platform is necessary to extend CRS-SI output into a data management system that is compatible with existing bridge management practices. The motive for the platform is to validate CRS-SI technology applications to bridge asset management. The platform should address bridge managers' need to overcome the difficult challenge of making sense of vast collections of heterogeneous bridge management data. Current bridge management tools fail to situate these analyses properly and support the interactive exploration of these data efficiently. The result is bridge maintenance decisions that are too localized and, thus, sub-optimal from both an economic perspective and, more importantly, a public safety perspective.

4.2.2 Overview of Visual Analytics techniques

The visual analytics system, designed collaboratively with inputs from municipal, state, and federal department of transportation representatives, leverages leading edge interactive visualizations supported by a knowledge repository of heterogeneous bridge data accessed via a service- oriented architecture to place bridge maintenance analyses in better context. While interactive visualizations alone can support the exploration of bridge maintenance data, knowledge is required to place such explorations in proper context. Knowledge has been described as the ability to distinguish concepts or ideas (Locke 1690). In other words, knowledge emerges from an understanding of the relationships among concepts. Given this description, analyzing or making sense of a phenomenon can be described, in part, as the process of discovering and understanding these connections. Klein et al.. (2006) appeared to emphasize this point in describing the activity of sense making as "a motivated, continuous effort to understand connections … in order to anticipate their trajectories and act effectively." In a very similar sense, bridge managers when analyzing bridge maintenance data must understand the relationships and rules (i.e., the connections) among the data. In the IRSV system, the knowledge helps to facilitate this essential activity by supporting the specification of concepts, objects, properties, relationships, and rules.

4.2.3 The Definition of Knowledge

To develop four knowledge conversion processes in knowledge-integrated visualization (Chen et al.. 2009), we must first know what knowledge is. In the knowledge management literature, it has been established that distinguishing between data, information, and knowledge is important to designing knowledge management programs (Jurisica 2005). Work by Syed and Shah (2006) reviews various definitions and explanations of the DIKW (data, information, knowledge, wisdom) hierarchy and focuses on presenting a model that explicates the relationship between data, information, and knowledge. In Syed and Shah's model, knowledge is defined as the range of one's information. However, Davenport and Prusak (1998) state that ``knowledge derives from information as information derives from data" and further define knowledge as ``a fluid mix of framed experience, contextual information, values and expert insight that provides a framework for evaluating and incorporating new experiences and information." In Davenport and Prusak's perspective, knowledge is the refined information in which human cognition has added value. In other words, information becomes knowledge through cognitive effort.

Nonaka and Takeuchi (1995) adopt Polanyi (1983) 's definition of tacit and explicit knowledge to understand how knowledge is shaped and how knowledge can be applied. In their definition, explicit knowledge can be processed by a computer, transmitted electronically, or stored in a database. On the other hand, tacit knowledge is personal and specialized and can only be extracted by human. We extend Nonaka and Takeuchi's concept on knowledge conversion modes and apply them to visualization. We believe that through the use of interactive visualization tools, analysts can experience the interaction between tacit and explicit knowledge. To further delineate tacit and explicit knowledge in knowledge-assisted visualizations, we propose that:

- Explicit knowledge is different from data or information.
- Tacit knowledge can only result from human cognitive processing (reasoning).
- Explicit knowledge exists in data, and is independent from the user or his tacit knowledge.
- Explicit and tacit knowledge are related and can be connected through the use of interactive visualization tools.

Explicit knowledge, extracted from data or information, is represented as a visualization, which is received both perceptually and cognitively by the user via an image. The cognitive processing leads to an understanding and an increase of user tacit knowledge which recursively affects subsequent perception and cognition. Tacit knowledge guides the user's interaction and exploration so that the visualization changes over time.

4.2.4 General Introduction to Ontological Knowledge Structure.

The ontological knowledge structure is a conceptualization of domain knowledge, which includes concepts, properties and their relationships. This conceptualization process aims to transfer both human tacit knowledge and explicit knowledge into computer- understandable formats. These concepts can be further utilized to facilitate other users' problem-solving processes. More specifically, a problem domain ontology (PDO) enables solving a complex problem where the underlying domain concepts have high interdependencies by building up a problem scenario based on concepts, properties and features in the ontological knowledge structure.

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.

4.2.5 Goal of Integrating Visual Analytics System with Ontological Knowledge Structure

The Integration, in current approach is to integrate between the Visual Analytic and Ontology components intends to provide sufficient synergy such that the users can use the visual knowledge to learn about the ontology required for data management and decision making process.

4.3 Theoretical Approaches in Integrating Visual Analytics System and Ontological Knowledge Structures

4.3.1 Introduction

Much research has focused on designing and developing different forms of such databases that could represent domain knowledge. The differences between these databases are not only reflected in their capacities, but also in their structural complexities. As shown in work by Garg et al.. (2008), a knowledge base could be as simple as a textual structure that contains inductive logic programming equations. On the other hand, the knowledge could also be described using extensive decision models, such as Markov decision process (MDP) in the artificial intelligence field. In our example, we choose to apply an ontology system for storing and retrieving domain specific knowledge.

The ontological knowledge structure is a conceptualization of domain knowledge, which includes concepts, properties and their relationships. This conceptualization process aims to transfer both human tacit knowledge and explicit knowledge into computer- understandable formats. These concepts can be further utilized to facilitate other users' problem-solving processes. More specifically, a problem domain ontology (PDO) enables solving a complex problem where the underlying domain concepts have high interdependencies by building up a problem scenario based on concepts, properties and features in the ontological knowledge structure

Although researches on ontological knowledge structure have advanced in the recent years, integrating such structure with a visual analytics system is still an open research area. In the following subsections, we first describe our understanding about how to integrate these two components, and further present our prototype of a knowledge-assisted visual analytics system.

4.3.2 A relationship between visualization and ontological knowledge structure

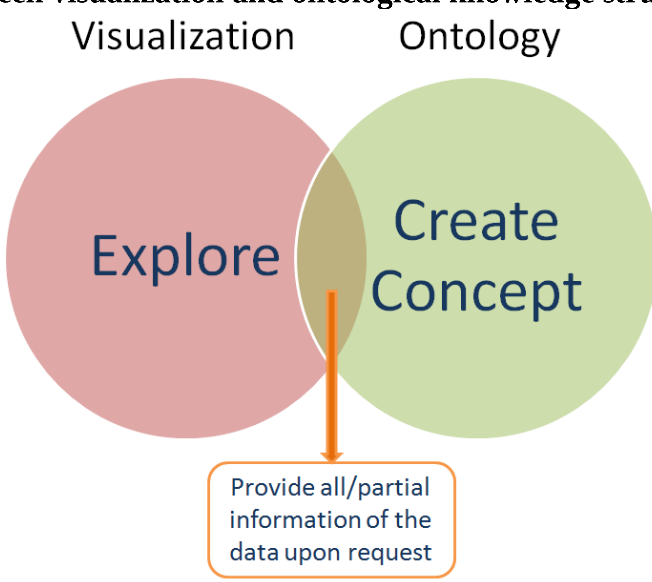

Figure 4.1 A relationship between visualization and ontology

While there is no definitive guideline on how to integrate visual analytics with ontological knowledge structure, we hypothesize that the integration of these two approaches could form a useful knowledge-assisted visual analytics environment. In order to have a better understanding of why this integration is meaningful and feasible, we examine visual analytics and ontological knowledge structure separately for their capabilities and strengths.

While visual analytics usually allows the user to interactively explore patterns of the underlying data from various perspectives, the ontological knowledge structure focuses more on representing the conceptualization of domain knowledge and the interdependencies among the concepts. Although through distinctive approaches, both visual analytics and ontological knowledge structure help the user to understand and discover different aspects of knowledge.

If these different approaches could be reasonably integrated, we expect that users could discover new concepts and knowledge through exploring the visualization and externalize such knowledge into the ontological knowledge structure for future references. We also want users to directly access the knowledge structure to acquire predefined domain concepts and rules to guide them through visual explorations and assist their decision-making processes

One important work that need to be recognized here is the knowledge-assisted visualization model proposed by Chen et al.. (2009). While both Chen's model and our extended van Wijk model are fundamentally the same in structure and goal, our model differentiates knowledge into tacit and explicit forms. Since our focus is trying to distinguish and identify the four knowledge conversion processes in a visual analytics environment, we choose to express them based on extending the van Wijk's model, which shows a clear interrelationship among user, visualization and data.

4.3.3 Knowledge Conversion Processes in Knowledge-assisted Visualization

Based on the proposed definitions of tacit and explicit knowledge, we provide four knowledge conversion processes in knowledge-assisted visualization: internalization, collaboration, externalization, and combination. These four knowledge conversions are first introduced by Nonaka and Takeuchi (1995), in which they focus on how knowledge can be processed and converted from one to another in business models. For knowledge-assisted visualizations, we propose that the four processes are also applicable because the functions of an analyst in perceptually and cognitively understanding represented information to create concrete knowledge using a visualization is similar to that of analysts in business practices. Here we present the four conversion processes as applied to visualizations.

4.3.3.1 Internalization

In psychology, internalization is defined as the process of accepting the established set of norms, which are influential to the individual (Meissner 1981). It is regarded as a cognitive process of acquiring skill and knowledge. In knowledge-assisted visualization, we propose that visually representing explicit knowledge would support analysts in understanding and transforming the explicit knowledge into tacit (internal) knowledge. As proposed by Nonaka and Takeuchi (1995) the internalization process starts with a user discovering what the explicit knowledge is, followed by a series of steps in understanding why the explicit knowledge is of value or why it makes sense, until finally the user accepts the knowledge as their own viewpoint or internal knowledge (Fig. 4-2). From a visualization perspective, this process parallels the concept of ‘‘insight discovery’’ that has been noted as the goal of visualization (Chang et al.. 2009). Since discovering insight is strongly related to building a user's tacit knowledge based on explicit knowledge in the data, the internalization process can be thought of as the primary goal and process of using a traditional (not knowledge- assisted) visualization.

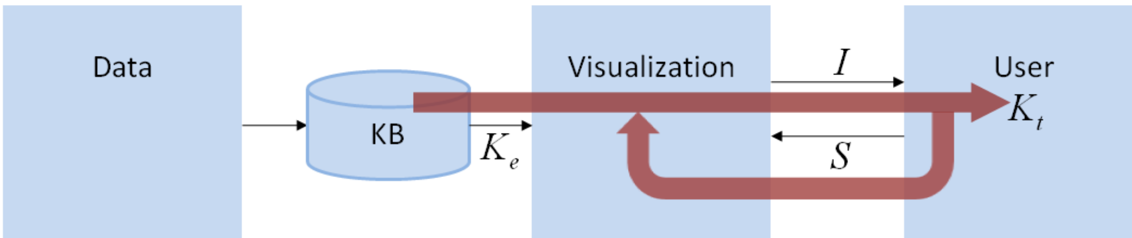

Figure 4.2 Internalization process (indicated by the red arrows).

Figure 4.2 explains that the user continuously builds tacit (internal) knowledge based on perceptually, cognitively, and interactively incorporating the represented explicit knowledge in a knowledge-assisted visualization. (For interpretation of the references to the color in this figure legend, the reader is referred to the web version of this article.)

4.3.3.2 Externalization

Externalization is the process of articulating tacit knowledge into explicit concepts (Nonaka and Takeuchi 1995). It is a generic knowledge creation process through which tacit knowledge becomes explicit based on the user's finding (insights), concepts, hypotheses, and models. Since tacit knowledge cannot easily be shared with others as a result of simply being written down, it should be converted to explicit knowledge by an externalization process beforehand to communicate and share with others.

In the visualization community, there have been a few applications that specifically focus on the externalization of one's tacit knowledge. Garg et al.. (2008) presented a model-driven approach to extract logic programming (LP) rules through a user's interactions and reused the rules in further analysis processes. Xiao et al.. (2006) studied how the knowledge-base could be used to improve understanding of complex network traffic data. They found that about 80% of network traffic could be classified correctly based on previously extracted experts' knowledge-base. Chen et al.. (2009) showed an example in which the user's insights can be externalized into a knowledge base. These applications have shown that not only is externalization in a visualization possible, it is in fact a very powerful method for storing and reusing knowledge.

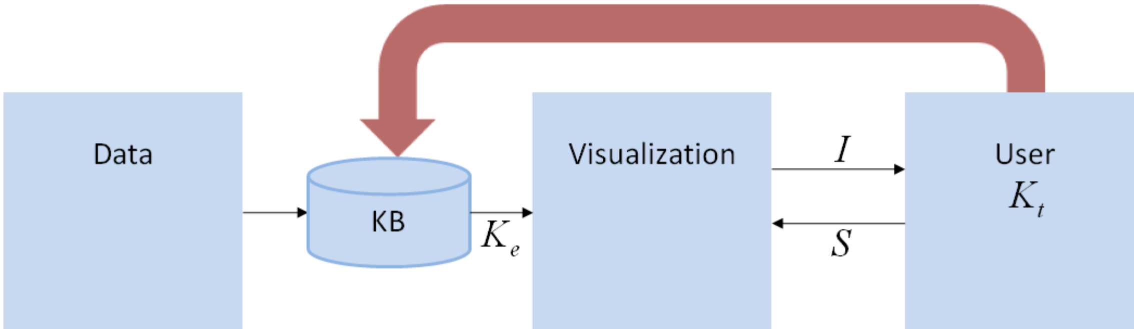

Figure 4.3 Externalization process (indicated by the red arrows).

Figure 4.3 shows how tacit knowledge can be externalized into explicit knowledge. In this figure, explicit knowledge is stored in a knowledge base and used to assist the creations of visual representations. Because of the complex nature of explicit knowledge, Nonaka and Takeuchi (1995) suggest that externalization is the process of concept creation and is triggered by dialogue or collective reflection. They further explain that the concept creation process can be expressed by applying analytical and non- analytical methods alike. The analytical methods are deduction and induction through which appropriate concept can be deduced and induced based on unorganized concepts. However, if applying analytical methods is not feasible, non-analytical methods such as metaphors and/or analogies could also be used. In visualization, we propose that both analytical and non-analytical methods should be considered for expressing explicit knowledge that can in turn be stored into a knowledge base (Garg et al.. 2008 and Xiao et al.. 2006).

4.3.3.3 Collaboration

Collaboration is the process of sharing tacit knowledge between people. In the knowledge management literature, it is defined as socialization (Nonaka and Takeuchi 1995). Although both collaboration and socialization represent learning from others, we use the term collaboration because it is commonly used in computer science and has a history of implying sharing knowledge, learning, and building consensus through the use of computers. In visualization, building collaborative visualization environments also has a long history (Coleman 1996 and Johnson 1998) defined that collaborative visualization is a subset of computer-supported cooperative work (CSCW) in which control over parameters or a product of the scientific visualization process is shared. Prior to that, Coleman et al.. 1996 provided generalizable reasons why collaborative visualization is compelling: (1) experts' knowledge could be available any time and at any place. (2) The expertize is transferred to others, improving the local level of knowledge. (3) Based on the supported accessibility, visualization products can be reviewed and modified as they are produced, reducing turn-around time. (4) Remote accessibility also helps to avoid relocating the expertise physically. More recently, Burkhard (2004) proposed a collaboration process of transferring knowledge between at least two persons or group of persons. Similarly, Ma et al.. (2007) noted that sharing visualization resources would provide the eventual support for a collaborative workspace. He discussed existing web-based collaborative workspaces in terms of sharing high-performance visualization facilities and visualizations and findings. He also showed several existing collaborative workspaces such as Tera-Grid (Binns et al.. 2007), Many Eyes (IBM 2009), etc. (see Ma et al.. 2007 for detail).

Fig. 4.4 shows how two visualization users could collaborate and share their tacit knowledge with each other. In this diagram, we show that the collaboration process can occur through the use of collaborated visual environments. However, the most natural method for sharing knowledge is still direct communication between the users (via phone, email, instant messages, etc.). In either case, the users are actively sharing their discoveries and tacit knowledge and incorporating each other's domain expertise into their own.

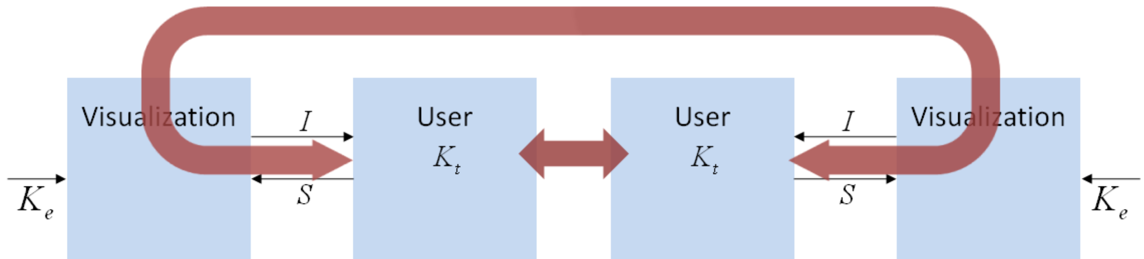

Figure 4.4 Collaboration process (indicated by the red arrows). Collaboration is a process of sharing tacit knowledge through the use of a visualization or through direct communication. (For interpretation of the references to the color in this figure legend, the reader is referred to the web version of this article.)

4.3.3.4 Combination

Combination is the process of systemizing explicit concepts into an explicit knowledge system Nonaka and Takeuchi 1995). Since explicit knowledge exists everywhere in books, research papers, and communication networks (user groups), etc., the process of combining different bodies of explicit knowledge is important. For instance, genomic data have been used in many different research areas: biology, bioinformatics, computer science (including visualization), health and medical science, etc., and depending on the domain, researchers have derived different, yet equally important findings. In order to fully comprehend the knowledge associated with such genomic data, it is necessary to combine findings from different domains and integrate them into a cohesive set of explicit knowledge.

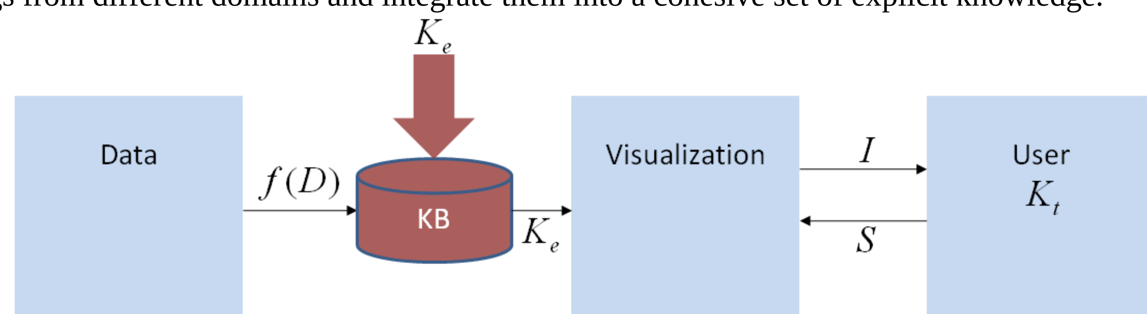

Figure 4.5 Combination process (indicated by the red arrow).

Figure 4.5 shows a simple model of combining explicit knowledge into an existing knowledge-base. Behind this simple diagram, however, additional considerations need to be addressed in order to maintain the quality and integrity of the knowledge-base when combining new explicit knowledge with an existing source. If unrelated or incorrect knowledge is combined with the existing explicit knowledge, it could degrade the overall trustworthiness of the knowledge-base as well as the benefits of representing knowledge in a visualization. While we are not aware of any known visualizations that support the verification and validation process when combining explicit knowledge, in the knowledge engineering literature, researchers have long been studying how to verify and validate underlying knowledge when developing a knowledge-based system (Tsai 1999). The specifics of knowledge management and engineering is outside the scope of this section, but will be discussed further in the future work section.

4.3.4 Applying Ontological Knowledge Structure to Visualization through Knowledge Conversion Processes.

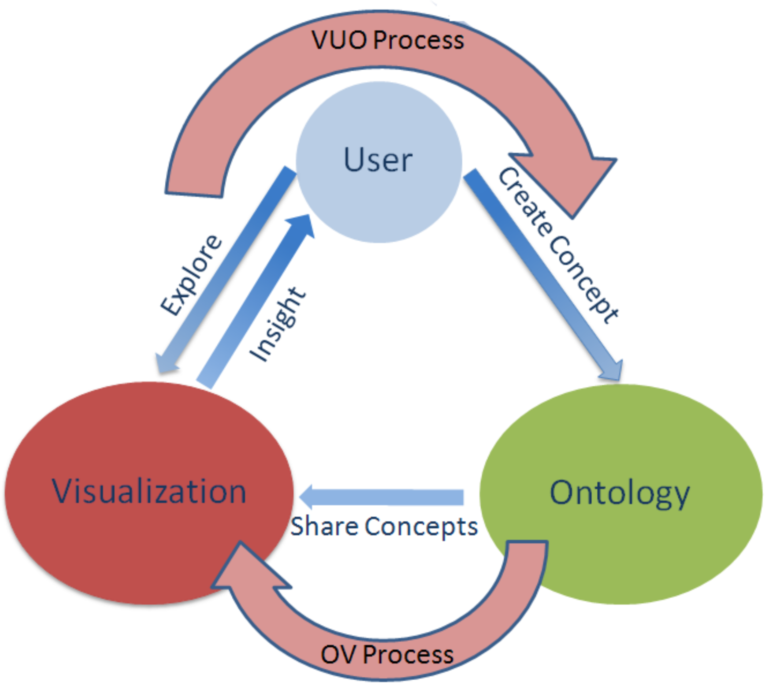

Figure 4.6 A correlation model between visualization and ontological knowledge structure

As shown in Fig. 4.6, a well-designed knowledge base plays an important role in supporting the knowledge internalization, externalization, collaboration, and combination processes. We believe that in order to design a useful visual analytics system that incorporates knowledge, a tightly integrated and well-designed knowledge base is essential.

There is, however, no definitive way to construct a knowledge base. Much research has focused on designing and developing different forms of such databases that could represent domain knowledge. The differences between these database are not only reflected in their capacities, but also in their structural complexities. As shown in work by Garg et al.. 2008, a knowledge base could be as simple as a textual structure that contains inductive logic programming equations. On the other hand, it could also be described by extensive decision models, such as Markov decision process (MDP) in the artificial intelligence field. In our example, we choose to apply an ontology for storing and retrieving domain specific knowledge.

The ontological knowledge structure is a conceptualization of domain knowledge, which includes concepts, properties and their relationships. This conceptualization process aims to transfer both human tacit knowledge and explicit knowledge into computer- understandable formats. These concepts can be further utilized to facilitate other users' problem-solving processes. More specifically, a problem domain ontology (PDO) enables solving a complex problem where the underlying domain concepts have high interdependencies by building up a problem scenario based on concepts, properties and features in the ontological knowledge structure.

Although researches on ontological knowledge structure have advanced in the recent years, integrating such structure with a visual analytics system is still an open research area. In the following subsections, we first describe our understanding about how to integrate these two components, and further present our prototype of a knowledge-assisted visual analytics system

4.4 The Design of a Knowledge Integrated Visual Analytics System

4.4.1 Overview of the Integrated Visualization System

With support from the US Department of Transportation (USDOT), we implemented a prototype of knowledge-integrated visual analytics bridge management system. Our system contains two major components: a visualization interface that provides interactive data exploration and an ontological knowledge structure that is customized to store and provide bridge management domain concepts and knowledge. Through cyclic communications between these two components, our system provides bridge managers with a comprehensive understanding about their bridge assets and facilitates their decision-making processes.

Visualization interface: As shown in Fig. 6, our system utilizes a highly interactive visualization interface to help depict bridge data from three aspects: geospatial, temporal, and relational. Utilizing the rich geo-information provided by Microsoft Virtual Earth (Microsoft 2006), our system provides an interactive geospatial view for the bridge managers to examine the distribution of bridges as well as their surrounding environments. To enable temporal analysis, we designed a Treemap-based (Bruls et al.. 2000) small multiples (Robertson 2008) view to represent the temporal trends of individual bridges with a spatial layout generated based on user-chosen dimensions. The parallel coordinate (Tufte 1990) and scatter plot views are dedicated to assist bridge managers in depicting the relational information among bridges and their attributes. By tightly coordinating these views together, our system provides the bridge managers an interactive data exploration environment that could help them comprehend complex bridge information from multiple perspectives simultaneously.

The ontological knowledge structure: In addition, an ontological knowledge structure is integrated into our system to provide domain concepts and information. Using an ontology-driven modeling approach (Lee et al. 2005 and 2006), this ontological knowledge structure contains bridge domain concepts, such as bridge structural types and locations. These individual bridge concepts are further connected through their interdependent relationships, which is modeled based on the experience of bridge managers and other domain users. By connecting concepts in such a manner, additional domain rules can be identified and created. For example, a rule, which suggests the bridge would have potentially undergone severe structural damage, can be described as: if a bridge's sufficiency rating is below 50 and its super-structure rating is less than 5. Such rule would be created into the knowledge structure and will be executed to alert users the situation upon requests. Utilizing such a rule-based ontological knowledge structure allows for great flexibility for our system to support precise examination of bridges and enables the system to better facilitate bridge management processes.

Communication between components: Through a server–client web interface, our system tightly coordinates the visualization interface with the ontological knowledge structure. Since these two components share the same underlying bridge ID number, the message passing becomes clear and feasible. For example, any results from the executed rules in the ontological knowledge structure will be immediately updated in each visualization window. Thus, exploring within visualization could lead to new concepts that can be further added into the ontological structure; while the knowledge stored in the ontology could assist decision- making during the visual exploration.

In order to assist bridge managers in executing the domain rules, our system presents an interactive knowledge window, which is automatically synchronized with rules within the ontological knowledge structure. With these two components tightly integrated together, the users always have access to the most up-to-date rules and concepts. The users simply have to execute the relevant rules, and they can see and interact with the bridges in detail immediately in the visualization environment.

Furthermore, our system enables the bridge managers to directly modify the knowledge structure. This function provides bridge managers an important interface to update the externalized knowledge and maintain its accuracy. Based on their discoveries during their interactions with the visualization, bridge managers could create new concepts or rules and directly insert them into the ontological knowledge structure. For example, through their interaction with visualization, bridge managers may find that the combination of low ratings (less than 4) on both ‘‘supporting structure’’ and ‘‘water adequacy’’ suggests water erosion and flood damage. The bridge managers could then insert this new discovery into the ontological knowledge structure and further re-apply it to check how many bridges have been affected by water-erosion or damage.

Embedded knowledge processes: Since this bridge management system is designed based on our definition of knowledge and its corresponding conversion processes, we can clearly identify the four different knowledge conversion processes—internalization, externalization, collaboration, and combination in its functions:

The internalization process embodies the transfer of knowledge from a computer to a user through the interactions with visualization. In our system, this process mainly happens through the user’s interaction with the coordinated visual analytics views. These views help the users inspect the data from different perspectives and assist the potential discovery of unexpected data patterns and trends that could become new domain knowledge.

- The externalization process happens upon the user’s acquisition of new domain knowledge or information that does not already exist in the ontological knowledge structure. This knowledge could come from both discoveries from interacting with the visualization system or from collaborating with other co-workers. Once acquired, the user could directly insert this new knowledge into the ontological knowledge structure to augment its knowledge base. The ontology will then store this knowledge and re-apply it during a user’s future investigations.
- The collaboration process takes place when a user interacts with our integrated system that incorporates domain knowledge of multiple experts. Through our integrated knowledge interface, each bridge managers connects to the same ontological knowledge structure. New knowledge or domain rules created by one manager would immediately be reflected in another bridge manager’s visualization system. In this manner, using the ontology as a central repository of knowledge, our system facilitates collaboration between multiple bridge managers.
- The combination process occurs when inserting new knowledge into the existing knowledge structure. The new knowledge could come from a new set of domain data, new perspectives or regulations on bridge inspections, etc. Since bridge inspection rules vary for different inspection

cycles due to new federal bridge inspection guidelines or regulations, the combination process is particularly important in ensuring that each bridge manager is inspecting their data with the most suitable domain knowledge. For example, to handle changes in the standards of water adequacy, our system combines different sets of those criteria and applies them accordingly to different inspection cycles.

4.4.1.2 The Visual Analytics Components

As the state DOTs noted, current BMSs are effective at storing data, but are insufficient at supporting analysis processes. In order to address this shortcoming and to provide support for bridge analysis, we worked with bridge managers at NCDOT to identify three analyses that are often essential to their decision-making process: structural analysis, temporal analysis, and geospatial analysis. According to these bridge managers, these analyses help them analyze bridge data from different perspectives and are integral to their daily workflows.

Dynamic Geospatial Analysis: Bridges exist in a dynamic environment with changing surroundings. Therefore, rather than using a static map, bridge managers often need to adapt to new situations and analyze bridges with additional information such as traffic patterns, flooding regions, and population densities. According to bridge managers, supporting dynamic geo-exploration is a primary area for bridge analysis.

High Dimensional Structural Analysis: Typically, the data representing bridge structures are high in dimensionality. Federal regulation requires bridge inspection to record nearly 130 structural variables biennially. Given the complexity of the data, a tool that could assist bridge managers' comprehension of these variables would be essential. Specifically, on a high level, bridge managers need to detect and identify causal relationships and trends in these variables so that they could identify phenomenon that are affecting all bridges. On a detailed level when inspecting a single bridge, bridge managers need to examine the overall structure integrity of a bridge across multiple variables and to focus on particular structural components inside that bridge.

Scalable Temporal Analysis: Through analyzing the temporal changes of a bridge's condition, bridge managers can compute the deterioration rate of the bridge. In addition, bridge managers can adjust the future maintenance plans by assessing the outcomes from previous work. Therefore, the ability to capture the temporal information is of great value to bridge managers when planning for future maintenances. However, temporal analysis in most existing BMSs is limited to analysis on a per bridge basis. Having an overview that could help the bridge managers spot bridges with abnormal temporal behaviors would be very beneficial.

Supporting individual manager's task routine: Our discussion also suggested that current BMS are quite rigid in supporting individual bridge manager's task routines. As noted in section domain characterization, bridge managers often need to develop their own analysis routines. Depending on available resources, a bridge manager's strategy can be very different from his peers', and would require a different combination of the above analysis processes. In addition, sometimes even the same manager need to take alternative analytical approaches due to changes in priorities. At the heart of these individual routines are the different combinations and sequences of the above analytical processes.

Therefore, it is rather important for a system to provide bridge managers with the flexibility to combine and sequence these analytical processes to fit their own workflows.

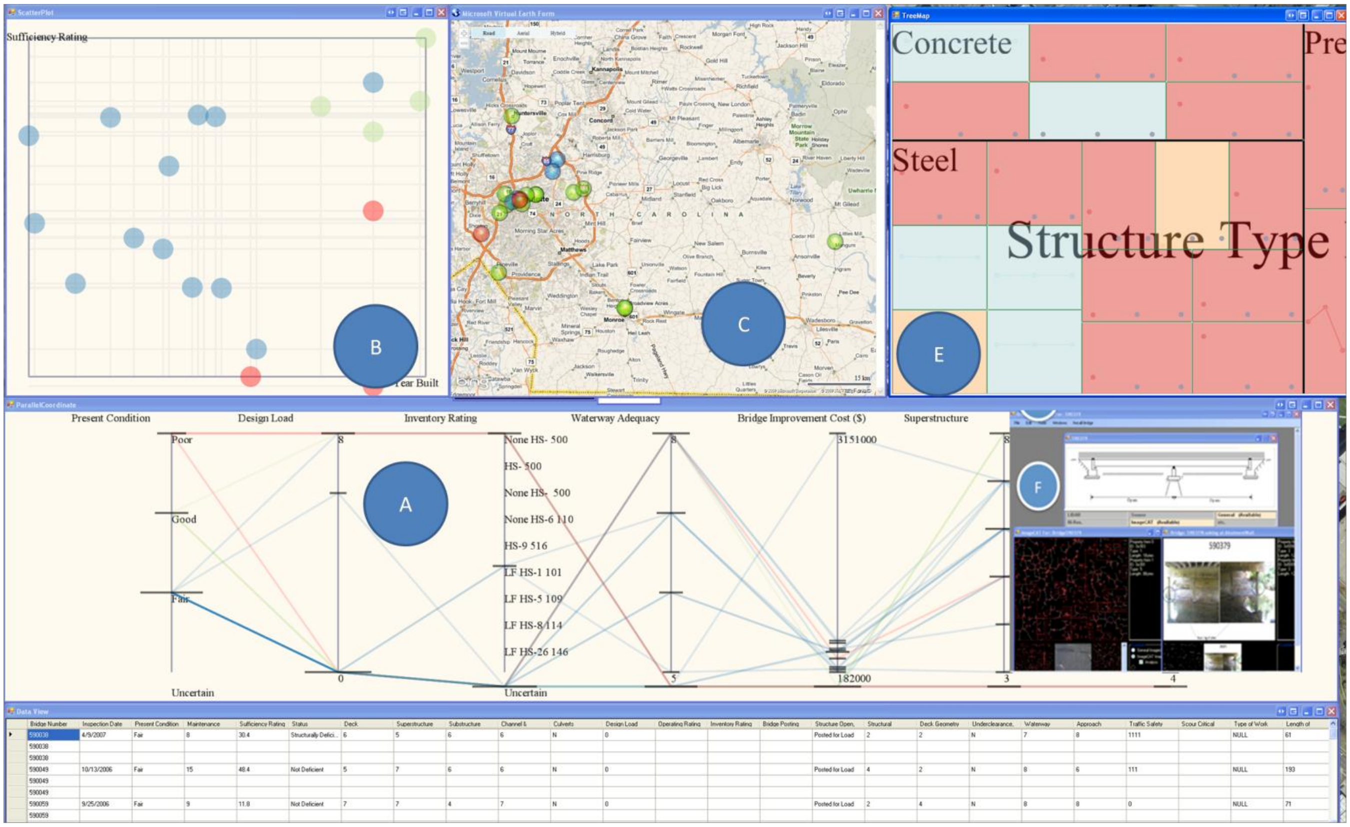

Figure 4.7. An overview for the visual analytics system

4.4.1.2.1 Supporting Decision-Making Process through Multiple Coordinated Visualization

Based on the requests of state DOTs as described above, we design an interactive visual analytics system (Figure 4.7) that supports a bridge manager's decision-making process and remains customizable to fit an individual manager's task routine. The design of our system is based on coordinated multiple views (CMV (Roberts 2007), as well as a modular software architecture that supports customization of the system depending on the bridge manager's preference.

In order to provide bridge managers with analytical capability, our system encodes the three analyses processes described in the previous section into a set of coordinated visualizations. In the following sections, we describe how each process is depicted in our system.

4.4.1.2.2 High Dimensional Structural Analysis

Our system includes three views for helping bridge managers to analyze bridge structures on both a high-level overview and a low-level detail view. On the high level, our system utilizes both a parallel coordinate view (PCView,see Figure 4.7 (A)) and a scatter plot view (SPView see Figure 4.7 (B)) to help bridge managers detect and identify causal relationships and trends in the data variables. The nature of parallel coordinates limits the number of dimensions that can be effectively displayed at a time. Our implementation therefore provides control panels to allow the user to select the dimensions of interest (Figure 4.7 (D)). Using this view, bridge managers can find correlations in the bridges' attributes.

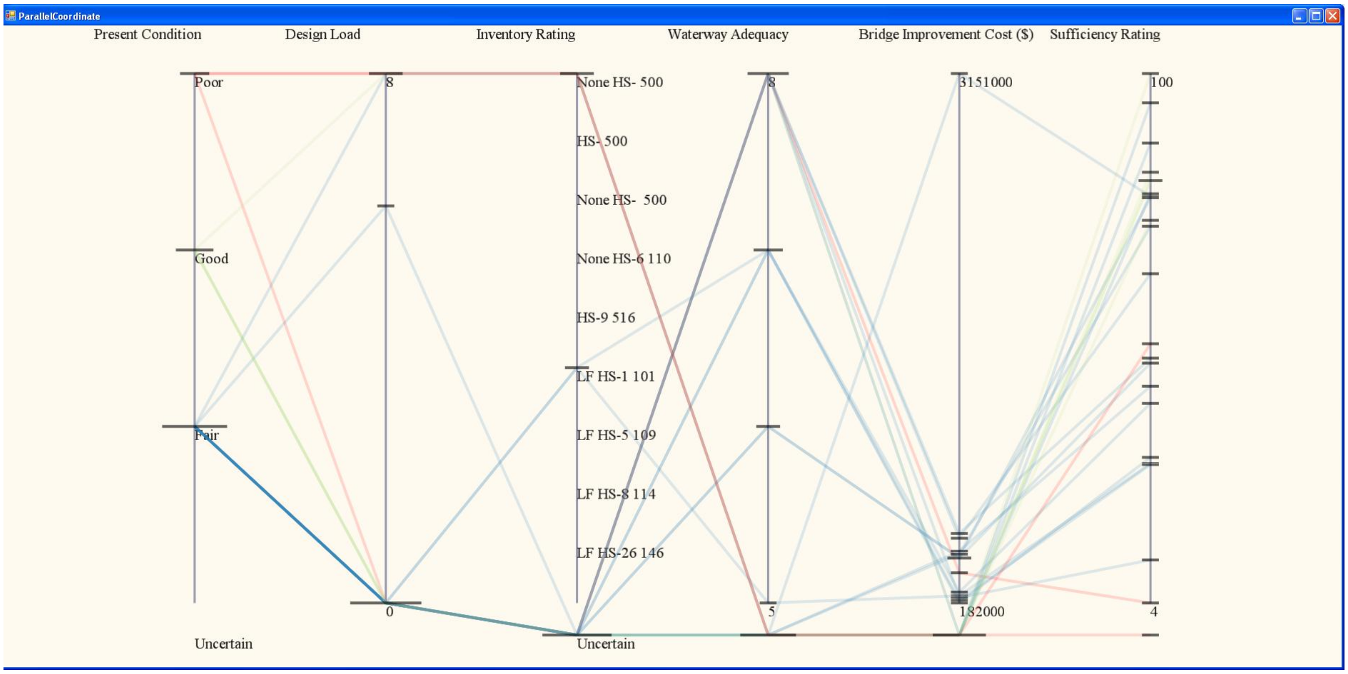

Figure 4.8. Parallel Coordinated View

A parallel coordinate is a common way of visualizing and analyzing multivariate data. In the PC-View (Figure 4.8), each bridges maps to one continuous horizontal line extending from left to right. Those vertical axes represent the selected structure attributes that bridge managers are interested in.

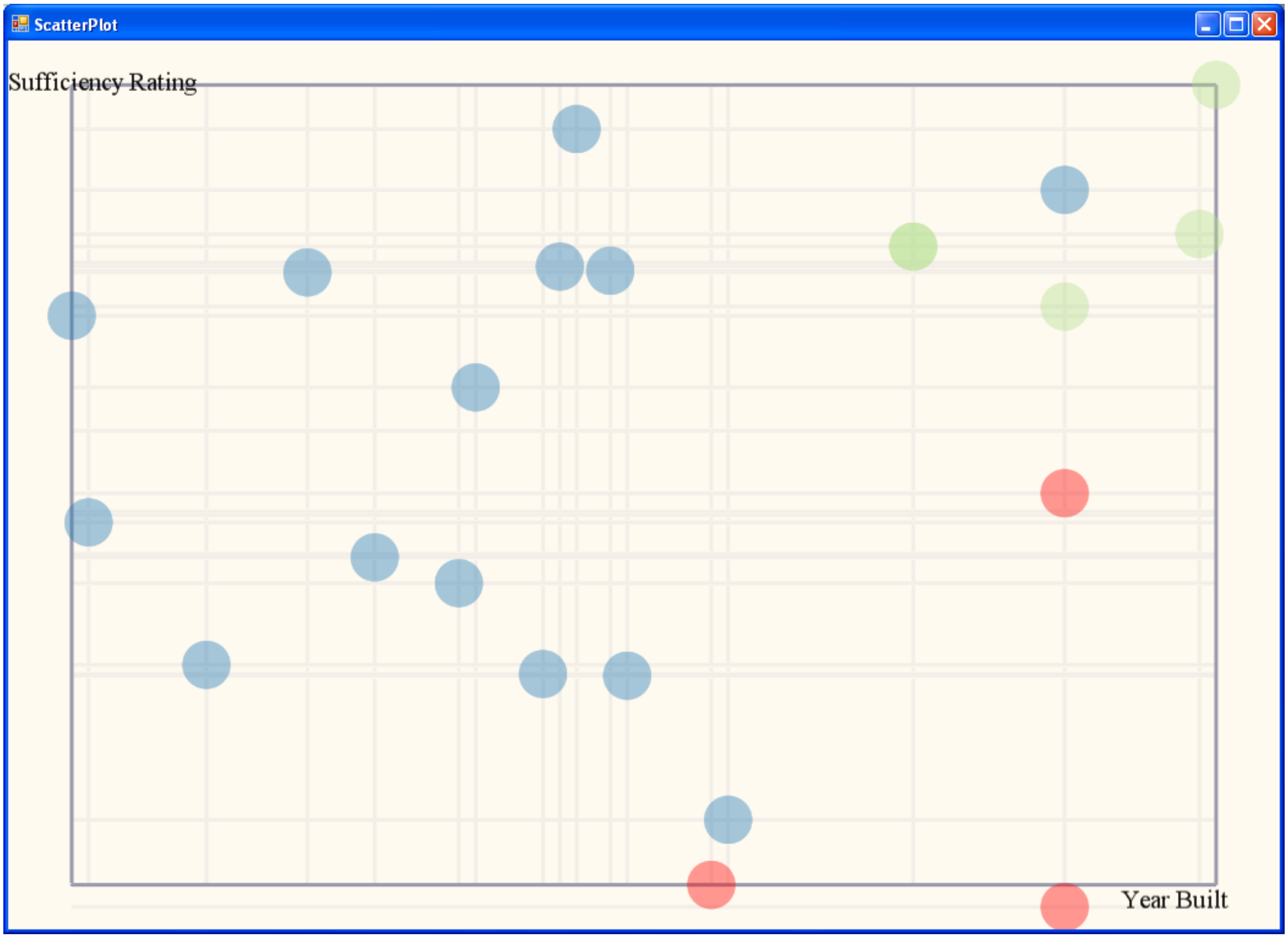

Figure 4.9. Scatter Plot View

On the other hand, the SP view is designed to depict relationships between bridges across two specific dimensions. The spatial layout of the view allows the user to see clusters and clearly identify outliers, and is a slightly more intuitive interface than the potentially complex PC view. In addition, given the importance of time in bridge analysis, our system also extends the ability to see temporal changes in both views. Similar to the trails and animation used by Robertson et al.. (2008) both SPView and PCView allow the user to explore the time dimension, which in turn allows bridge managers to interactively explore and compare information from different inspection cycle. Together, these two visualizations give bridge managers the ability to see high-level trends and patterns in the data's variables.

Figure 4.10. Structure Detail View

On a detailed level, when inspecting a single bridge, bridge managers need to examine both the overall structural integrity of a bridge across multiple variables, as well as focusing on particular structural components inside that bridge. Therefore, we design a structural detail view to automatically link information between each bridge component and provide bridge managers with an intuitive visualization to interactively analyze the corresponding structural information.

Based on existing bridge design guidelines, we model general bridge components into an interactive bridge schematic diagram (see Figure 4.7 (A)). In this diagram, bridge managers can directly select the major bridge structures, and analyze each component individually. In addition, a line graph enables bridge managers to monitor temporal changes for individual bridge structures. Associated with overall temporal information presented in the small multiples view, this structural temporal component helps bridge managers to gain insight into the affects of structural changes, and to efficiently identify the key factors in the overall deteriorations.

4.4.1.2.2 Small Multiples for Temporal Analysis

Bridge managers have expressed the need of having a tool to help them analyze the temporal changes of bridge data. They want to be able to perform analysis over time on a large number of bridges as well as one bridge at a time. The ability to monitor and understand the temporal changes of the bridges is of great value for bridge managers to make maintenance decisions. For example, through examining the temporal information, the bridge managers can learn how different types of bridges deteriorate, so that they can plan maintenance in advance to prolong the life span for those bridges. Traditionally, bridge managers analyze the temporal information on a case-by-case basis.

Thus, we design a small multiples view (Tufte 1990) to help them achieve temporal analysis of large number of bridges. Our design is based on small multiples views in the literature (Keefe et al.. 2009) - similar to the work by Robertson et al.. (2008), our small multiples view shows deterioration changes of each bridge using trend lines.

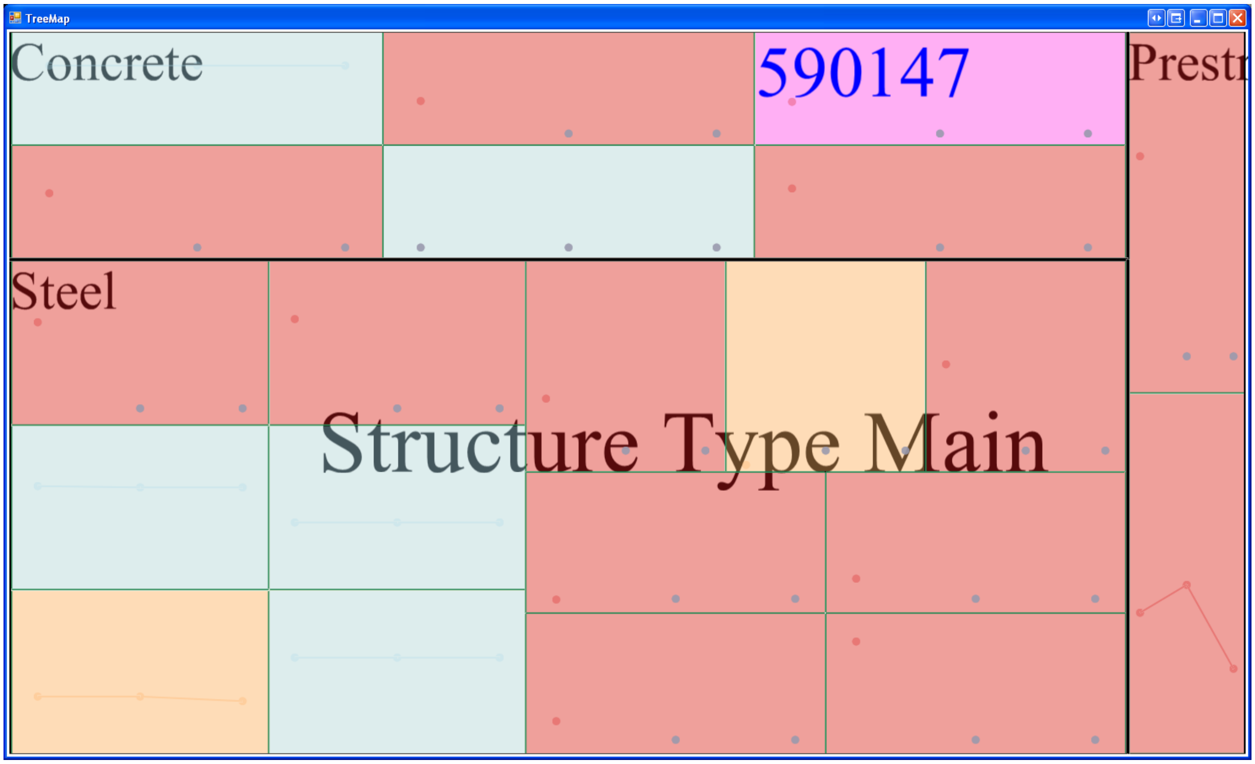

Figure 4.11. Temporal Analysis View

In terms of overview, each bridge is first visually categorized base on a user-selected data dimension. For example, as shown in Figure 4.11, the categorization is based on the "Main Structure Type". All categories in data dimension are used to further group the bridges inside the Tree-map Layout (11). Each cell in this visualization symbolizes one bridge, where its x-axis represents inspection cycles and y-axis suggests the structural attribute values in that inspection cycle. The structural attribute values are then connected to construct a timeline to represent the temporal changes for each bridge (grey dots presents missing data). The bridges, represented as cells, are further sorted and grouped based on the standard deviations of their attribute axes (y-axis).

Additionally, since it is often necessary for bridge managers to understand the temporal patterns for a certain group of bridges, we applied a customizable Treemap spatial layout to group the small multiples based on particular structures. For example, Figure 4.11, shows the bridges divided based on their construction material (note the black lines separating regions of the treemap). In this example, the layout enables bridge managers to discover the uncommon temporal pattern where several recently built, known-to-last, concrete structure bridges show significant deterioration. It is therefore mentioned by bridge managers that the capability in finding such insight is not only valuable for their maintenance decisions, but also can help optimize their future construction planning.

Besides visual representation, multiple interaction techniques are supported within the temporal view. Through drag-and-drop interaction, bridge managers can easily change the data dimension by picking up another dimension (such as "Year Built", "Type of Service", etc.) and drop it in the Tree-map layout. Besides the drag-and-drop interaction, the temporal view also provides other rich interactions to help bridge managers depict detailed information.

4.4.1.2.3 Geospatial Analysis

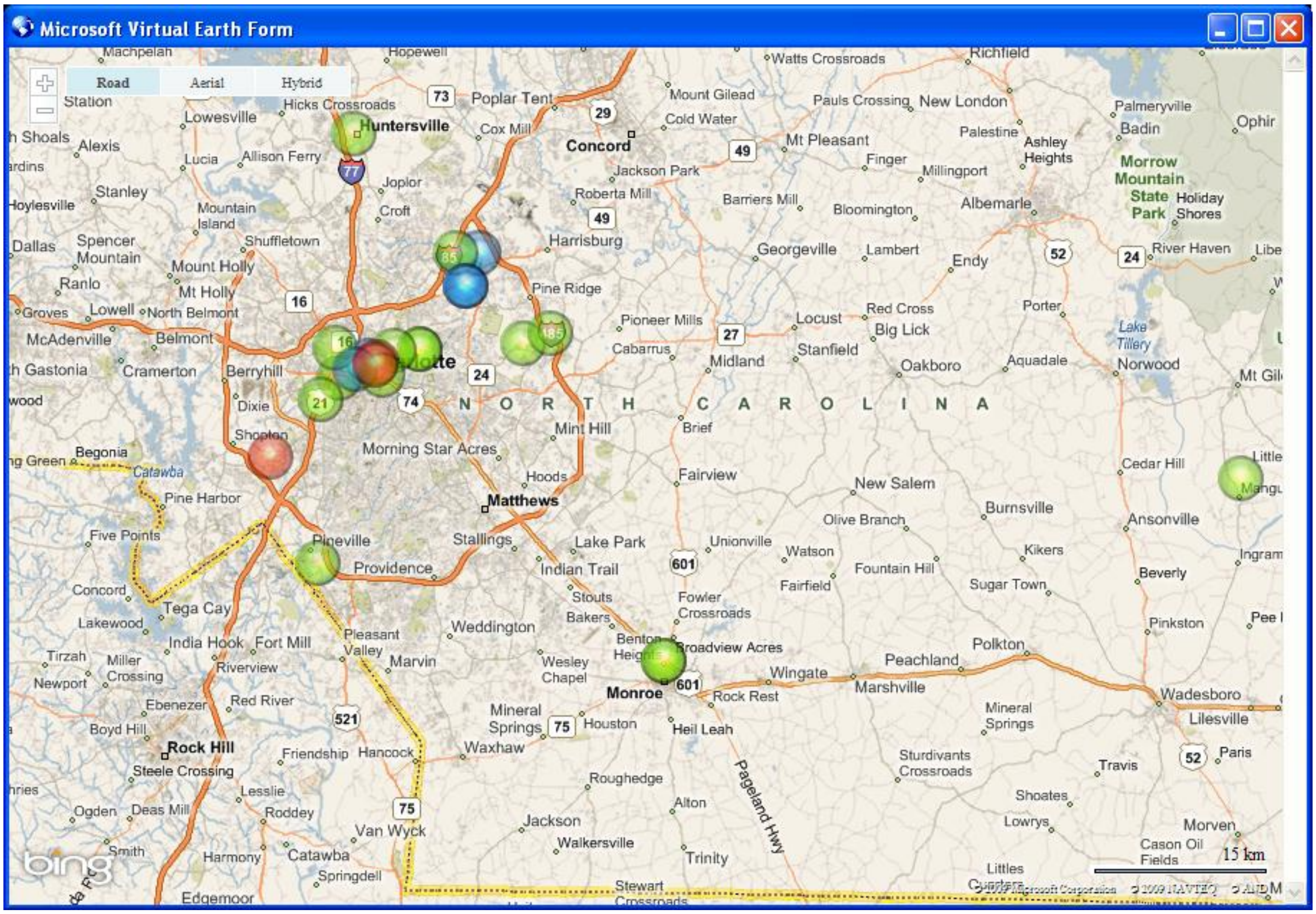

Figure 4.12. Geospatial View

Extensive research on geospatial visualization have shown the benefits of utilizing online map systems such as Google Maps and Microsoft Virtual Earth. Similar to work by Fisher et al.. (2007), we also utilize Microsoft Virtual Earth (MSVE Microsoft (2009)) to provide bridge managers with dynamic and interactive geospatial analysis (see Figure 4.7 (C)). By placing the bridges onto the scalable map, detailed geographic relationships and patterns immediately become apparent.

By adopting online map systems such as MSVE, our system can have the most up-to-date geospatial information such as road structures and 3D building models. However, we further extended MSVE in our system to overlay large amounts of (proprietary) geo-coordinated information over the map, such as traffic distribution patterns and satellite images, and can utilize that information to perform extensive geospatial analysis.

4.4.1.2.4 Supporting Customization of the System

To adapt to the development of emerging domain technologies, our system is built on top of a modular architecture that allows bridge managers to extend the system to incorporate advanced visualizations and more effective data models. This is made possible largely because inspections and analysis results are tightly associated using a unique bridge identification number.

Therefore, each visualization component integrated in our current system is designed to be interchangeable with other equivalent visualizations if they both use the bridge identification numbers. Using our architecture, if bridge managers suggest new suitable visualizations for their analysis, our system would be ready to incorporate those visualizations to provide additional functionalities.

Furthermore, this approach enables bridge managers to combine the traditional National Bridge Inspection Standards (NBIS) dataset with their locally collected information. As of the paper, we have helped NCDOT bridge managers to associate bridge structural information with extensive data collected in the North Carolina region. This extensive information includes, as shown in Figure 4.7 (F), field inspections imageries, LIDAR scans for each structure, and pavement crack analysis results.

4.4.1.2.5 Coordination and Interaction

Since every bridge is reported with a unique ID number, our system currently uses this number to coordinate among different views. Our system tightly coordinates all the user generated views such that an action performed in one view affects all the others. The bridge managers can now interact with geo-locations, temporal changes, structural attributes, etc., and understand the correlations are among these aspects. This is significantly more powerful than using any of the visualization views separately.
For example, when a bridge manager selects a region of interest in the geospatial view, all the corresponding cells in the small multiples view are highlighted to show the temporal changes for those bridges (see Figure 4.7) At the same time, the lines in PCView and the bubbles in SPView are highlighted to show the correlations among those bridges. By interactively highlighting bridges among different views, our system enables bridge managers to locate certain bridges and analyze both their geospatial and temporal trends and patterns.

In addition, inspired from Butkiewicz et, al. (2008), our system allows multiple selections in all the visualization views. This is especially useful for bridge mangers to compare different groups of bridges, as well as understanding the correlations among bridge structural attributes. For instance, selecting multiple regions on a geospatial view would provide comparisons of patterns and trends among bridges in various geo-locations, while highlighting multiple items in SPView would allow the examination of correlations among different bridges.

Using the coordinated views, our system provides the bridge managers a interactive data exploration environment that could help them to depict the bridge information from multiple aspects.

4.4.1.3 The Ontological Knowledge Components

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. 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 (Lee et al.. 2005) provides functionalities to browse, access, query and reason about complex bridge inspection process.

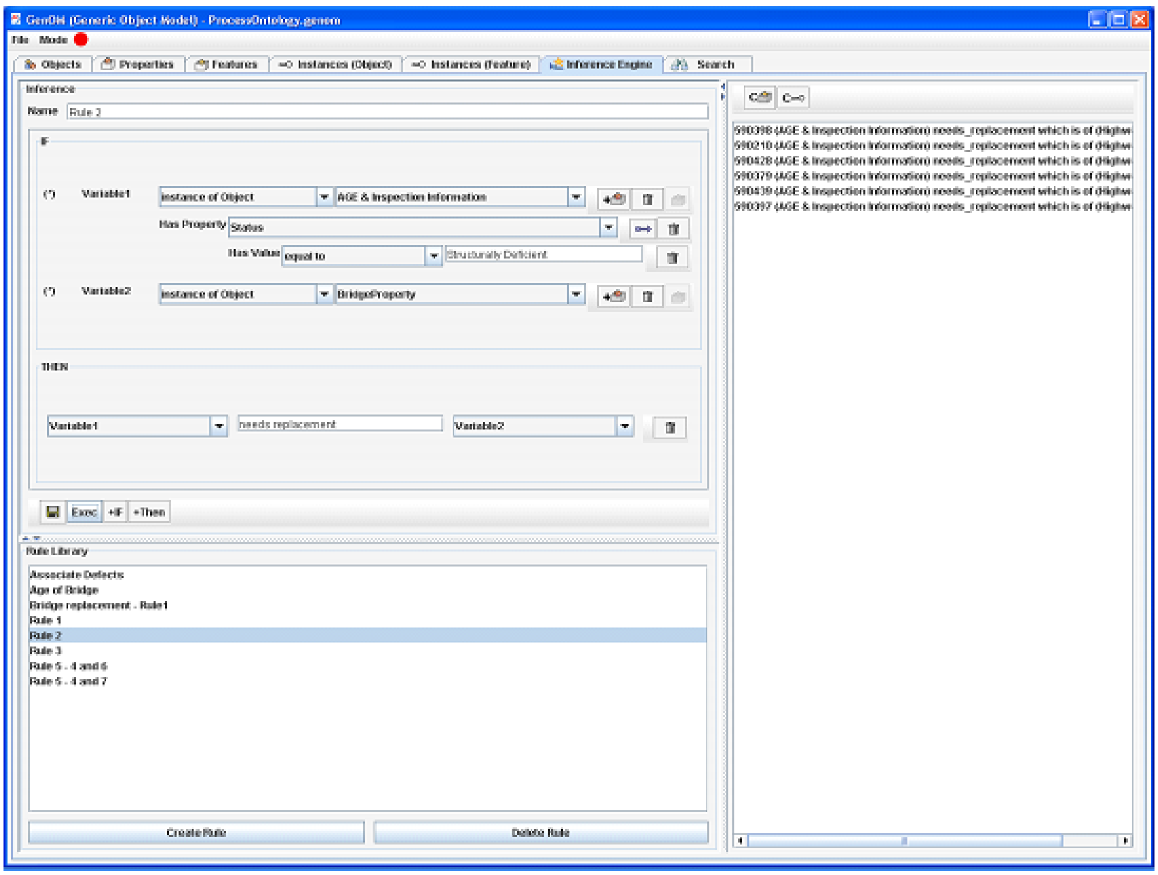

Figure 4.13. GenOM system

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.

4.4.1.4 Communication between Visualization and 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. 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.

4.4.2 Use cases for the system

We performed a qualitative (expert-based) evaluation of our system with bridge managers from North Carolina and City of Charlotte Department of Transportation and identified the following scenarios that demonstrate how our knowledge- assisted visualization system could assist bridge managers' daily jobs of examining bridges and making maintenance decisions.

4.4.2.1 Understanding cause of deterioration

Identifying and understanding the cause of bridge deterioration is a key step for bridge managers to come up with corresponding maintenance strategies. It has been observed that there are generally three stages in achieving this step, namely, selecting bridge candidates, detailed examination, and identifying potential causes for damage. The following scenario was identified together with Charlotte DOT's bridge management team for their annual bridge maintenance planning.

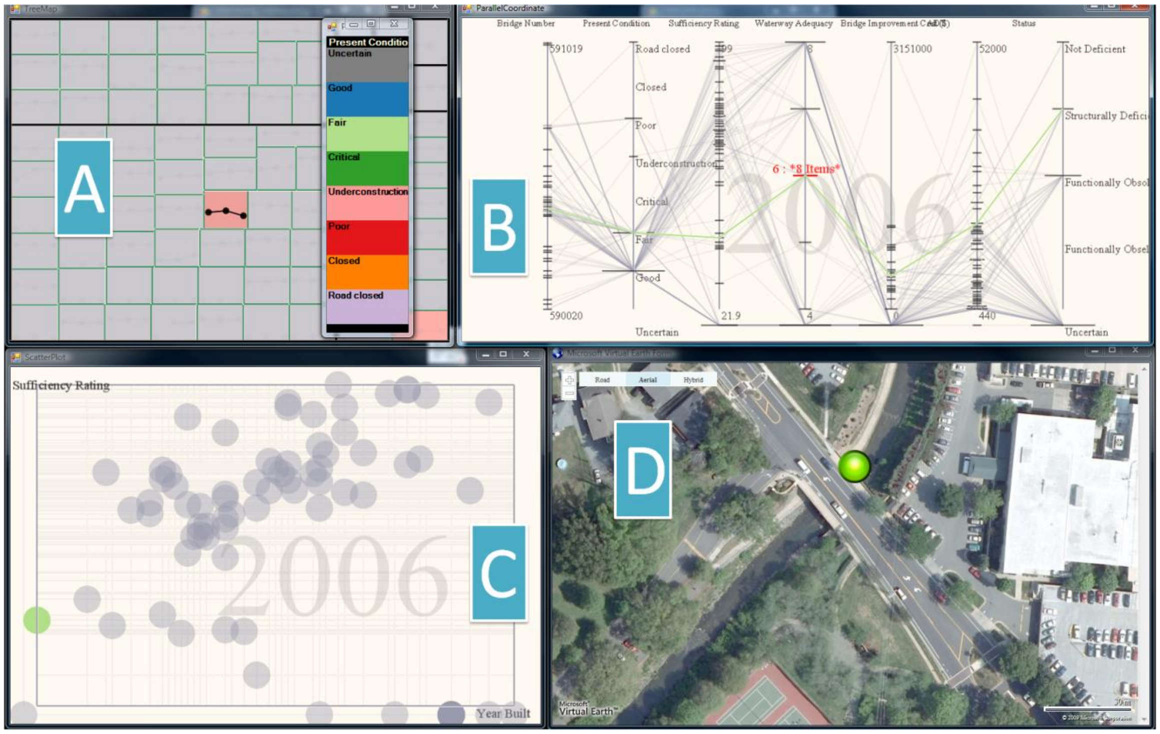

Figure 4.14. Scenario one, understanding cause of deterioration

Our system was initialized with data from previous three inspection cycles: years 2000, 2004, and 2006. The bridge management team started the maintenance process by searching for bridges with significant changes in sufficiency rating in the previous years. They utilized the small multiples view to see if any interesting bridge changing patterns could be identified. As shown in Figure 4.7 (E), the team found a set of bridges with warmer colors in the small multiples view, and they also identified several bridges with significant downward trends in the past years. By highlighting these bridges in the scatter plot view (see Figure 4.14 (C)), the team noticed that one of them was actually the oldest bridge in the Charlotte area. Suggested by both the small multiple view and the scatter plot view, this bridge actually shared the lowest overall rating in that year and had had drastic deteriorations since 2004.

To have a closer look at the bridge, the team used our geospatial view and zoomed into the bridge to check its surrounding environments. As shown in Figure 4.14 (D), this bridge was constructed over a river stream, and had supported high traffic volume because it had been chosen as a part of a detour route for a major interstate highway. These findings immediately raised several questions: could the bridge's deterioration be caused by water erosion, overloaded traffic, or flood damage? Although these were all possible causes of the deterioration, bridge managers had no definitive answers to confirm these hypotheses by looking at the geospatial view alone.

Trying to verify their hypotheses, the management team started to find clues from the structural reports of that bridge. By plotting the corresponding criteria in the parallel coordinate view, they found that the traffic amount on that bridge had not changed significantly in the previous years, and therefore ruled out the possibility of traffic pattern being the cause of the deterioration. However, the PC view showed that the water adequacy rating had dropped significantly during the past two inspections, suggesting the bridge had undergone severe water damage. To extract more detail, the team brought up the bridge's detailed structural view. As shown in Figure 4.10 (D), the supporting pillar for this bridge had shown heavy warping, and the bridge showed clear marks of water erosion near the bottom of the pillar. A quick reference check on the county's flood history confirmed that three significant flooding took place in years 2003, 2005, and 2006 around that area, which gave the bridge managers significant reasons to conclude that water damage, especially flooding, was a key factor in causing the deterioration of this bridge.

4.4.2.1 Finding misleading information

In this scenario, the bridge manager from CDOT was interested in evaluating bridges within his jurisdiction, which is centered on the area near the University of North Carolina at Charlotte. Intuitively, he used the geospatial view to zoom into the specific region and interactively selected the bridges that he wanted to examine. When highlighting one bridge that was built near the back entrance of the university (Figure 4.15 (A)), he was surprised to see that our system indicated that there were actually two bridges, as shown in both the tooltip in geospatial view and other opened views. Since he was not aware of a second bridge in that area, based on his experiences, he thought this could be caused by data duplication in the database.

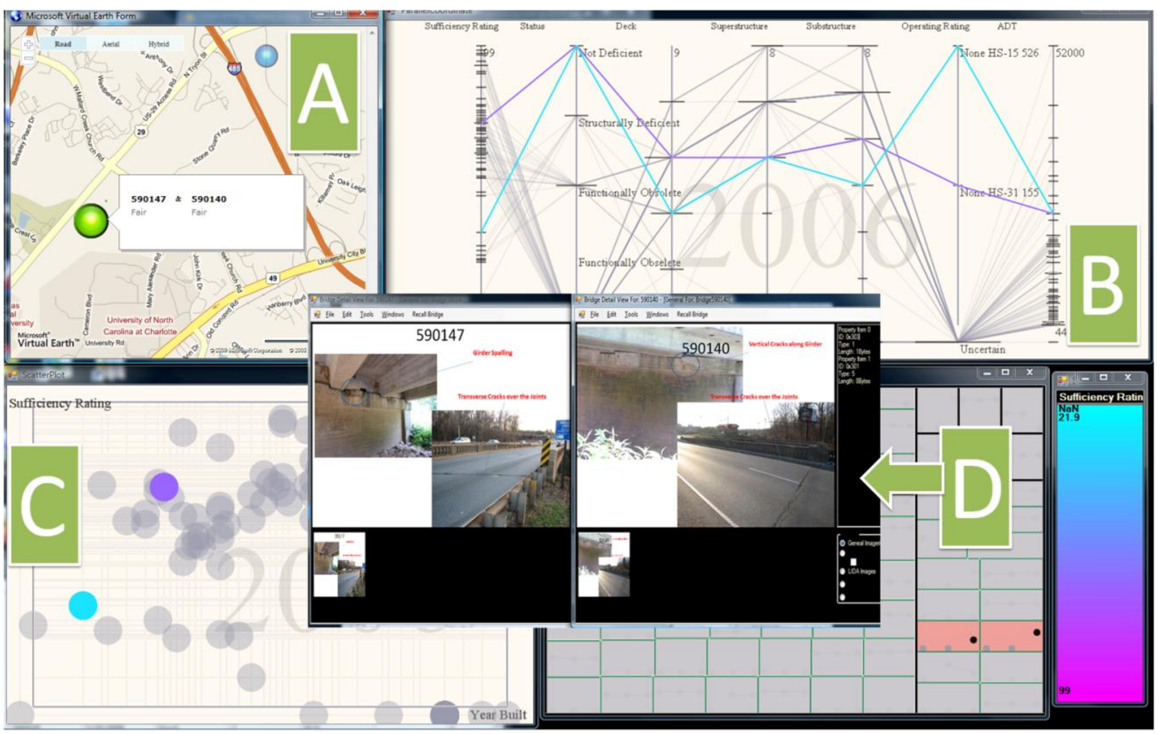

Figure 4.15. Scenario two, finding misleading information

Trying to confirm his hypothesis, the bridge manager used the relational views to further verify if these bridges shared the same structural grading as well. Quite unexpected, he not only found that these two bridges had significant differences in structural grading values (Figure 4.15 (B)), but also that they were constructed separately in a time span of thirteen years (Figure 4.15 (C)). A further examination on from detailed views for both of these bridges confirmed that they were indeed different structures, as shown in Figure 4.15 (D).

After referring to some construction documents, it became clear to him that this was an unusual situation: The bridge was originally designed and built in 1938 as a one-lane bridge; however, with the increasing traffic and the establishment of the university in 1946, a second single-lane bridge was attached to it 1951. Although they are inspected at the same time, each lane of this entire bridge structure is still inventoried as an individual bridge in current database.

This scenario shows how our system would help the bridge managers to interactively discover unexpected bridge information and further lead them to verify and validate those discoveries.

4.4.2.1 Augmenting visualization through the use of an ontology

According to bridge managers, water erosion and flooding can cause severe damages to bridges. The pattern for this type of deterioration is in general typical along river streams. In this scenario, we demonstrate how our system could help bridge managers to quickly identify the cause of unexpected bridge deteriorations through the knowledge internalization process. This scenario was identified together with city of Charlotte bridge management team during their examination of causes of water damage.

Figure 4.16 Scenario three

Close examination of the geospatial view shows that although these three bridges are on the same river stream, their conditions are different. The bridge over the upper stream is currently under repair and reconstruction.

Since the criterion for ‘‘bridge above water’’ has already been externalized in our ontological knowledge structure, the bridge managers can easily highlight all these bridges in the geospatial view and examine them individually. Through quick examination on the geospatial view, the bridge managers immediately noticed an interesting pattern in South Charlotte. Although located over the same river, as shown in Fig. 4.16, the three bridges over that river showed different ‘‘present conditions’’. The one over the upper stream has already been filed for replacement and has been under construction. However, the other two are still in good condition. This pattern is interesting because if there was a flood, all three bridges should share similar deterioration patterns; or at least, they should deteriorate at a similar pace. Even though temporal information suggests that these bridges were built at similar times, the changes in their conditions are drastically different. This inconsistency raised the bridge managers’ interests.

After a detailed examination of these bridges in the geospatial view, the bridge managers realized that the cause of this inconsistency was due to the different turns of the river. According to one of the bridge managers, although there was flood in both the upper and lower parts of this river, the bridge over the upper stream received the most impact since there were no bends in the river before the water hit it. On the other hand, due to the slow down of the river's speed when the water passed the second and third bridges, these two bridges received much less impact. Based on this observation, the bridge management team was able to quickly identify and internalize this pattern and reuse it for future reference.

In this scenario, the bridge managers gained insightful knowledge from interacting with our visualization system and incorporated it into their tacit knowledge (internalization). Although it would be more beneficial and efficient if this kind of knowledge could be externalized, due to the complexity of modeling such knowledge, our current ontological knowledge structure does not support an explicit externalization for it.

4.4.3 Evaluation with DOT bridge managers.

In this section, we report the feedback from evaluations conducted with bridge managers at both NCDOT and City of Charlotte DOT (CDOT). Our evaluations were conducted by first demonstrating the design of the system and the utilities of each visualization. Then, we invited bridge managers to perform in-depth analyses using the system. Although the degree and depth of analyses differed in each evaluation session, the bridge managers generally agreed that our system provided more analytical capability than any existing BMSs, and that it is flexible enough for them to quickly incorporate the use of our system into their daily routine.

4.4.3.1 Visual facilitation of decision-making processes

One benefit of our system that was noted by all bridge managers was that it provided a visual exploration environment to help them analyze information from multiple aspects. The capability of being able to perform not only geo-temporal analysis, but also structural analysis was of great value to bridge managers' decision-making process. One of the managers commented that, ``[the] linked visualizations provide me with a cohesive understanding about the data that I am working on. It reduces the time I spent on manually searching for information, and helps me focus more on the task itself."

As demonstrated in the scenarios our system helped bridge managers to effectively analyze their data across multiple dimensions and assist them in determining the cause of deterioration. All the bridge managers found the system practical, and believed that the system would be valuable in their daily routines. One of the managers from NCDOT noted that, ``...using your system, I can see correlations that I normally wouldn't be able to see. This is much easier than making the similar observation from using our current system."

In particular, many bridges managers pointed out that the temporal analysis in our system provided them with the capability to effectively monitor changes in bridge conditions and identify maintenance candidates. In addition, many bridge managers noted that the capability to examine bridge structures from multiple levels (overview and detailed view) could effectively guide them from examining large amounts of data to inspecting bridges one at a time.

In summary, one bridge manager from NCDOT commented that, ``...using your system, we can now see what we normally can't see. We also could have a cohesive understanding about our bridge assets. This would be helpful for us to identify and prioritize bridges...". This confirms the utilities of our system.

4.4.3.2 The flexibility to assist individual workflow

At the heart of our system is a modular software architecture. This design provides bridge managers with the flexibility to customize system, and allows them to only utilize the necessary visualizations in their practices. As pointed out by a manager from CDOT, ``[your system] will greatly shorten the catch-up time between my learning to use the system and my actual use of it."

Additionally, this modular design also allows our system to keep up with the development of the bridge inspection technologies. We are currently working with NCDOT to integrate their extensive inspection data into the system and customize the system for their needs. According to a bridge manager from USDOT, ``true to the goal of the project, this system allows us to think about how we could have more practical impacts with integration of other technologies. As such, it gives us an opportunity to deploy the system to other state DOTs".

4.5 Summary and Conclusions

Maintaining bridges is a multi-faceted operation that requires both domain knowledge and analytics techniques over large data sources. Although current bridge management systems are very efficient at data storage, they are not as effective at providing analytical capabilities. In this paper, we present our interactive visual analytics system that extends the capabilities of current BMSs.

As shown in Figure 4.7, our system was designed in collaboration with bridge managers in national, state, and local DOTs, and has been implemented specifically to provide them with interactive data exploration, cohesive information correlation and domain-oriented data analyses. Our system enables bridge managers to customize the visualization and data model to fit each individual's task routines. In our expert evaluations, bridge managers expressed their interest in using our analysis system and confirmed its novelty and utility over existing BMSs. With such encouraging feedbacks from domain experts, we are planning to deploy our system to multiple state DOTs and put our system in to real-world environments.

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Appendix B. Images for the studied 20 bridges

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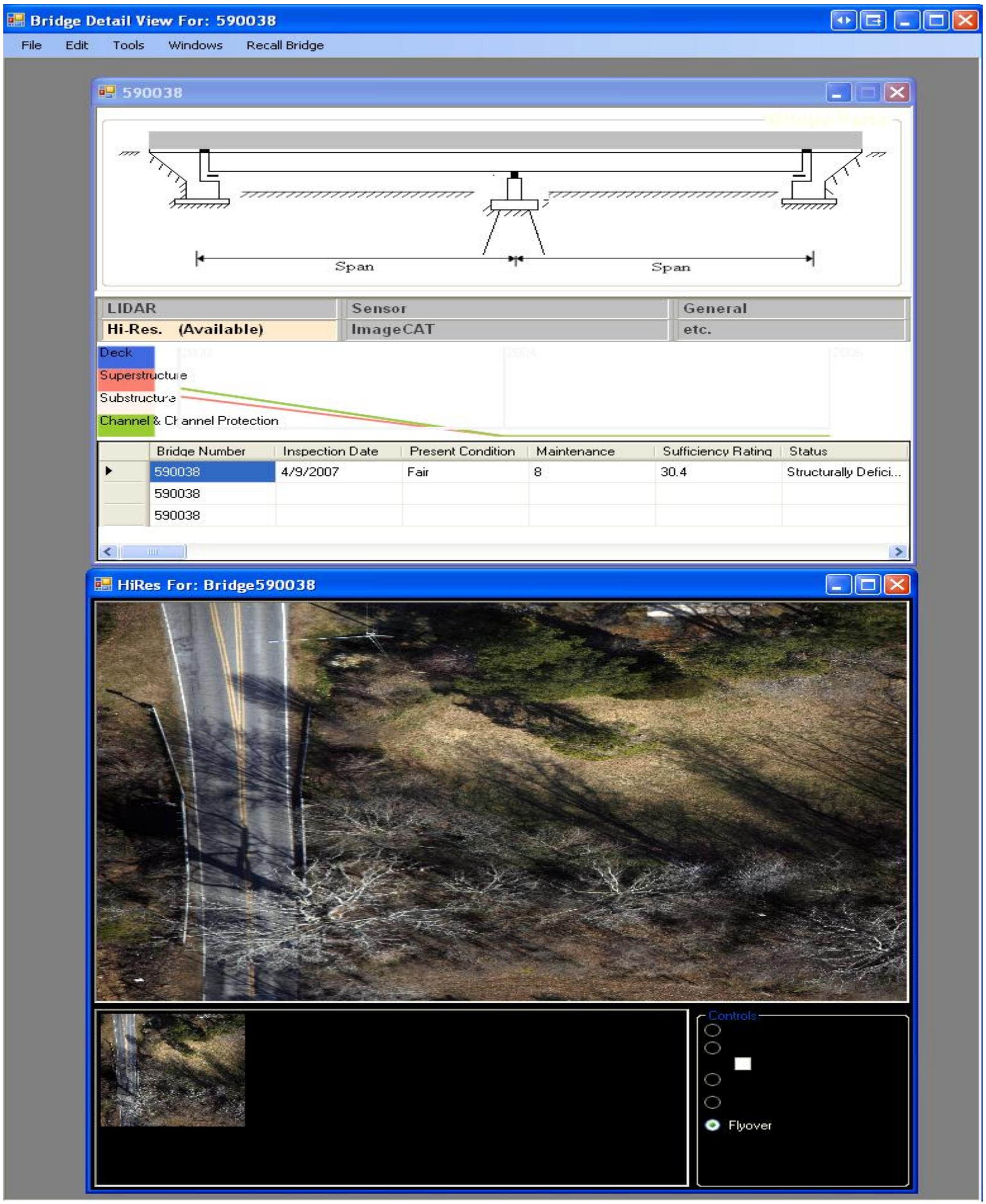

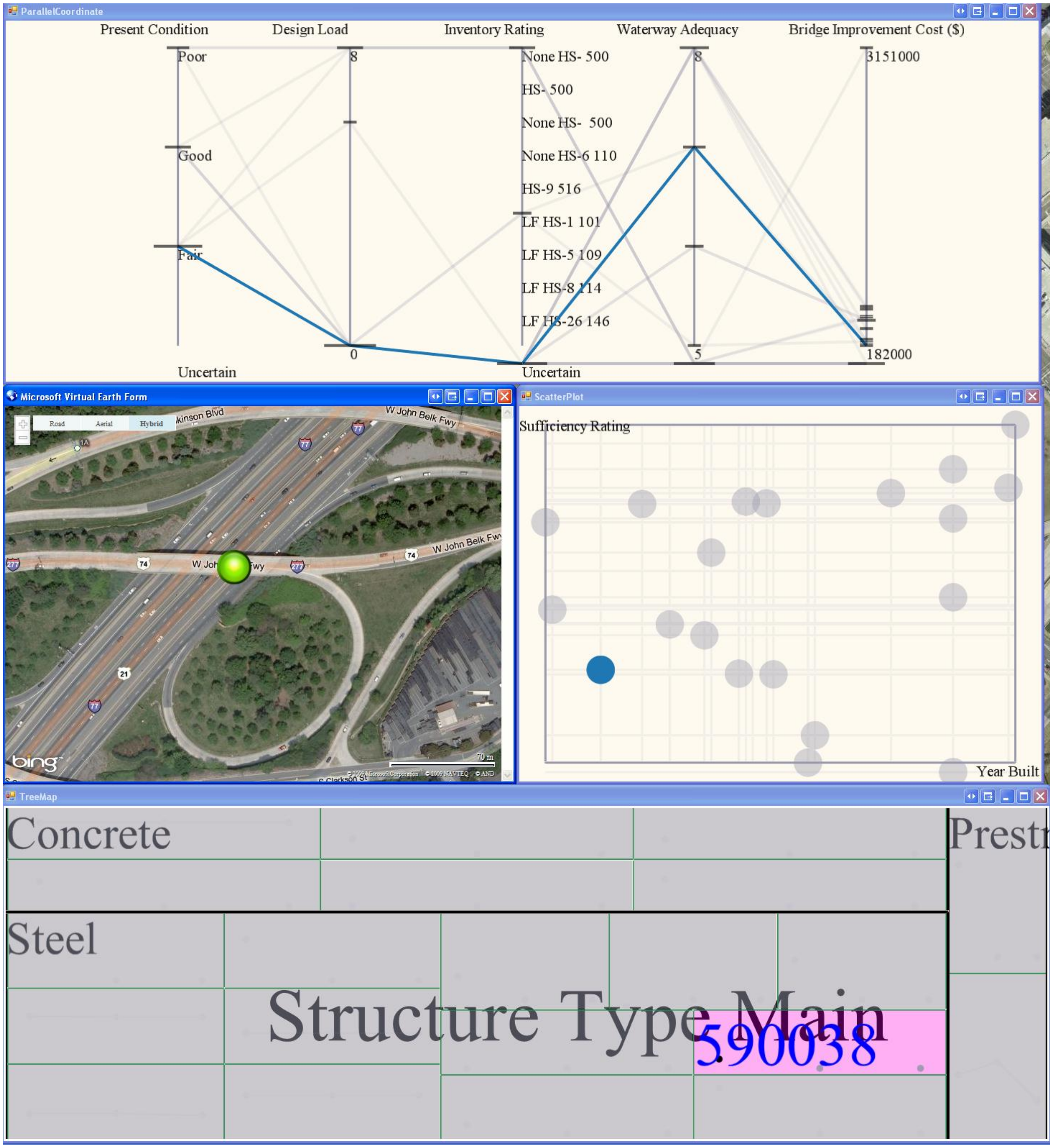
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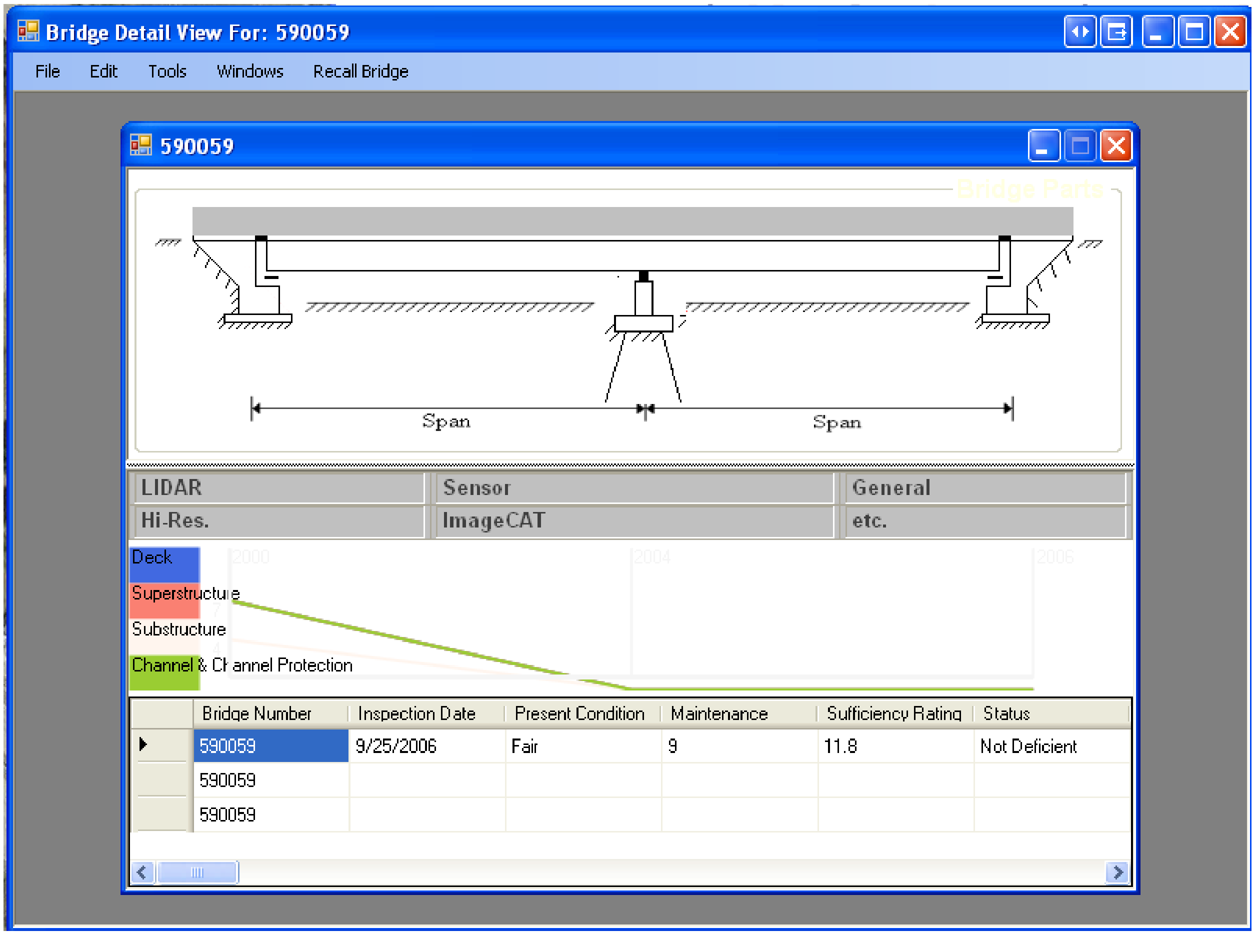
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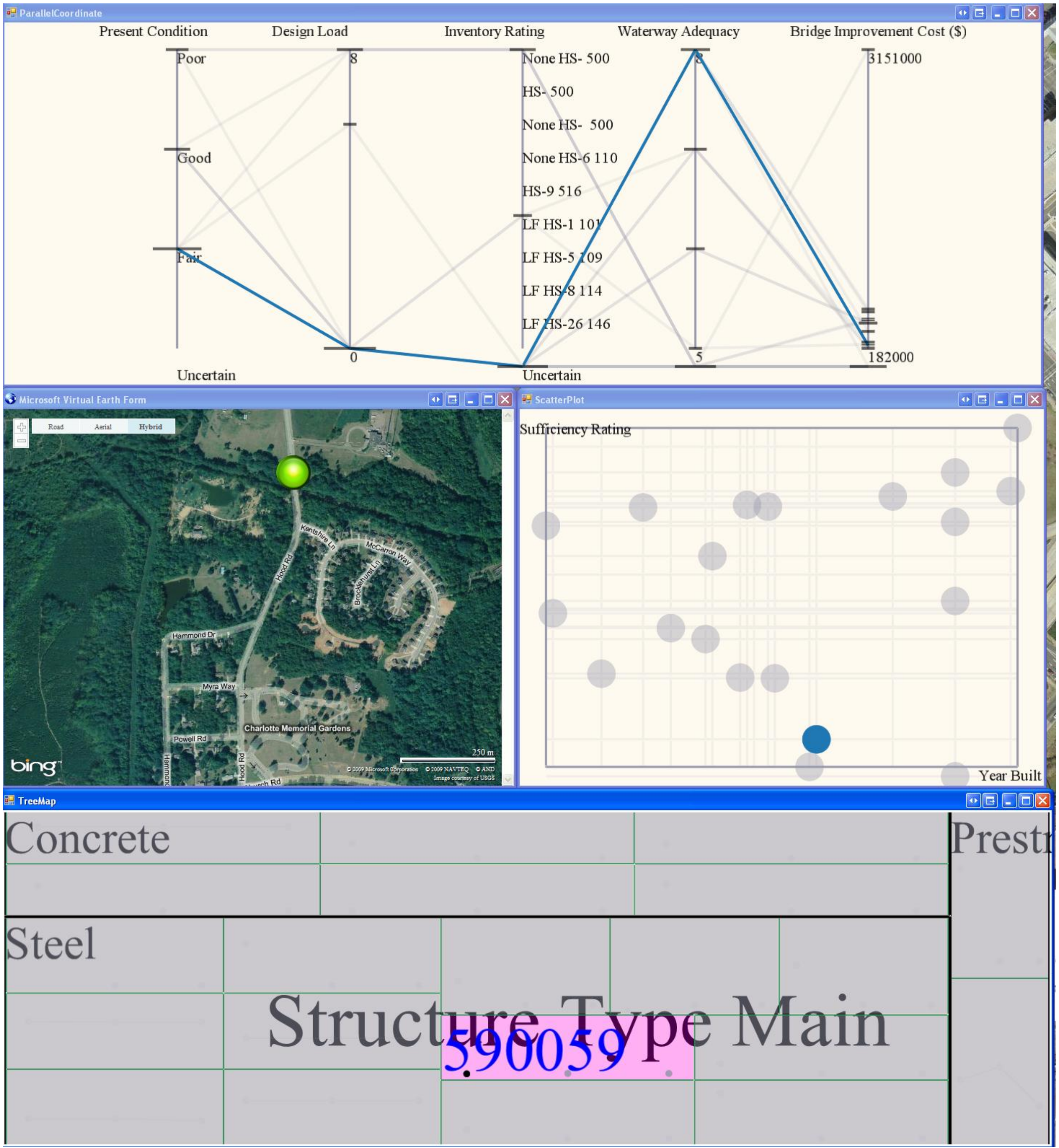
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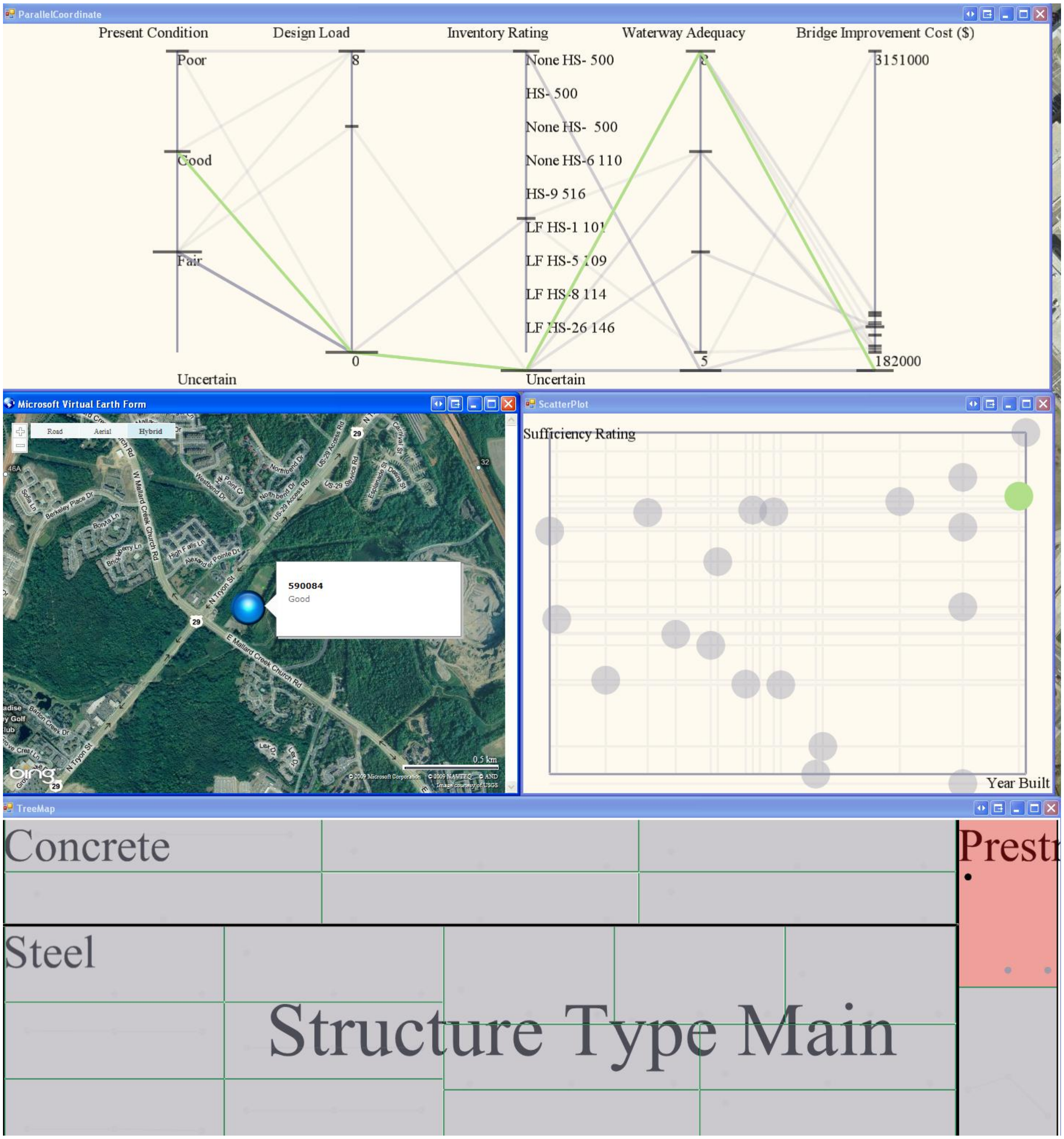
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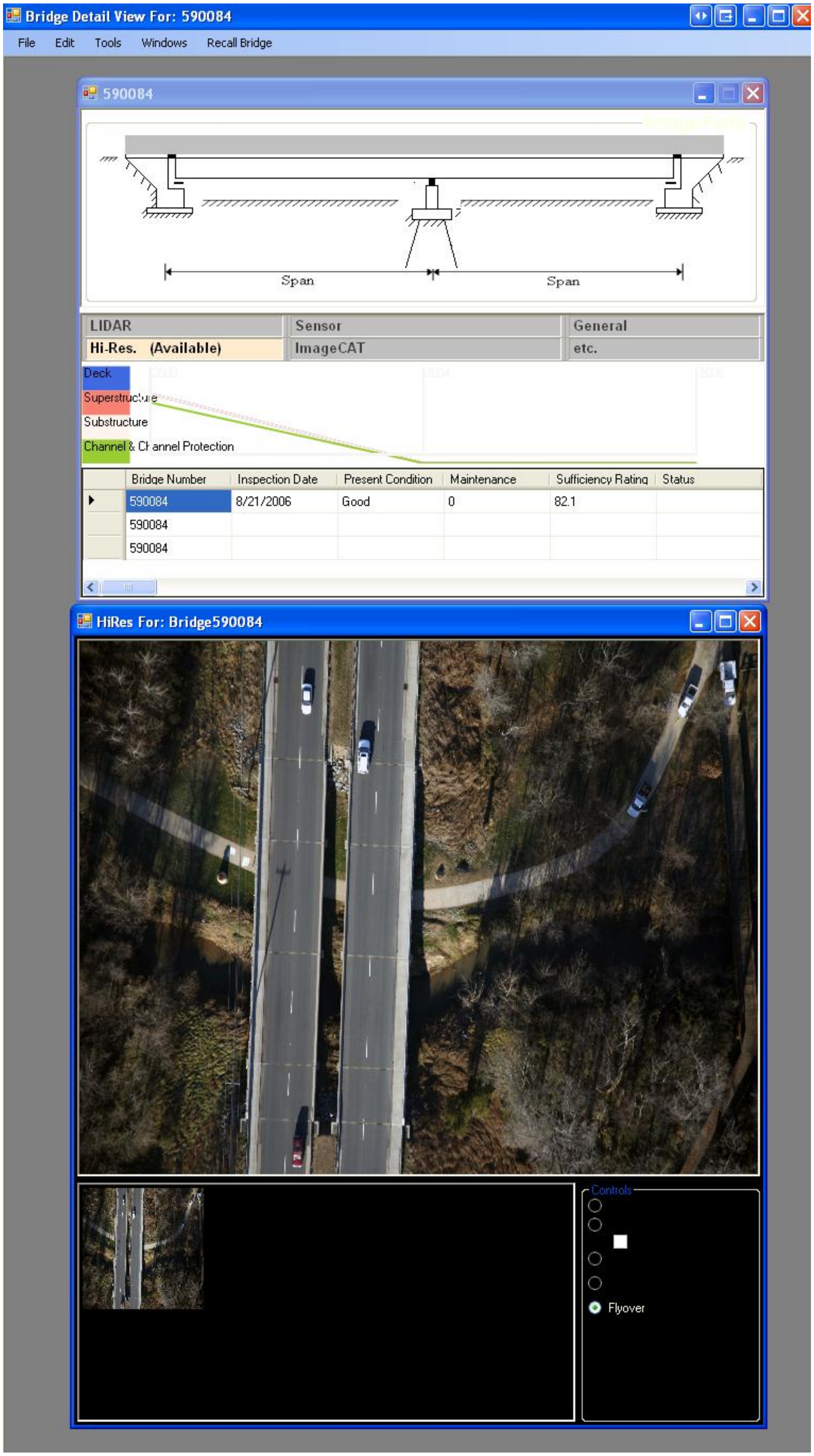
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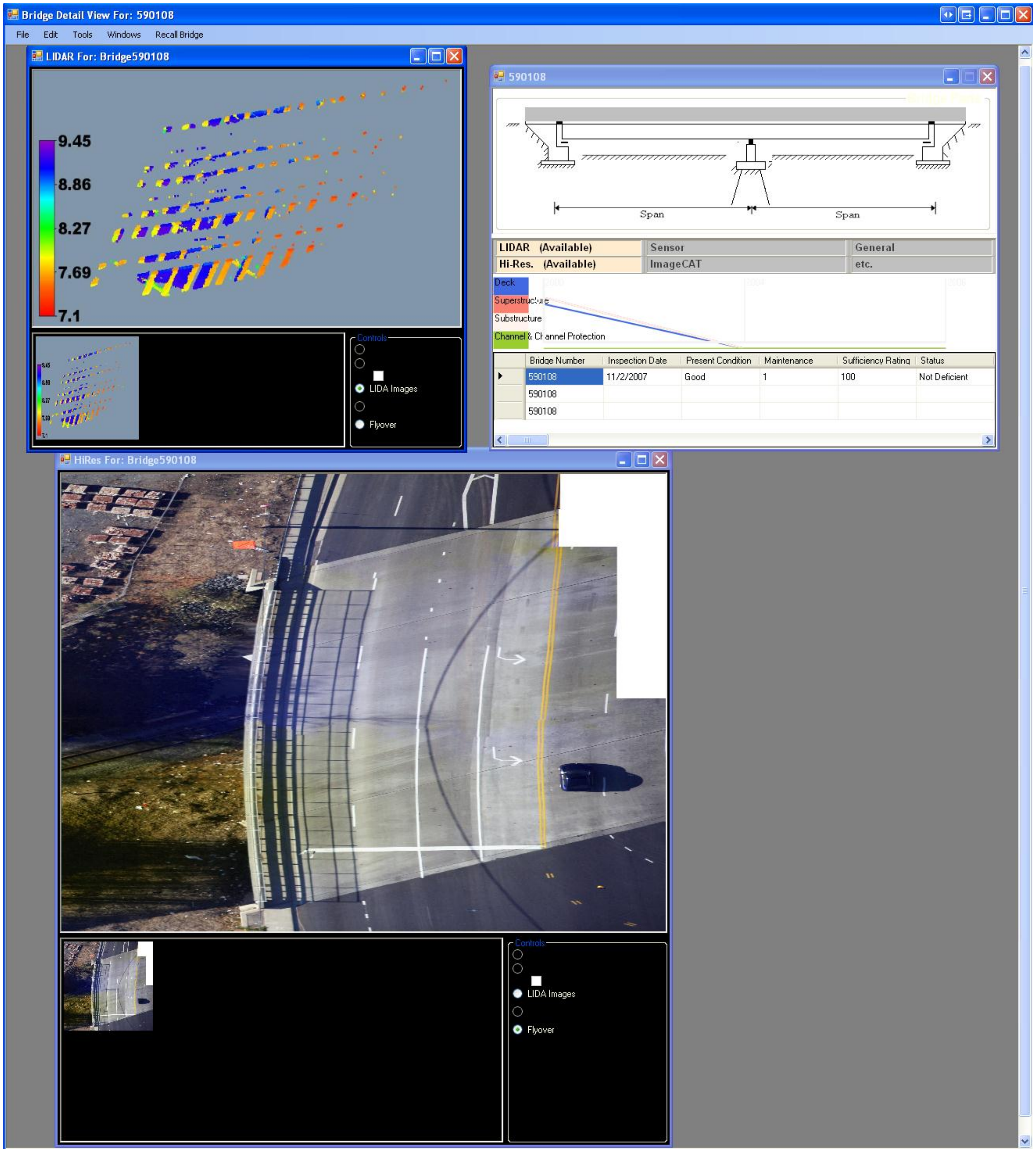
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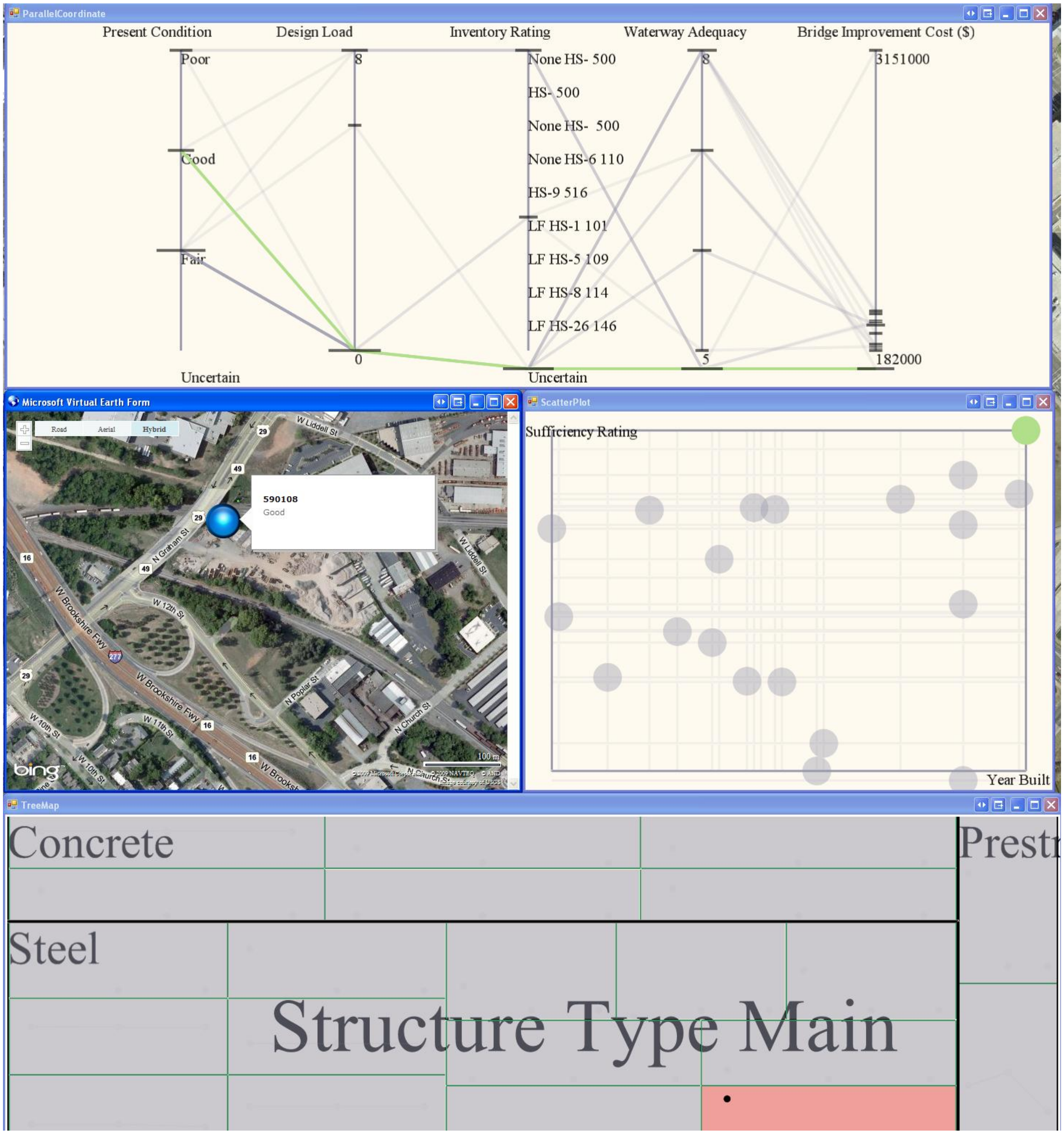
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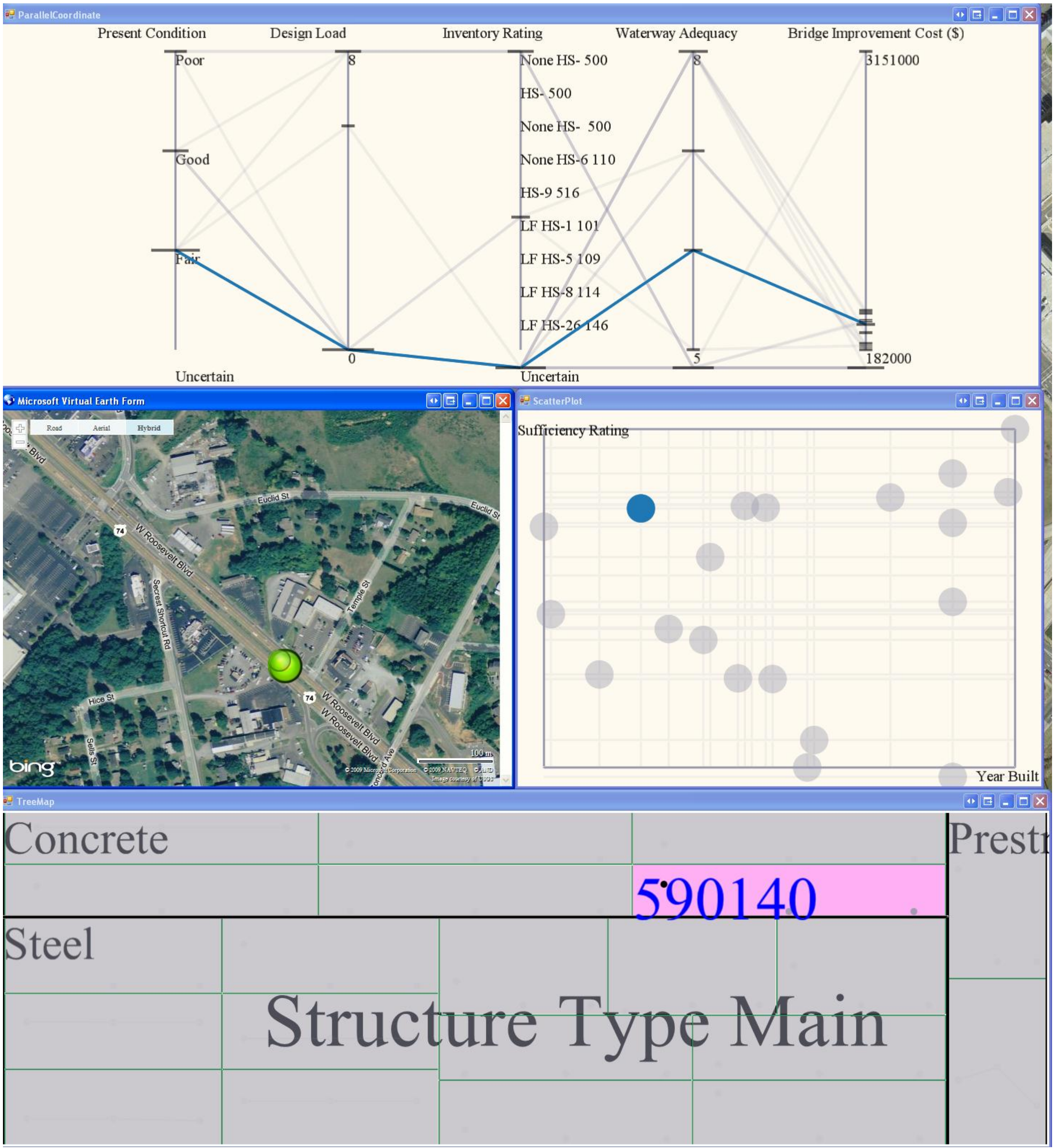
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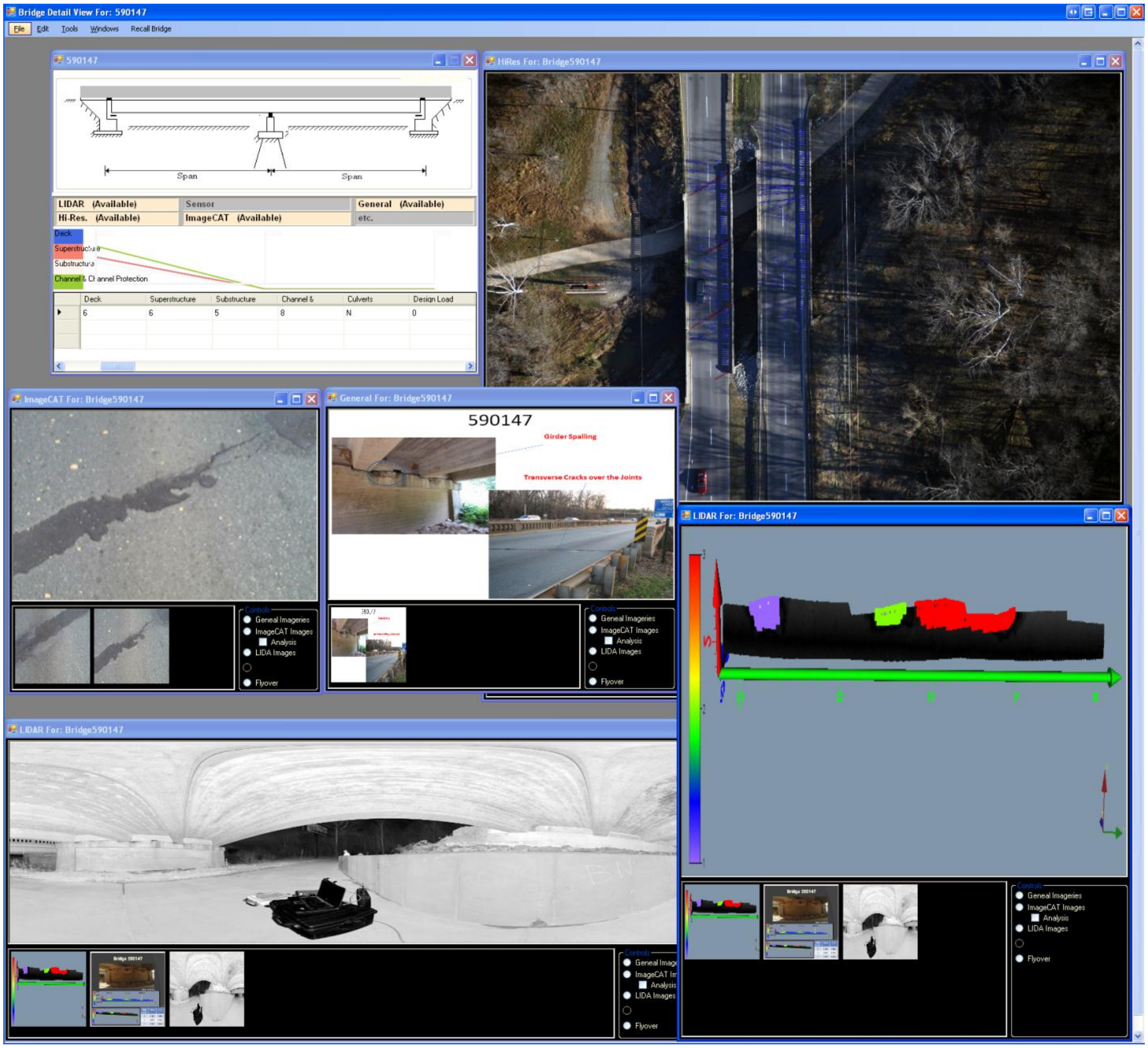
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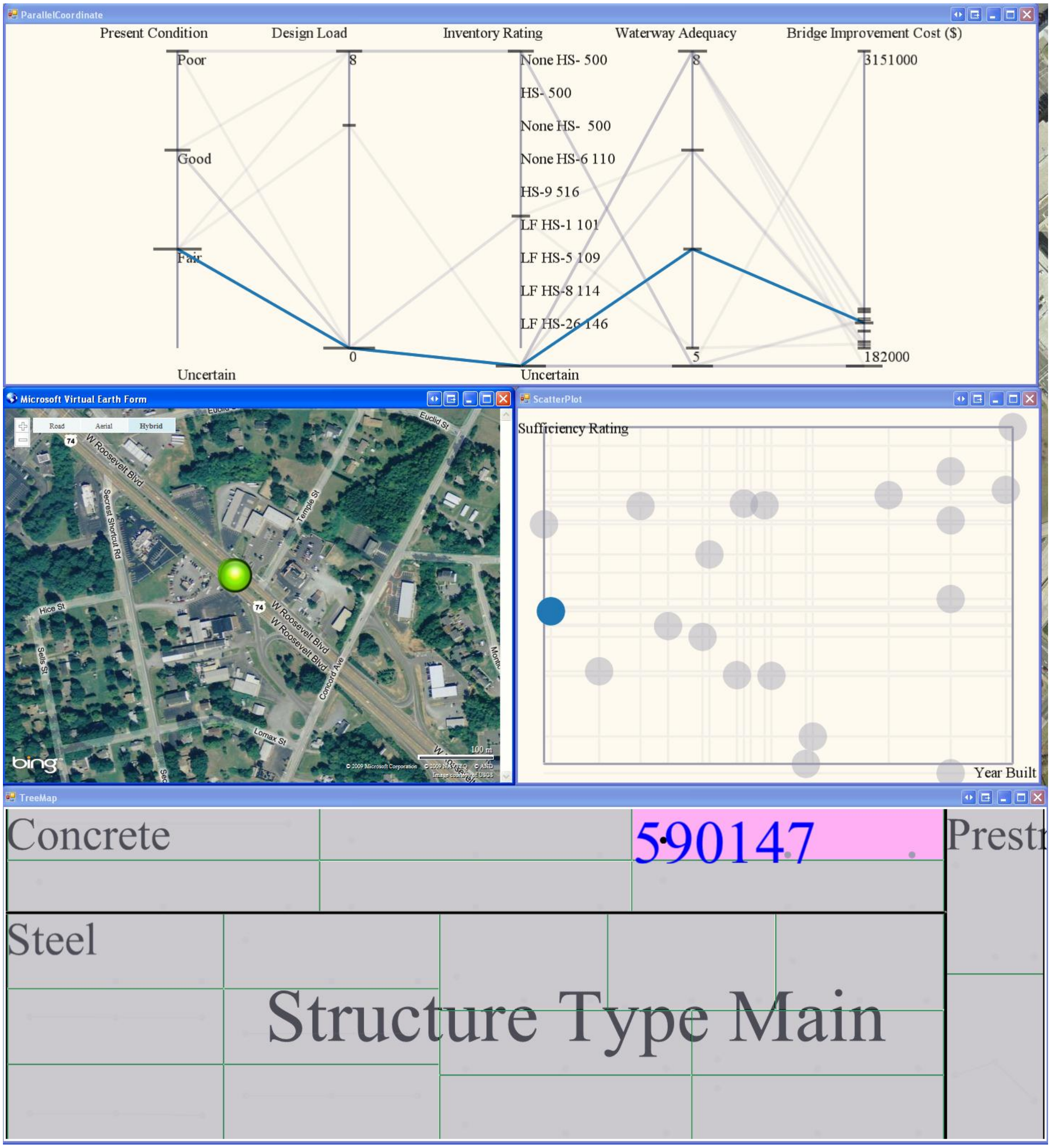
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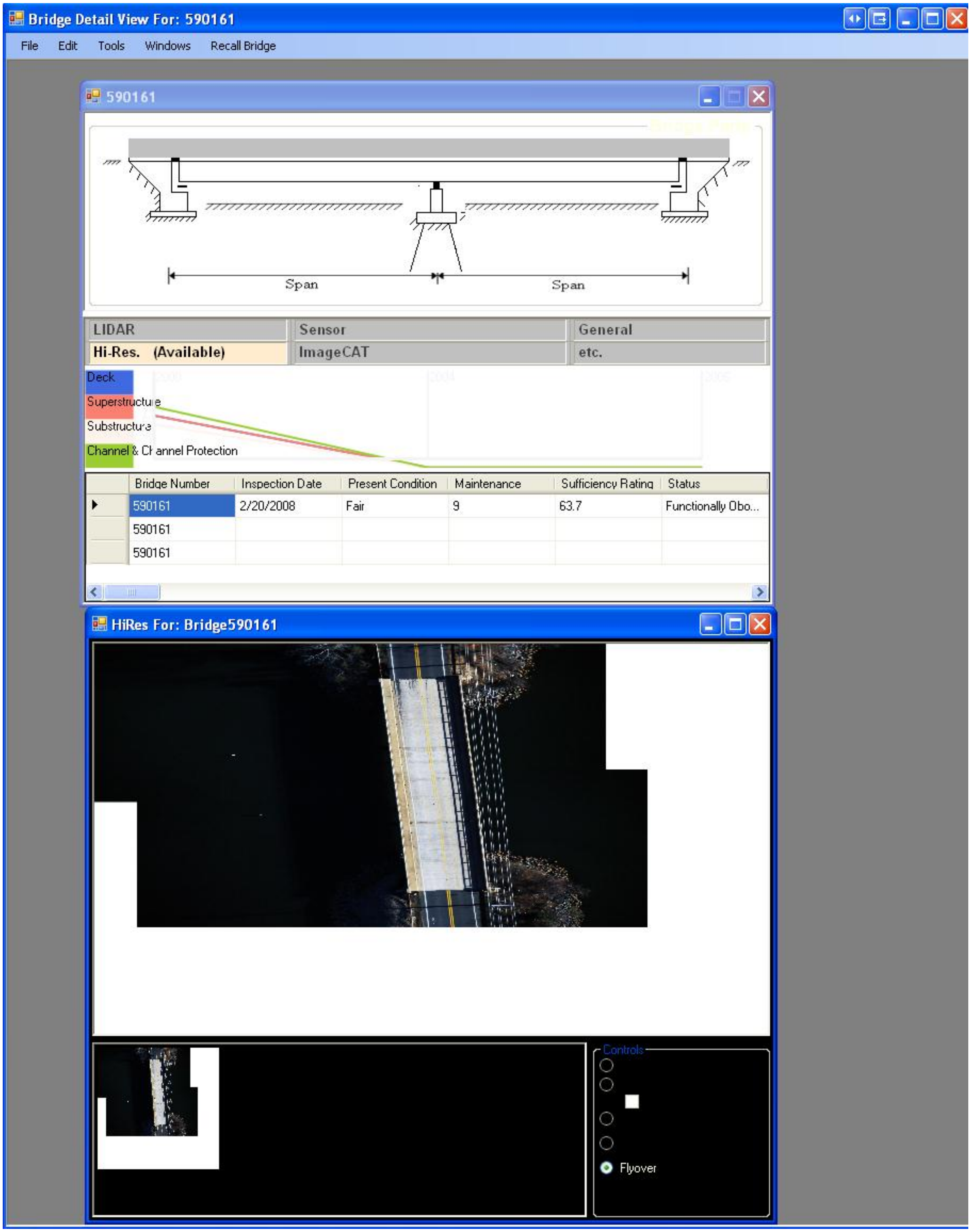

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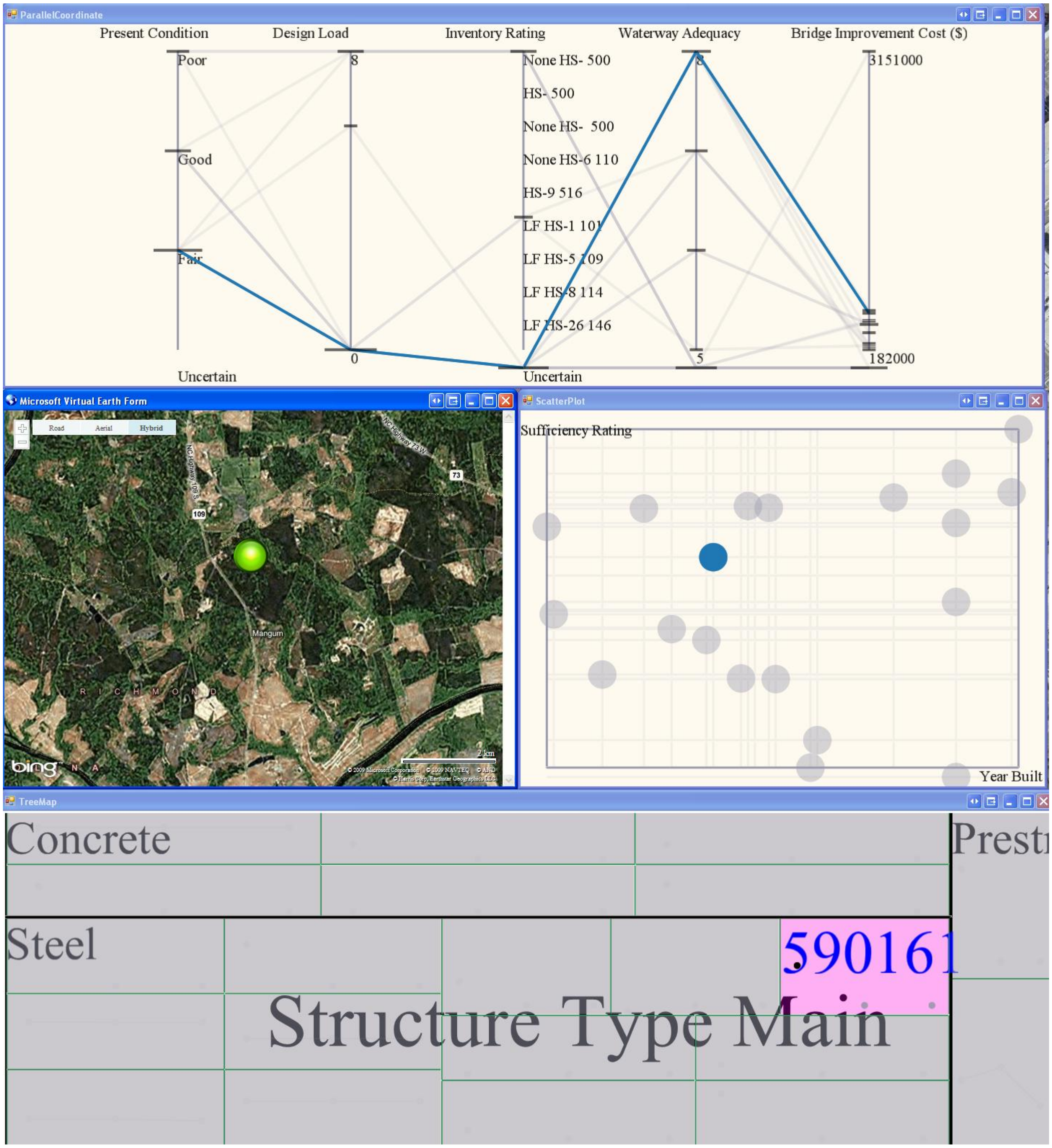
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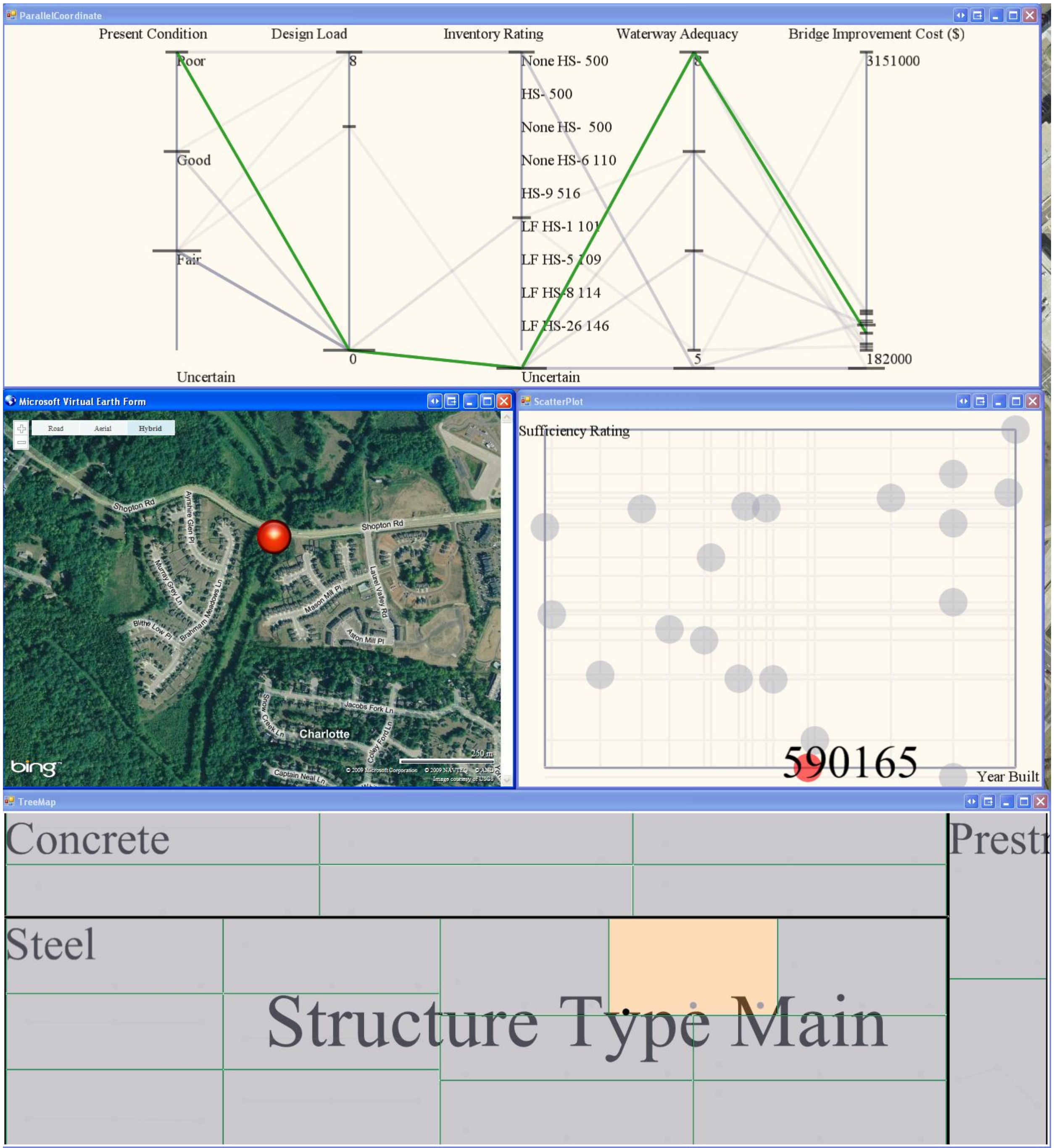
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Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
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Good
Fair
Uncertain
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None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
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182000
Microsoft Virtual Earth Form
Road
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bing
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Sufficiency Rating
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Year Built
TreeMap
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Prestr
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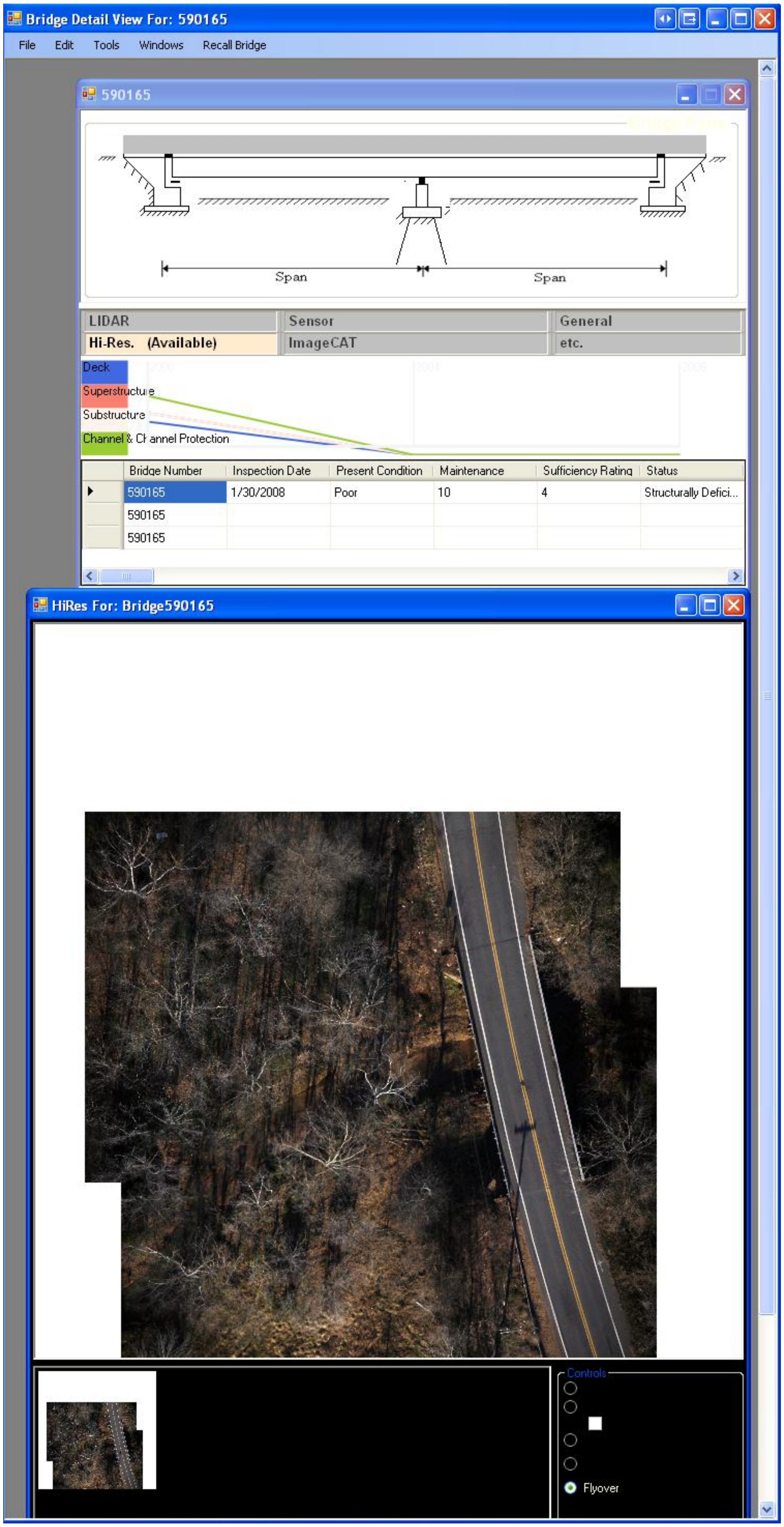
Structure Type Main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ImageCAT
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
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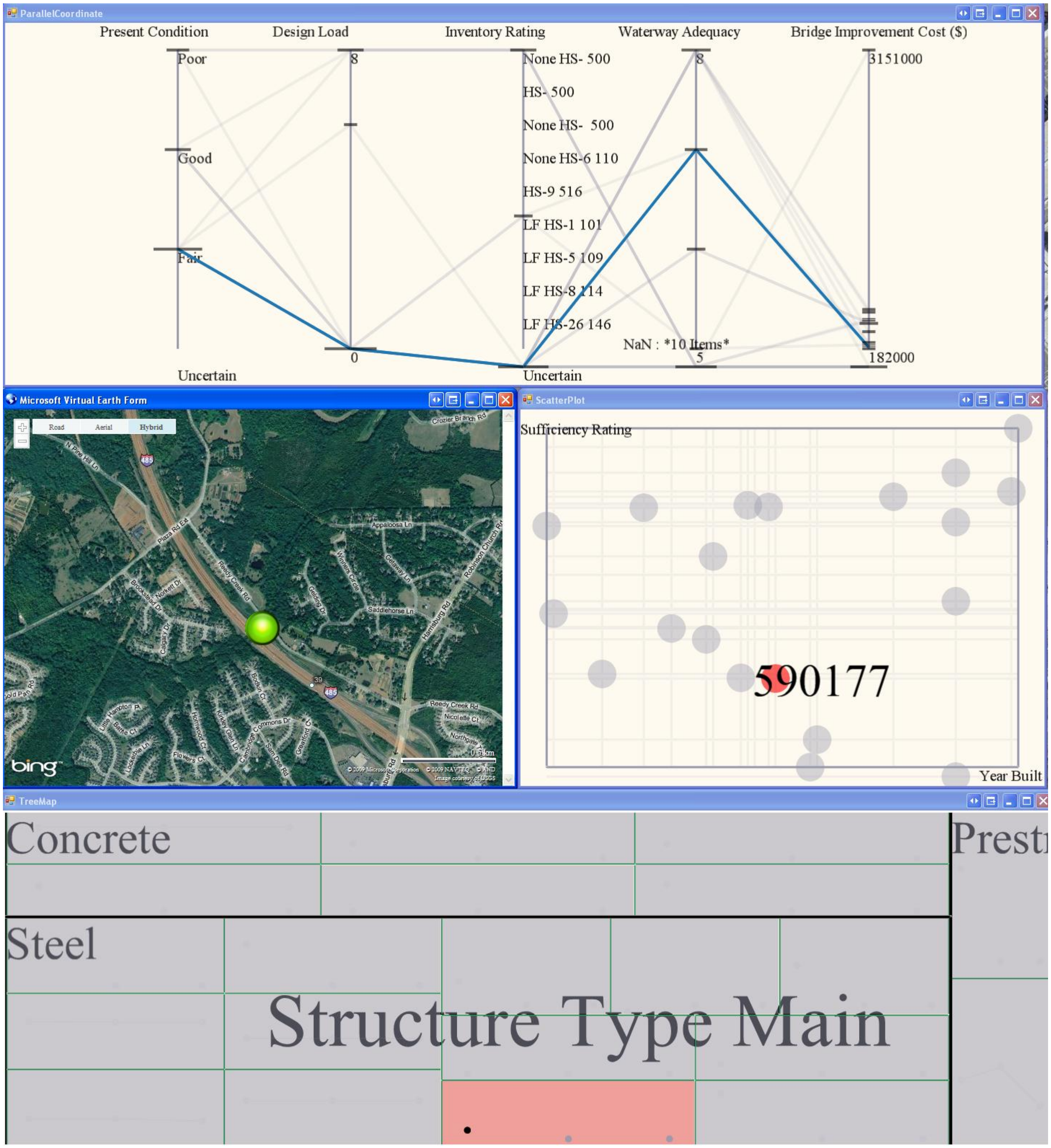
Controls
Flyover

590177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Inventory Rating
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
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LF HS-8 114
LF HS-26 146
Uncertain
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182000
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ScatterPlot
Sufficiency Rating
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Year Built
TreeMap
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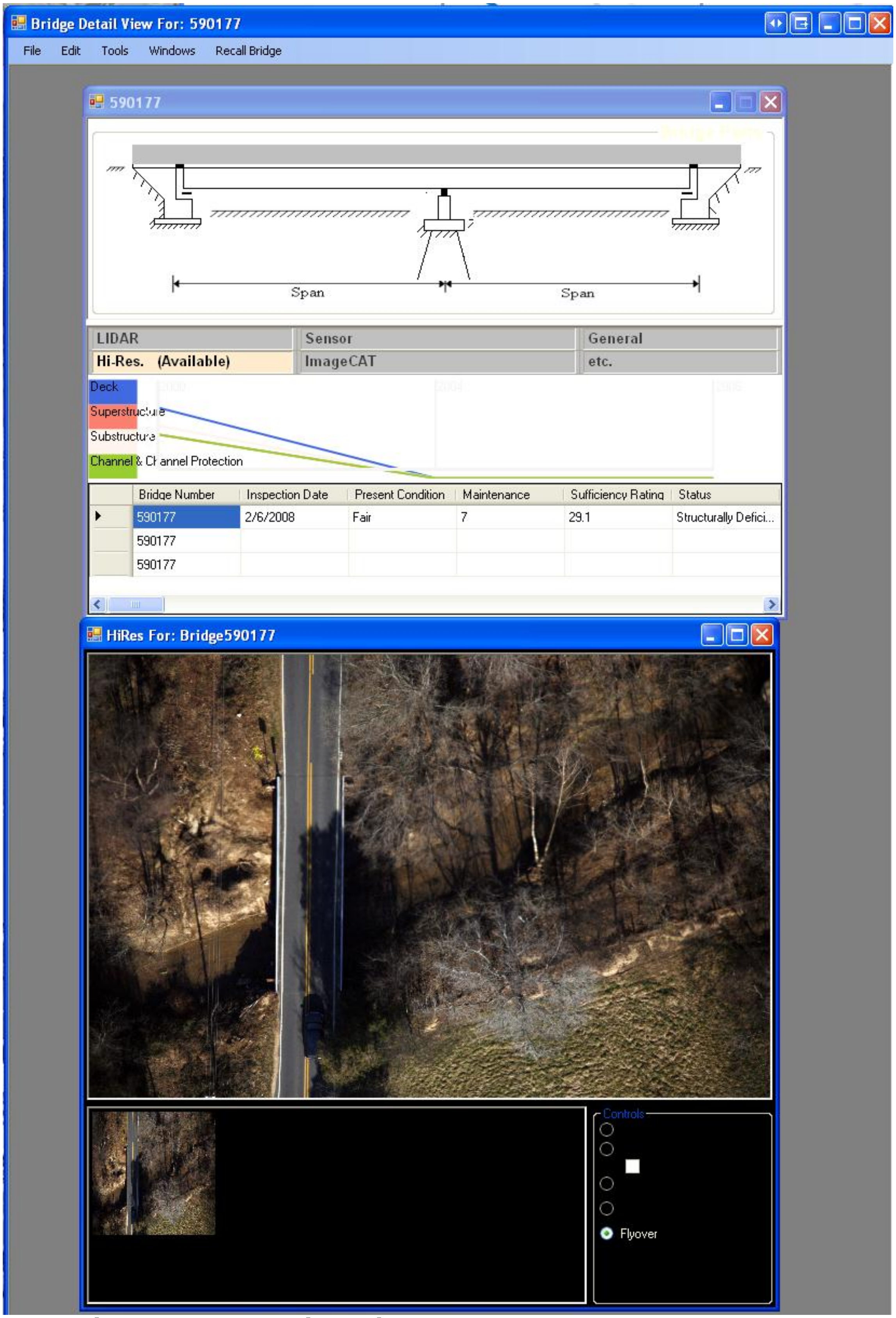
Prestr
Steel
Structure Type Main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etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
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2/6/2008
Fair
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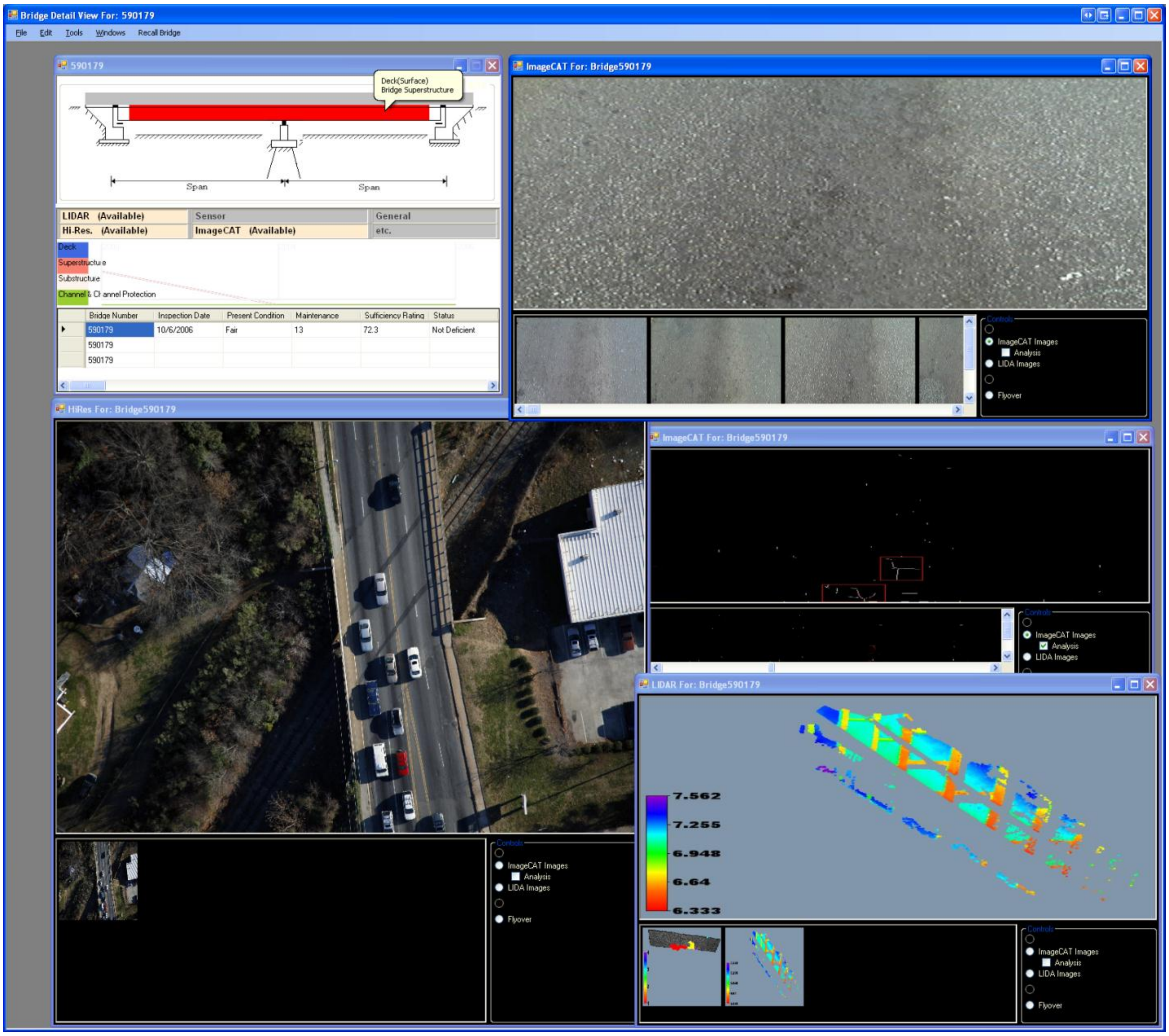
HiRes For: Bridge590177
Controls
Flyover

590179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ImageCAT (Available)
General
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
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10/6/2006
Fair
13
72.3
Not Deficient
590179
590179
ImageCAT For: Bridge590179
HiRes For: Bridge590179
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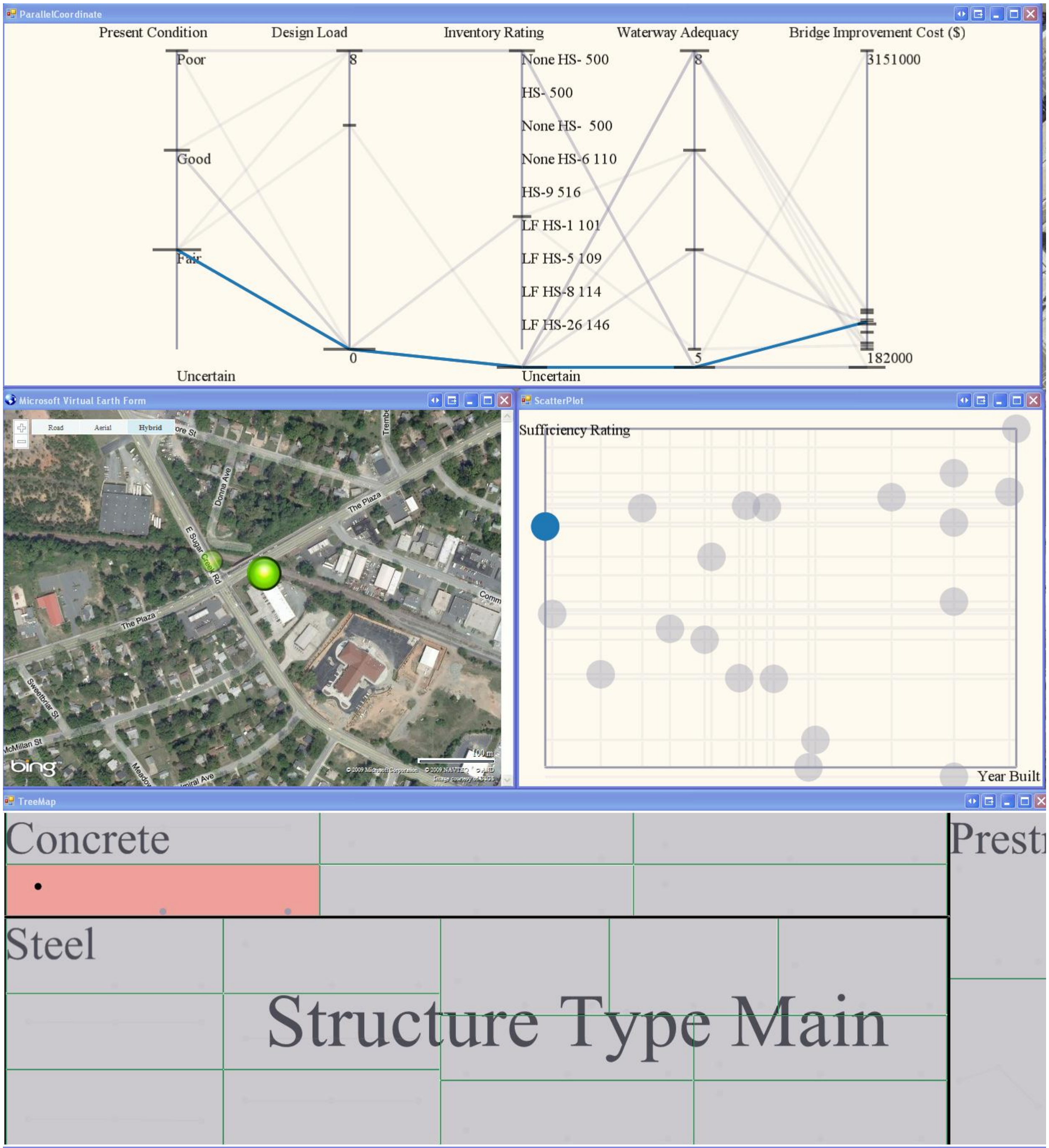
6.333
ImageCAT Images
Analysis
LIDA Images
Flyover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Waterway Adequacy
Bridge Improvement Cost ($)
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Good
Fair
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
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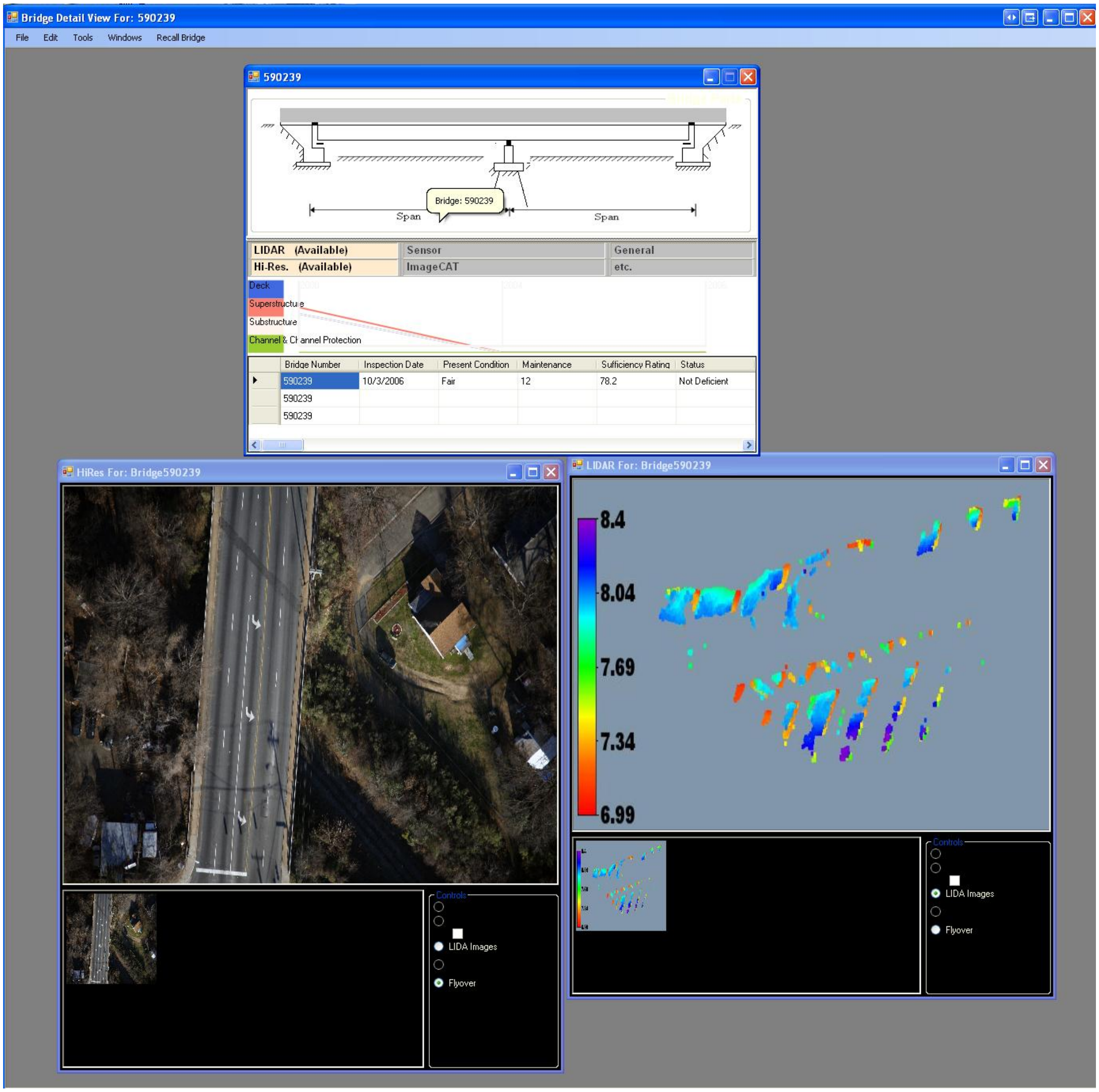
Microsoft Virtual Earth Form
ScatterPlot
Sufficiency Rating
Year Built
TreeMap
Concrete
Steel
Structure Type Main
Prest

590239



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Sensor
ImageCAT
General
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
590239
10/3/2006
Fair
12
78.2
Not Deficient
590239
590239
HiRes For: Bridge590239
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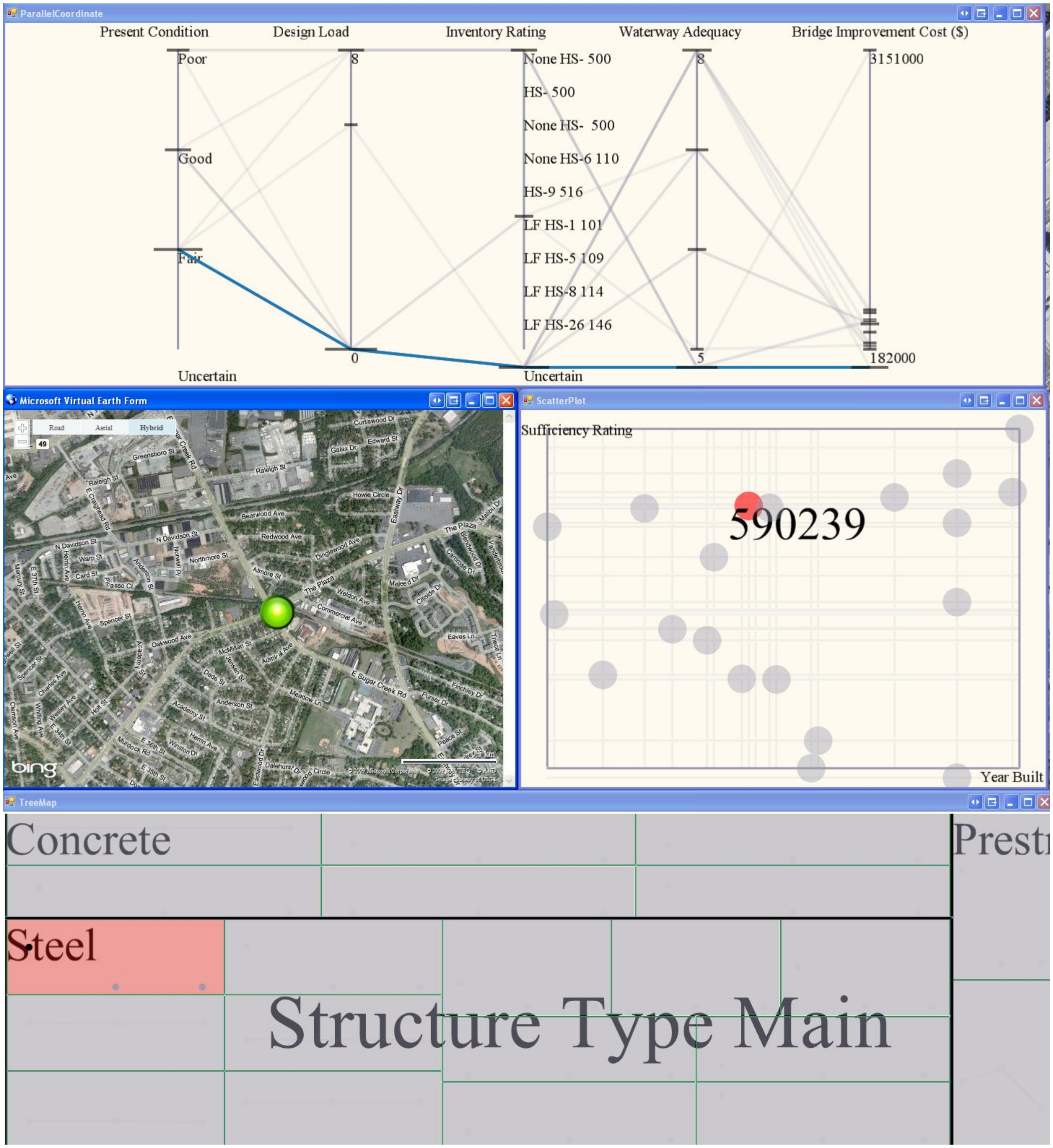
Controls
LIDA Images
Flyover
Controls
LIDA Images
Flyover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Present Condition
Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
Poor
Good
Fair
Uncertain
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0
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
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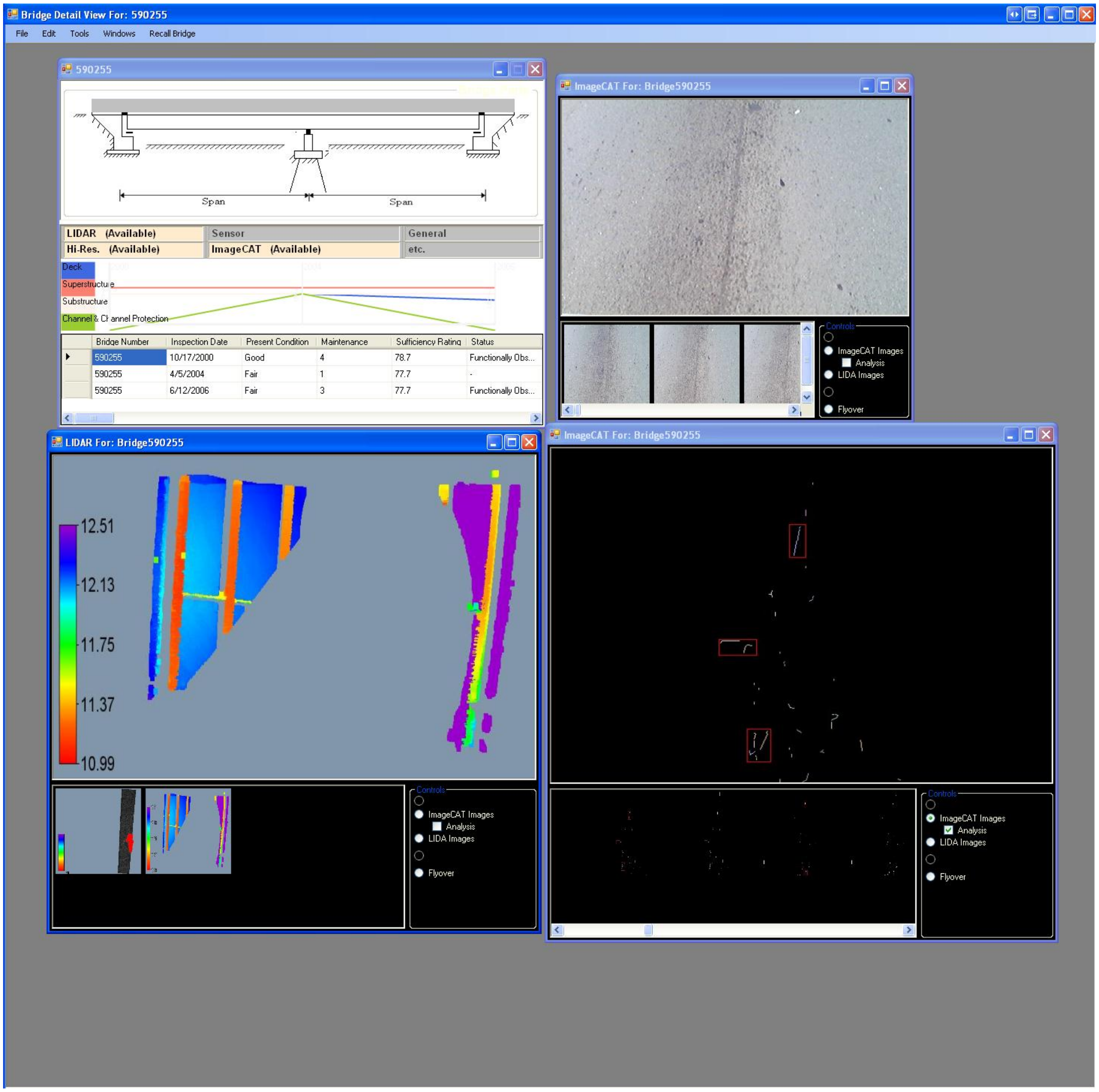
3151000
182000
Microsoft Virtual Earth Form
ScatterPlot
Sufficiency Rating
590239
Year Built
TreeMap
Concrete
Prest
Steel
Structure Type Main

590255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Tools
Windows
Recall Bridge
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Span
Span
LIDAR (Available)
Hi-Res. (Available)
Sensor
ImageCAT (Available)
General
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
590255
10/17/2000
Good
4
78.7
Functionally Obs...
590255
4/5/2004
Fair
1
77.7
-
590255
6/12/2006
Fair
3
77.7
Functionally Obs...
ImageCAT For: Bridge590255
Controls
ImageCAT Images
Analysis
LIDA Images
Flyover
LIDAR For: Bridge590255
12.51
12.13
11.75
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Controls
ImageCAT Images
Analysis
LIDA Images
Flyover
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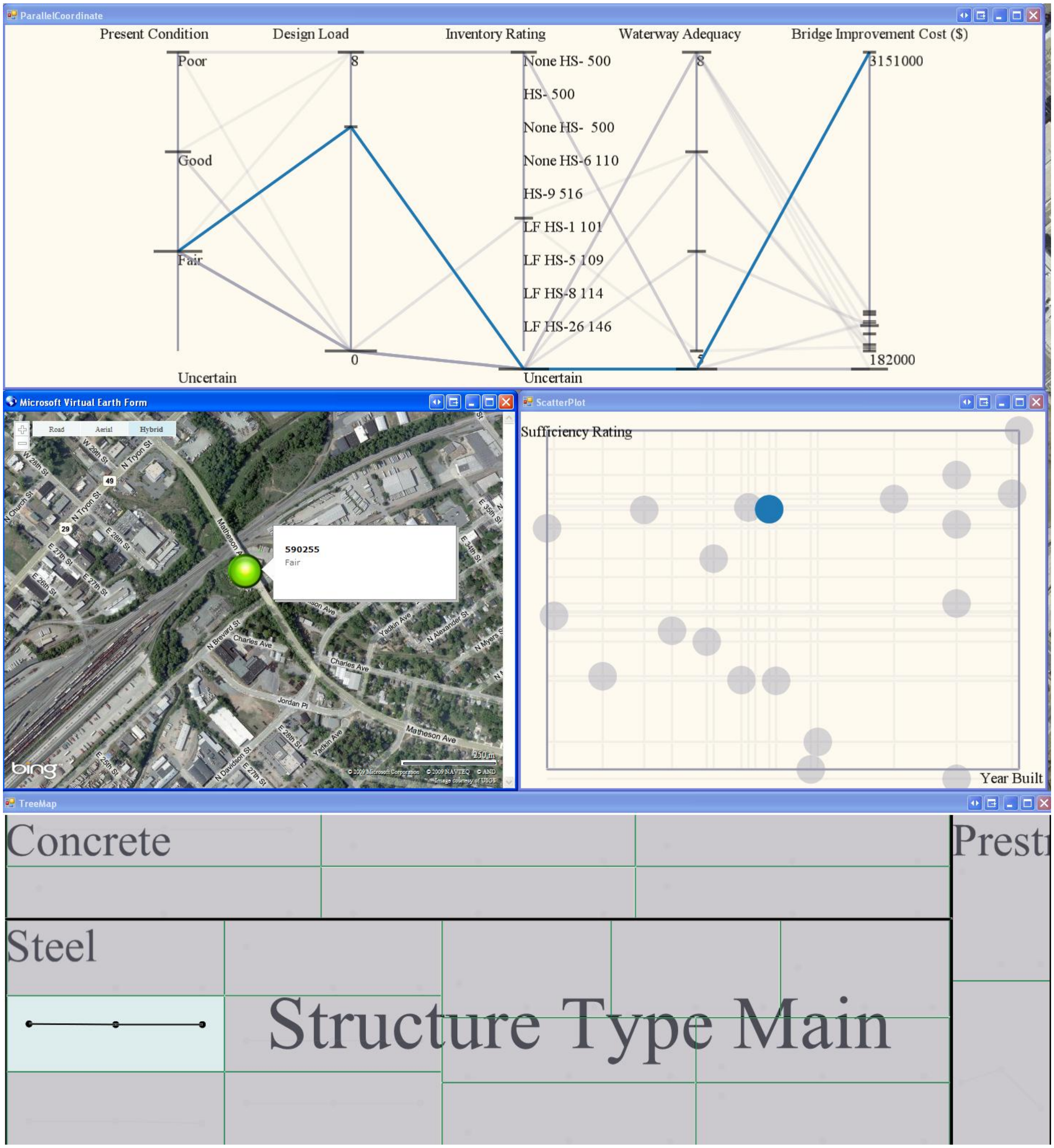
Controls
ImageCAT Images
Analysis
LIDA Images
Flyover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Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
Poor
Good
Fair
Uncertain
8
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
3151000
182000
Microsoft Virtual Earth Form
Road
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Hybrid
590255
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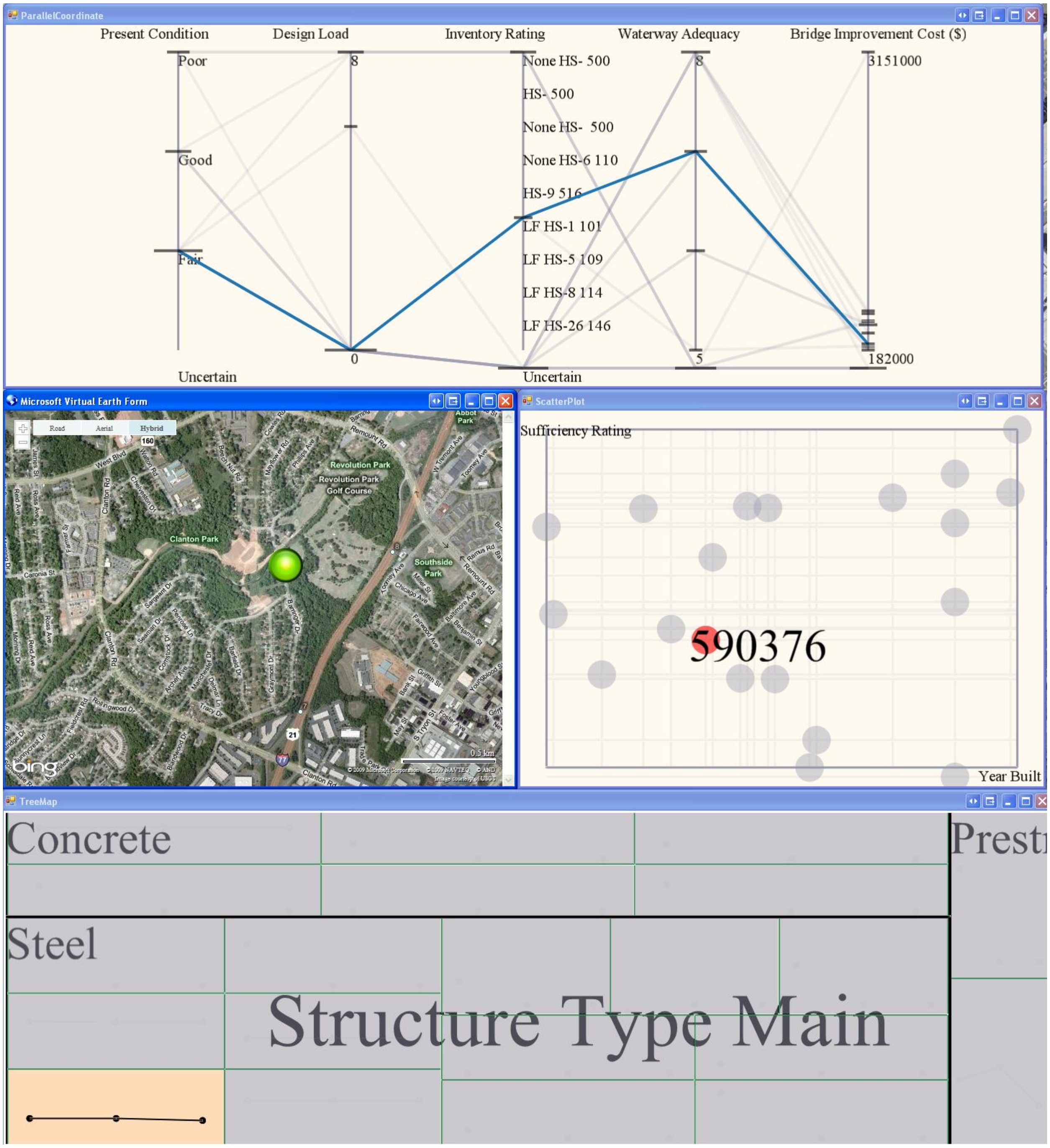
ScatterPlot
Sufficiency Rating
Year Built
TreeMap
Concrete
Prestr
Steel
Structure Type Main

590376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Present Condition
Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
Poor
Good
Fair
Uncertain
8
0
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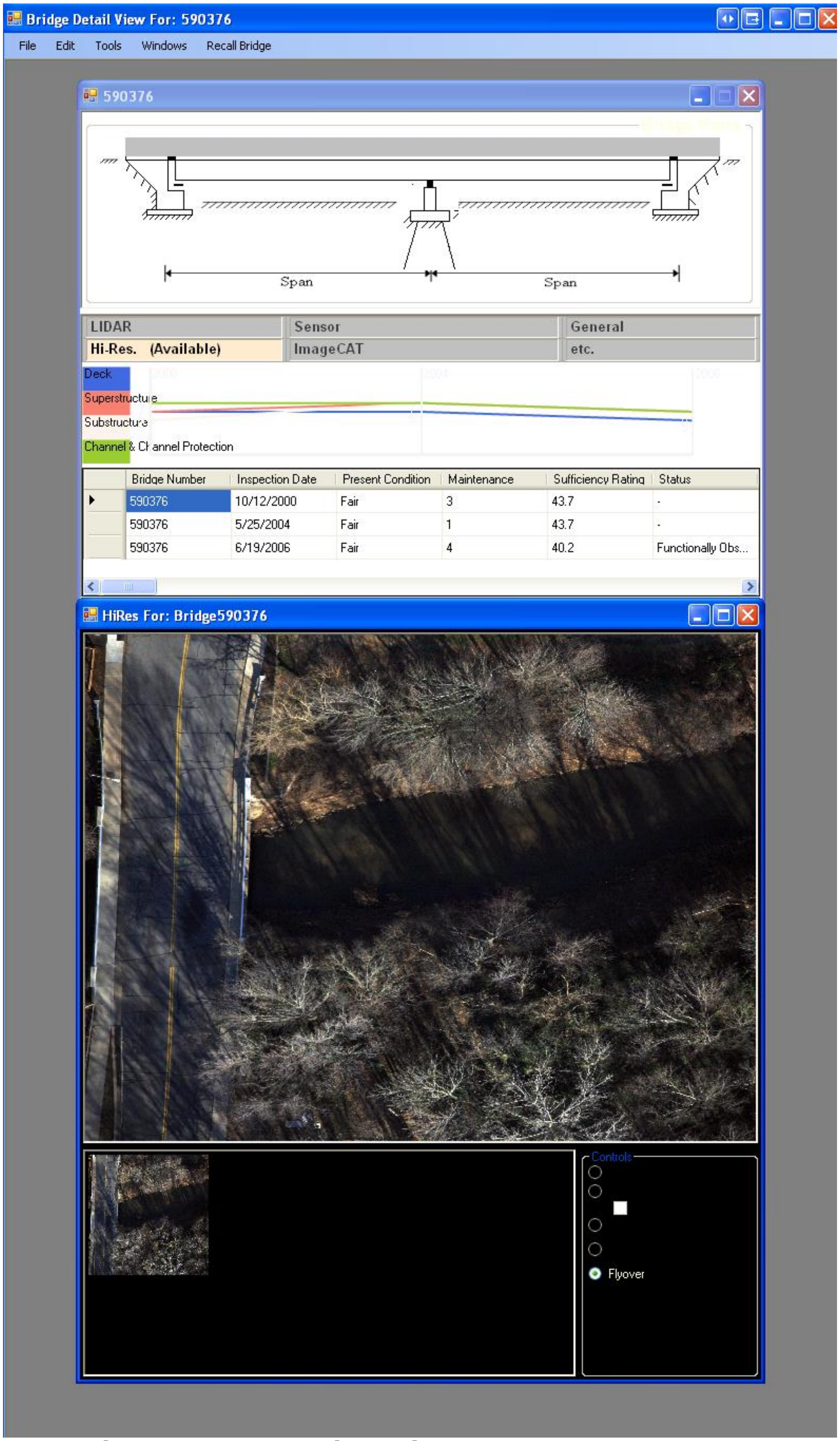
HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
5
3151000
182000
Microsoft Virtual Earth Form
ScatterPlot
Sufficiency Rating
590376
Year Built
TreeMap
Concrete
Prest
Steel
Structure Type Main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Tools
Windows
Recall Bridge
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Span
LIDAR
Sensor
General
Hi-Res. (Available)
ImageCAT
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
590376 10/12/2000 Fair 3 43.7 -
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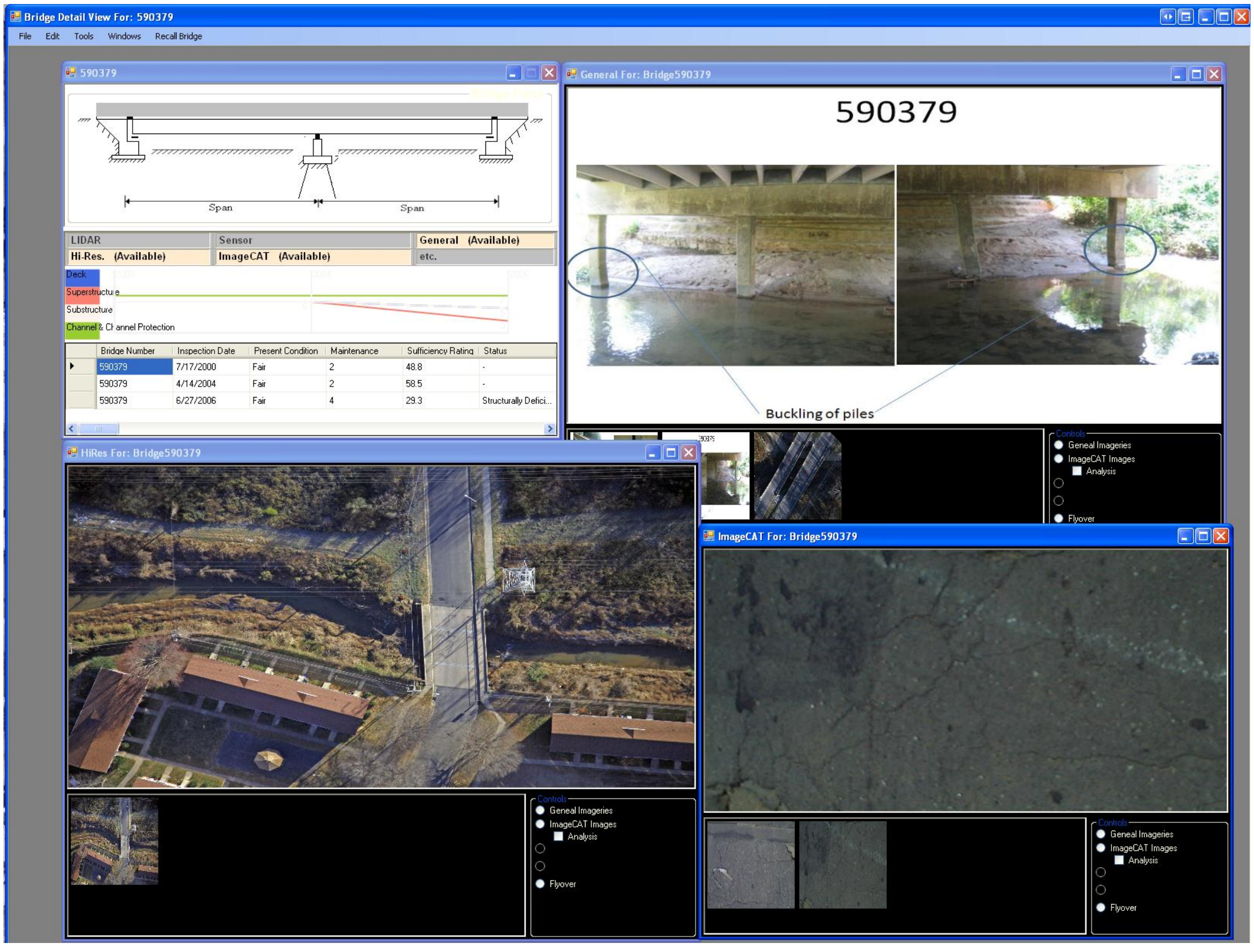
590376 6/19/2006 Fair 4 40.2 Functionally Obs...
HiRes For: Bridge590376
Controls
Flyover

590379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Tools
Windows
Recall Bridge
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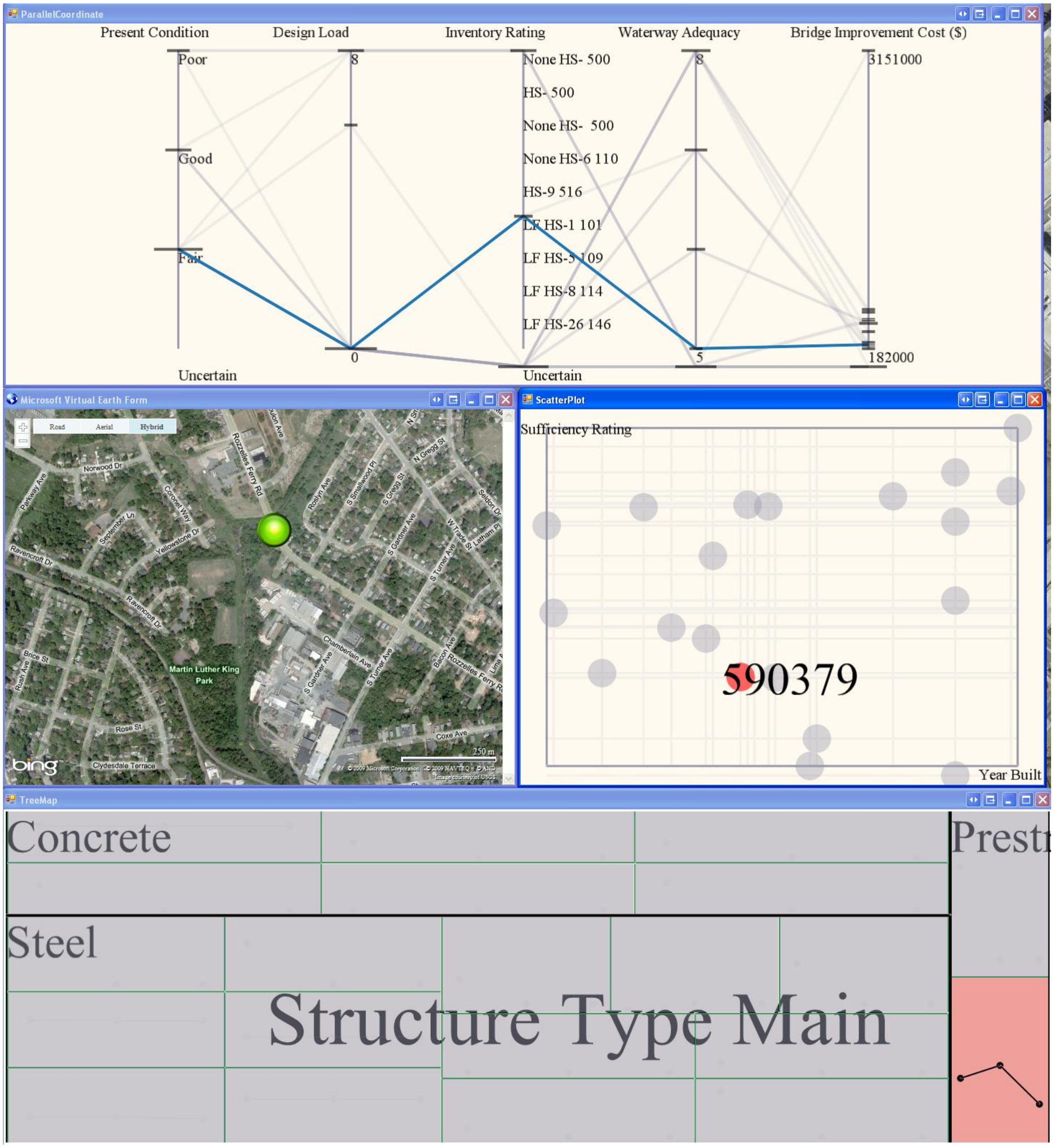
Span
Span
LIDAR
Sensor
General (Available)
Hi-Res. (Available)
ImageCAT (Available)
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
590379
7/17/2000
Fair
2
48.8
-
590379
4/14/2004
Fair
2
58.5
-
590379
6/27/2006
Fair
4
29.3
Structurally Defici...
General For: Bridge590379
590379
Buckling of piles
Controls
Geneal Imageries
ImageCAT Images
Analysis
Flyover
HiRes For: Bridge590379
Controls
Geneal Imageries
ImageCAT Images
Analysis
Flyover
ImageCAT For: Bridge590379
Controls
Geneal Imageries
ImageCAT Images
Analysis
Flyover


ParallelCoordinate
Present Condition
Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
Poor
Good
Fair
Uncertain
8
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
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182000
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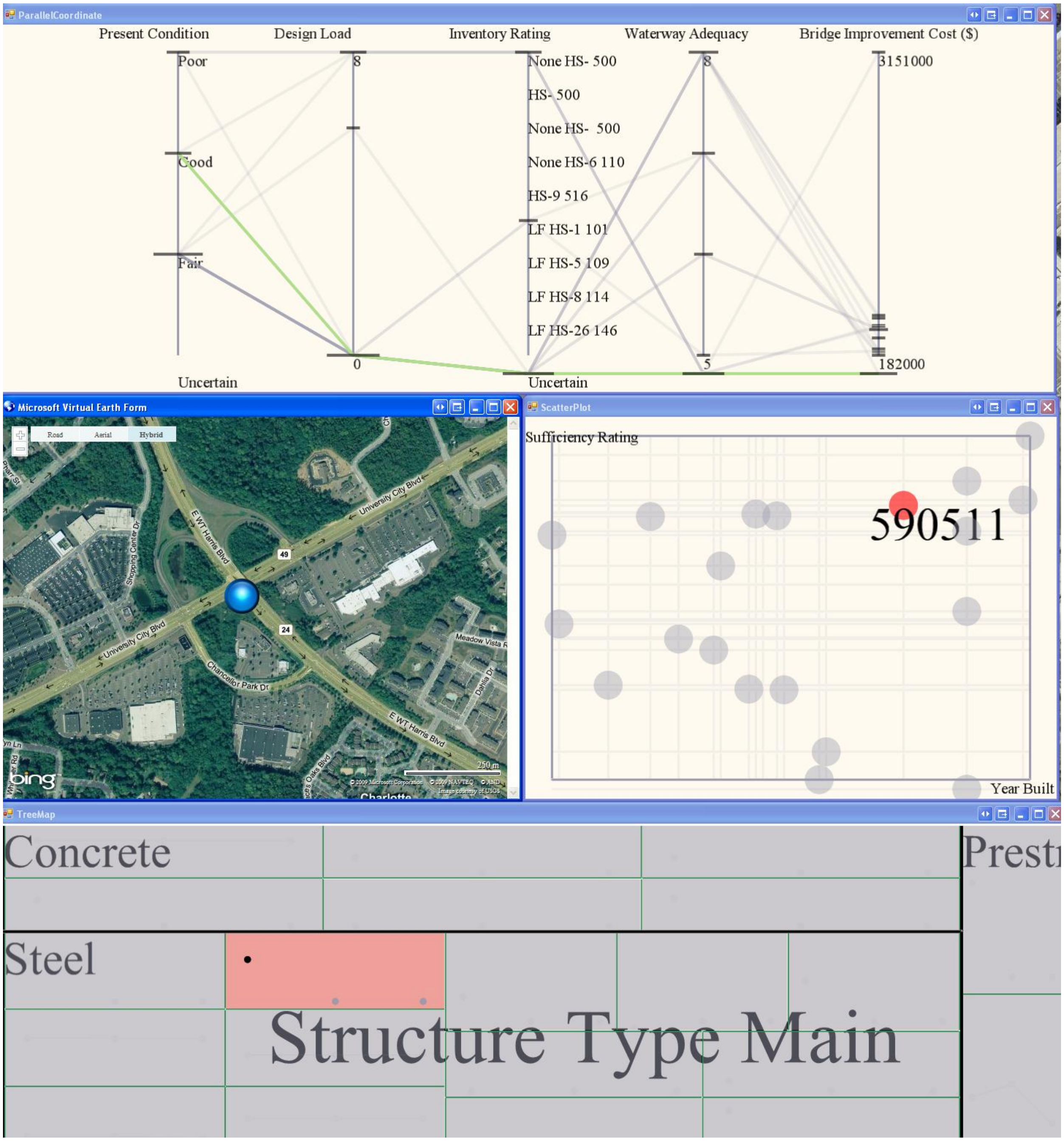
ScatterPlot
Sufficiency Rating
590379
Year Built
TreeMap
Concrete
Prestr
Steel
Structure Type Main

590511


ParallelCoordinate
Present Condition
Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
Poor
Good
Fair
Uncertain
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
5
3151000
182000
Microsoft Virtual Earth Form
Road
Aerial
Hybrid
University City Blvd
E WT Harris Blvd
Shopping Center Dr
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Meadow Vista Rd
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ScatterPlot
Sufficiency Rating
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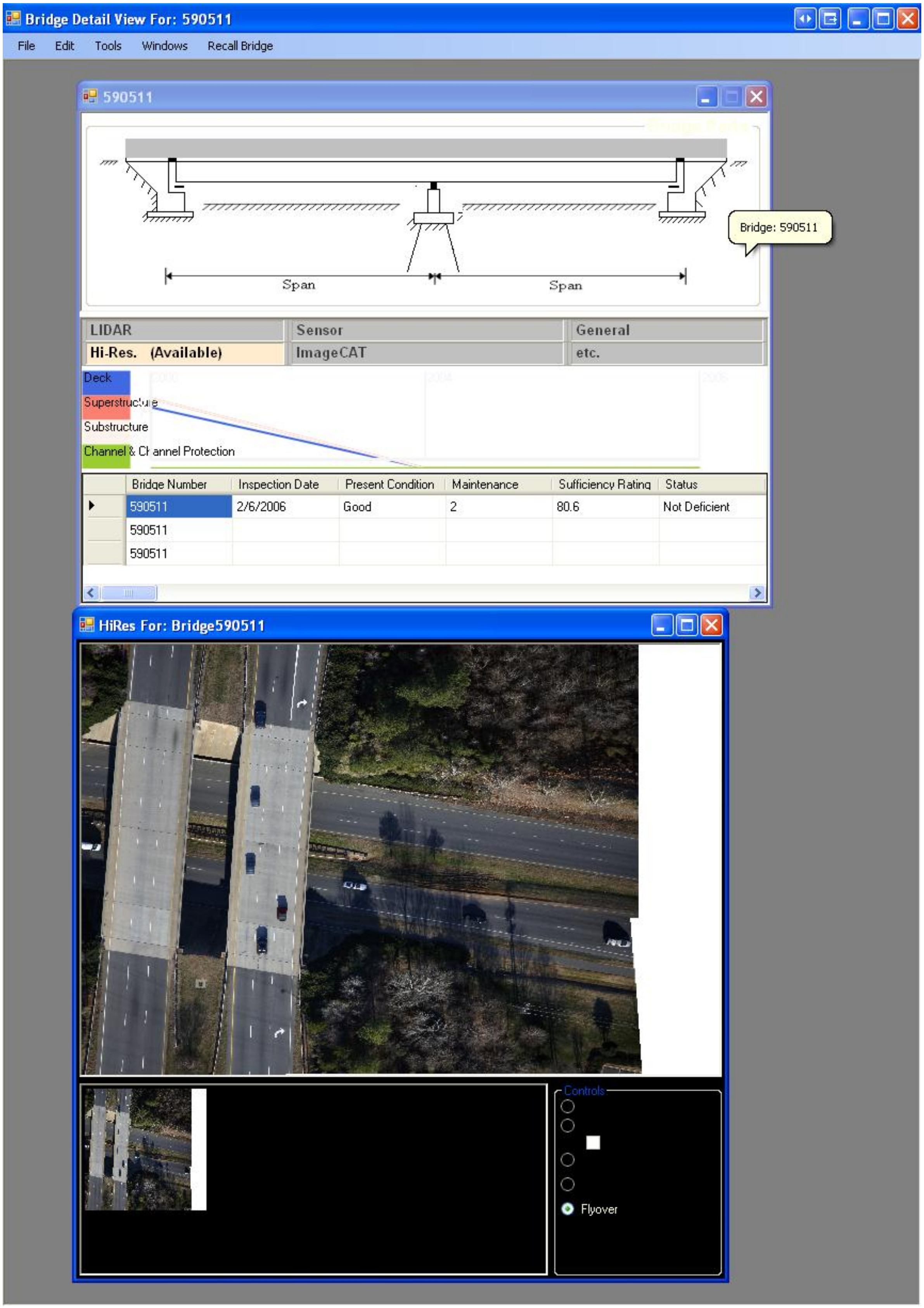
Year Built
TreeMap
Concrete
Prestr
Steel
Structure Type Main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Recall Bridge
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Span
Bridge: 590511
LIDAR
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Hi-Res. (Available)
ImageCAT
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
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590511
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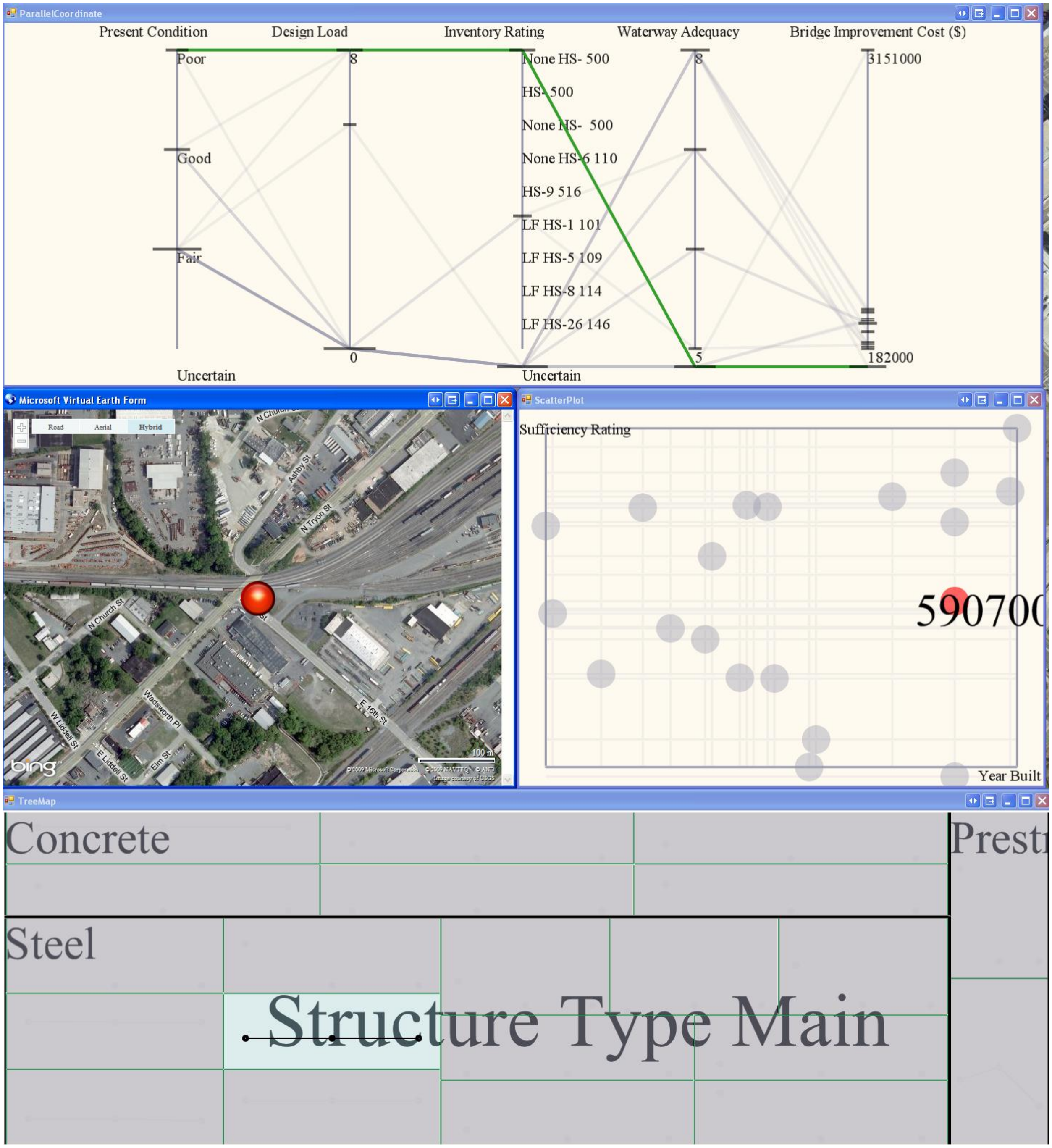
Controls
Flyover

590700



ParallelCoordinate
Present Condition
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Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
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Good
Fair
Uncertain
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HS- 500
None HS- 500
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HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
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Microsoft Virtual Earth Form
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Hybrid
bing
ScatterPlot
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Prestr
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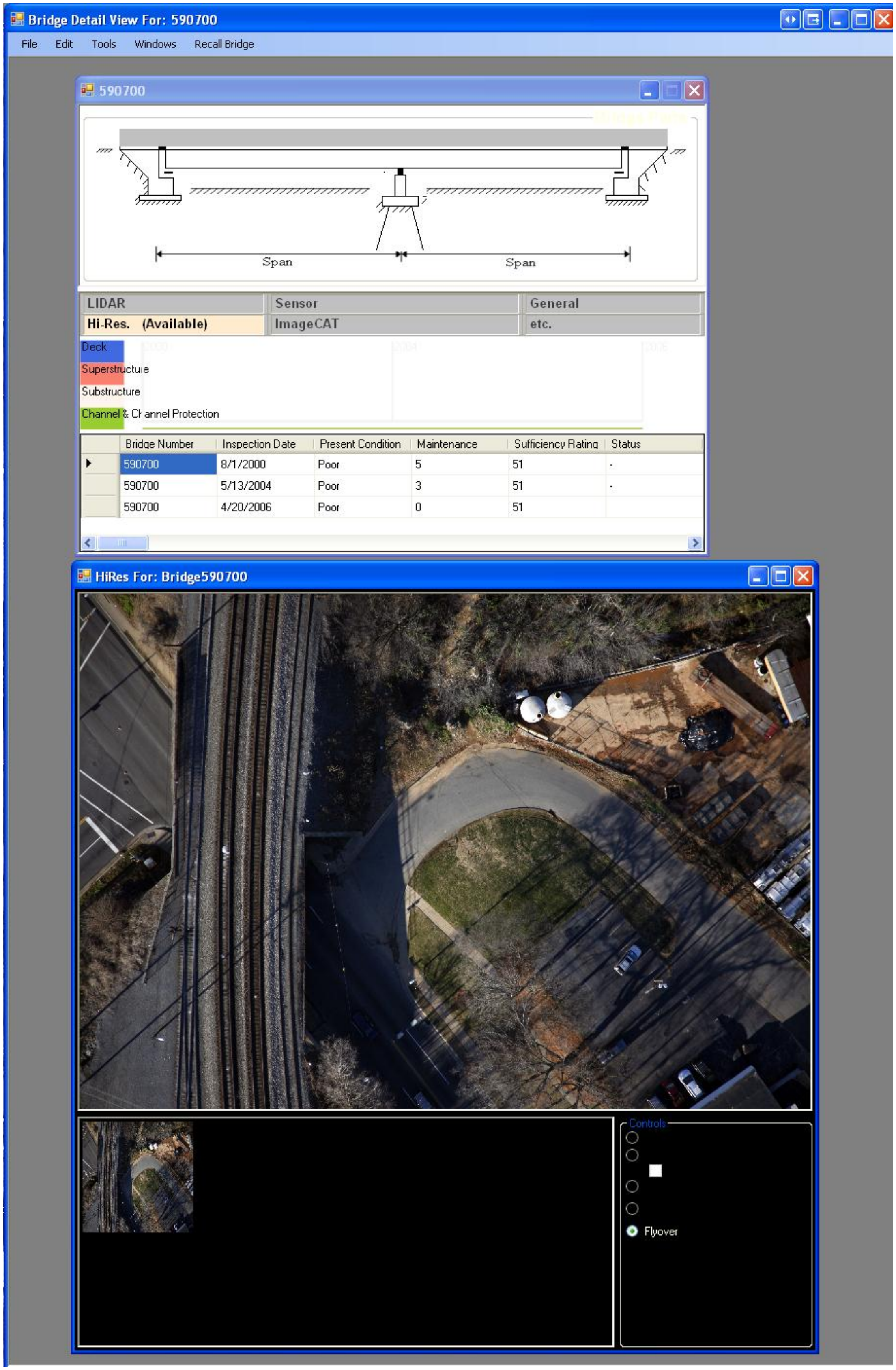
Structure Type Main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Recall Bridge
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LIDAR
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General
Hi-Res. (Available)
ImageCAT
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
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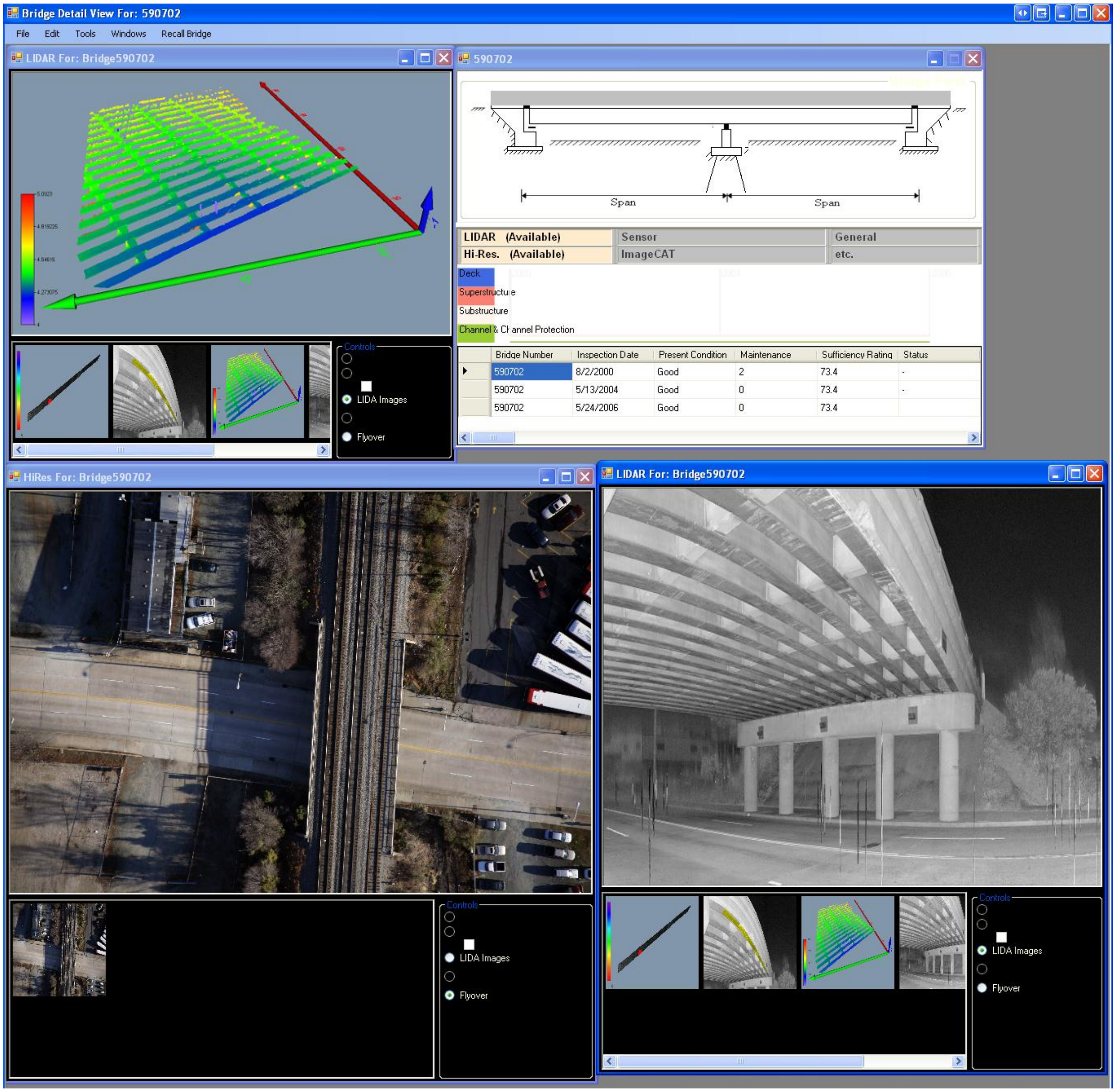
Controls
Flyover

590702



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Windows
Recall Bridge
LIDAR For: Bridge590702
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LIDAR (Available)
Hi-Res. (Available)
Sensor
ImageCAT
General
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
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8/2/2000
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2
73.4
590702
5/13/2004
Good
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73.4
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5/24/2006
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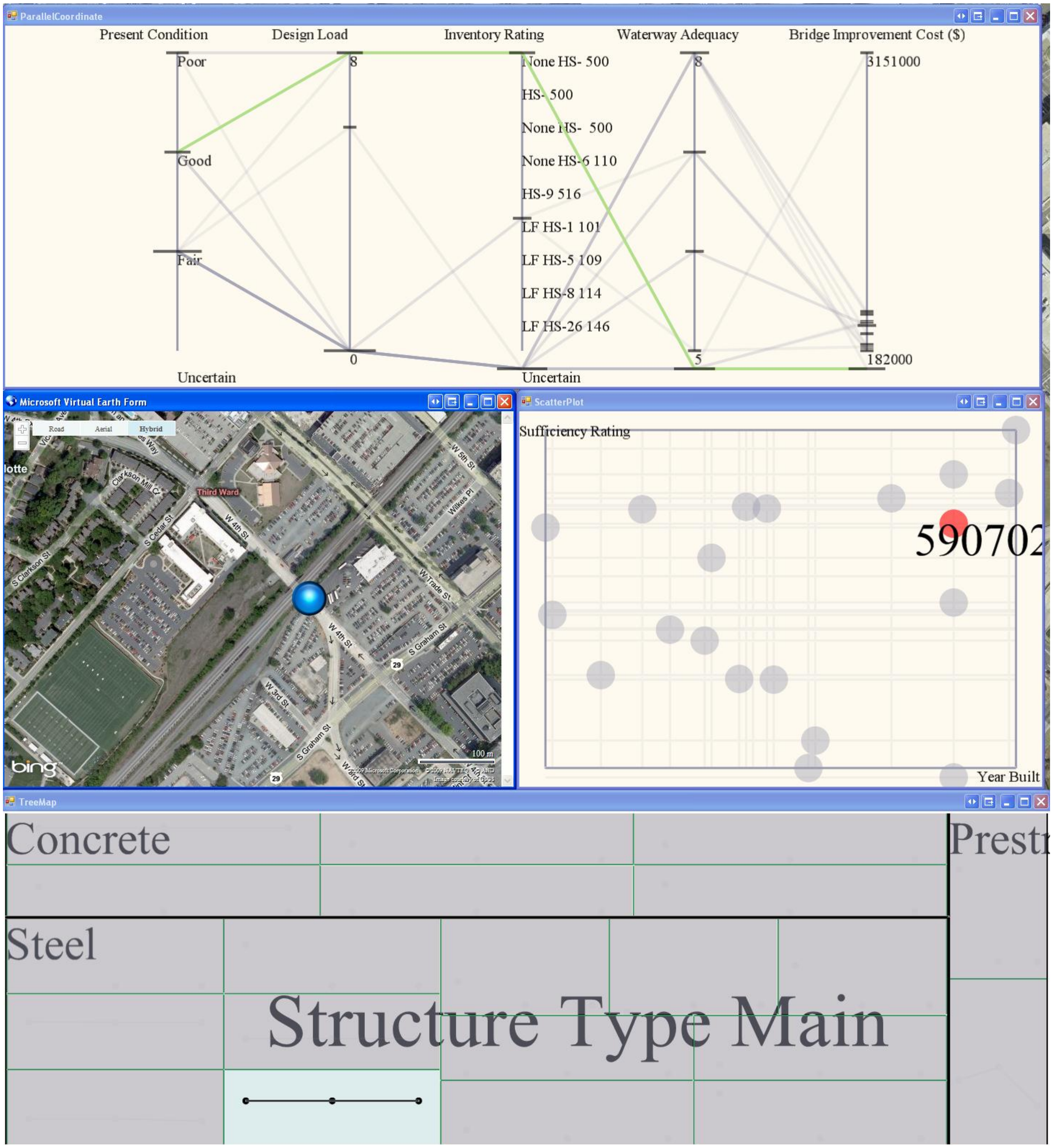
73.4
Controls
LIDA Images
Flyover
HiRes For: Bridge590702
LIDAR For: Bridge590702


ParallelCoordinate
Present Condition
Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
Poor
Good
Fair
Uncertain
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
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ScatterPlot
Sufficiency Rating
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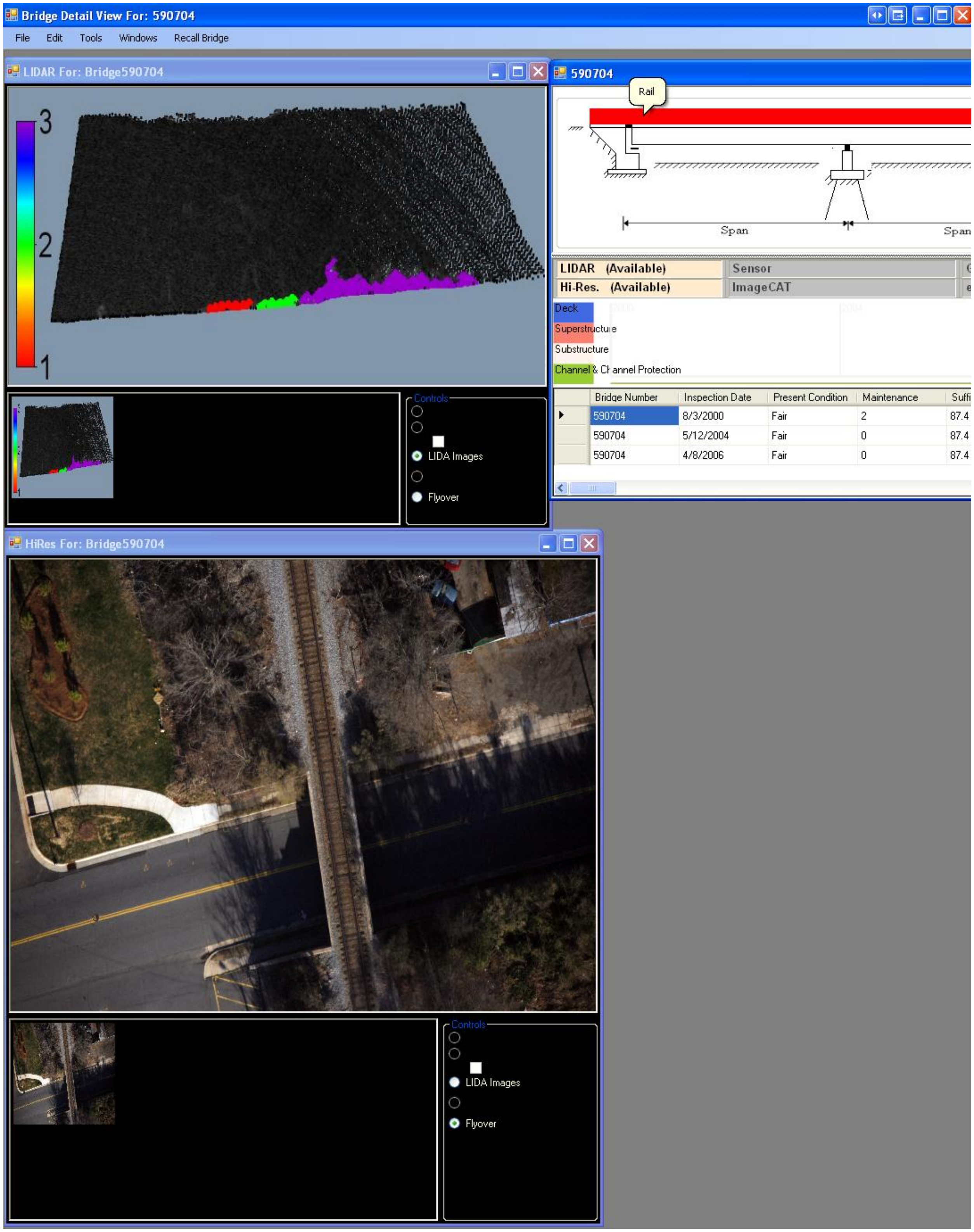
Year Built
TreeMap
Concrete
Prestr
Steel
Structure Type Main

590704



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Edit
Tools
Windows
Recall Bridge
LIDAR For: Bridge590704
3
2
1
Controls
LIDA Images
Flyover
590704
Rail
Span
Span
LIDAR (Available)
Hi-Res. (Available)
Sensor
ImageCAT
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
590704
8/3/2000
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4/8/2006
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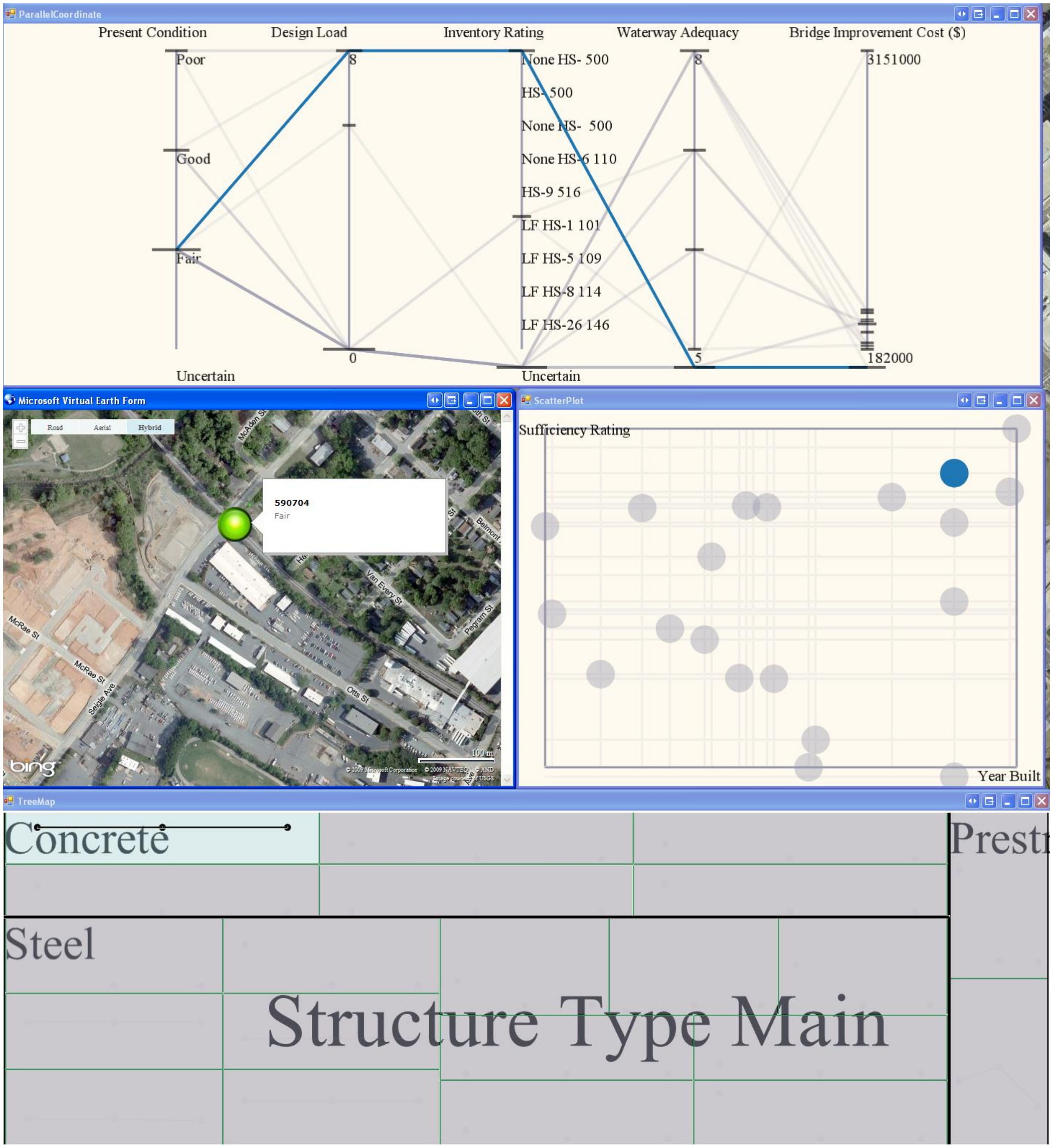
HiRes For: Bridge590704
Controls
LIDA Images
Flyover


ParallelCoordinate
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Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
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Good
Fair
Uncertain
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
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3151000
182000
Microsoft Virtual Earth Form
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Hybrid
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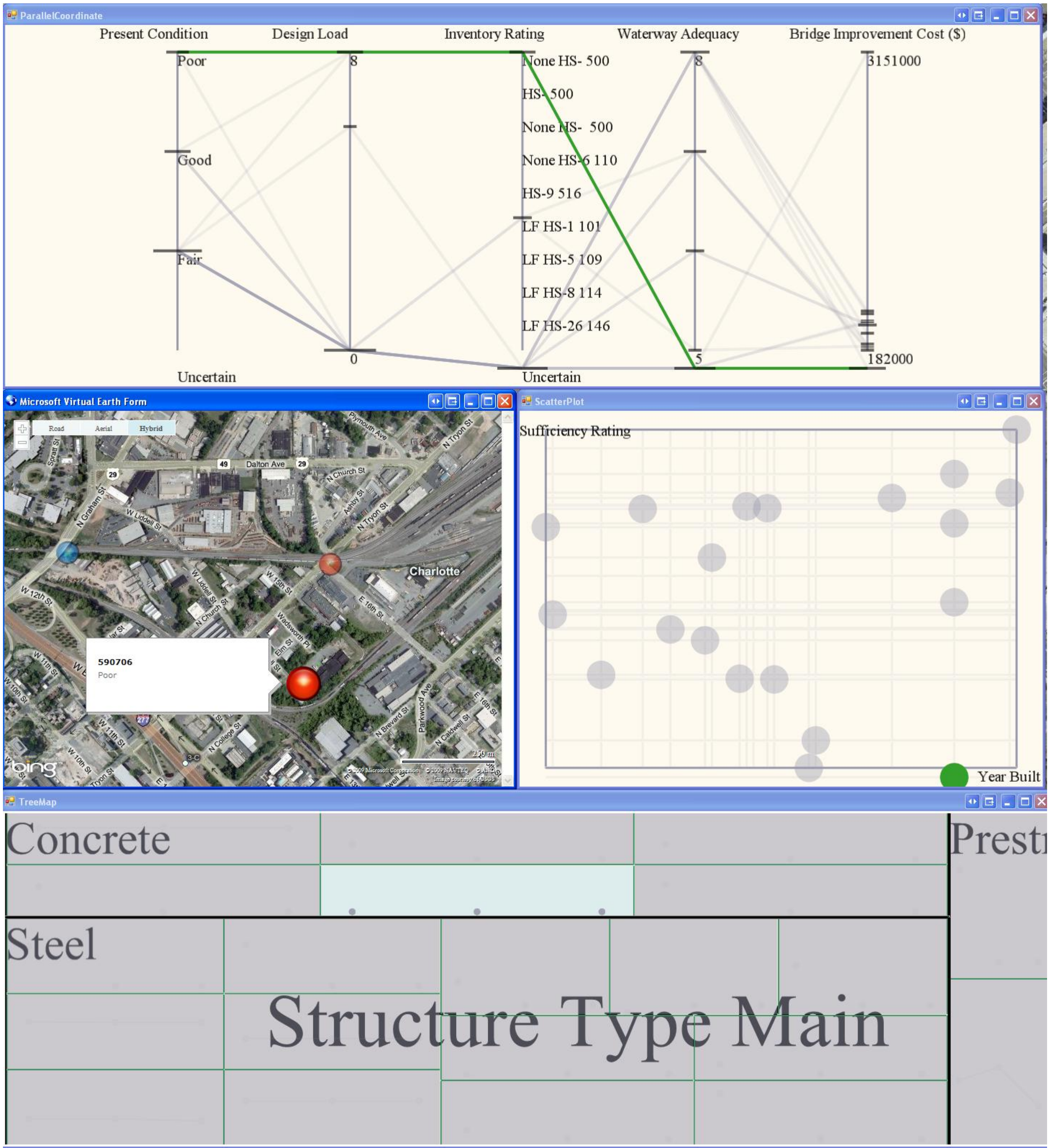
Fair
bing
ScatterPlot
Sufficiency Rating
Year Built
TreeMap
Concrete
Prestr
Steel
Structure Type Main

590706



ParallelCoordinate
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Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
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Good
Fair
Uncertain
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HS- 500
None HS- 500
None HS-6 110
HS-9 516
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LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
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182000
Microsoft Virtual Earth Form
Road
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Hybrid
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Charlotte
590706
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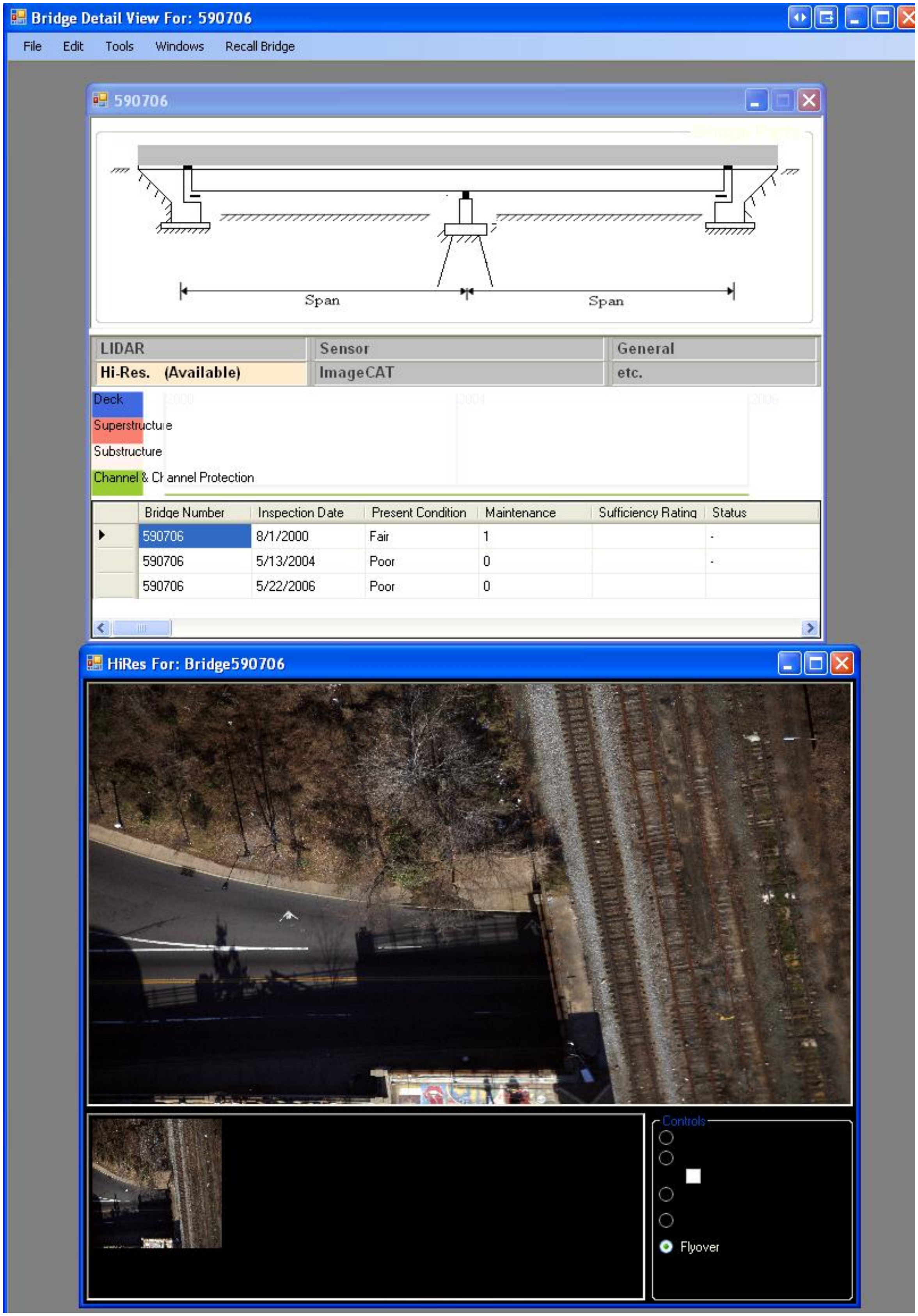
ScatterPlot
Sufficiency Rating
Year Built
TreeMap
Concrete
Prestr
Steel
Structure Type Main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Edit
Tools
Windows
Recall Bridge
590706
Span
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LIDAR
Sensor
General
Hi-Res. (Available)
ImageCAT
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
590706
8/1/2000
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5/13/2004
Poor
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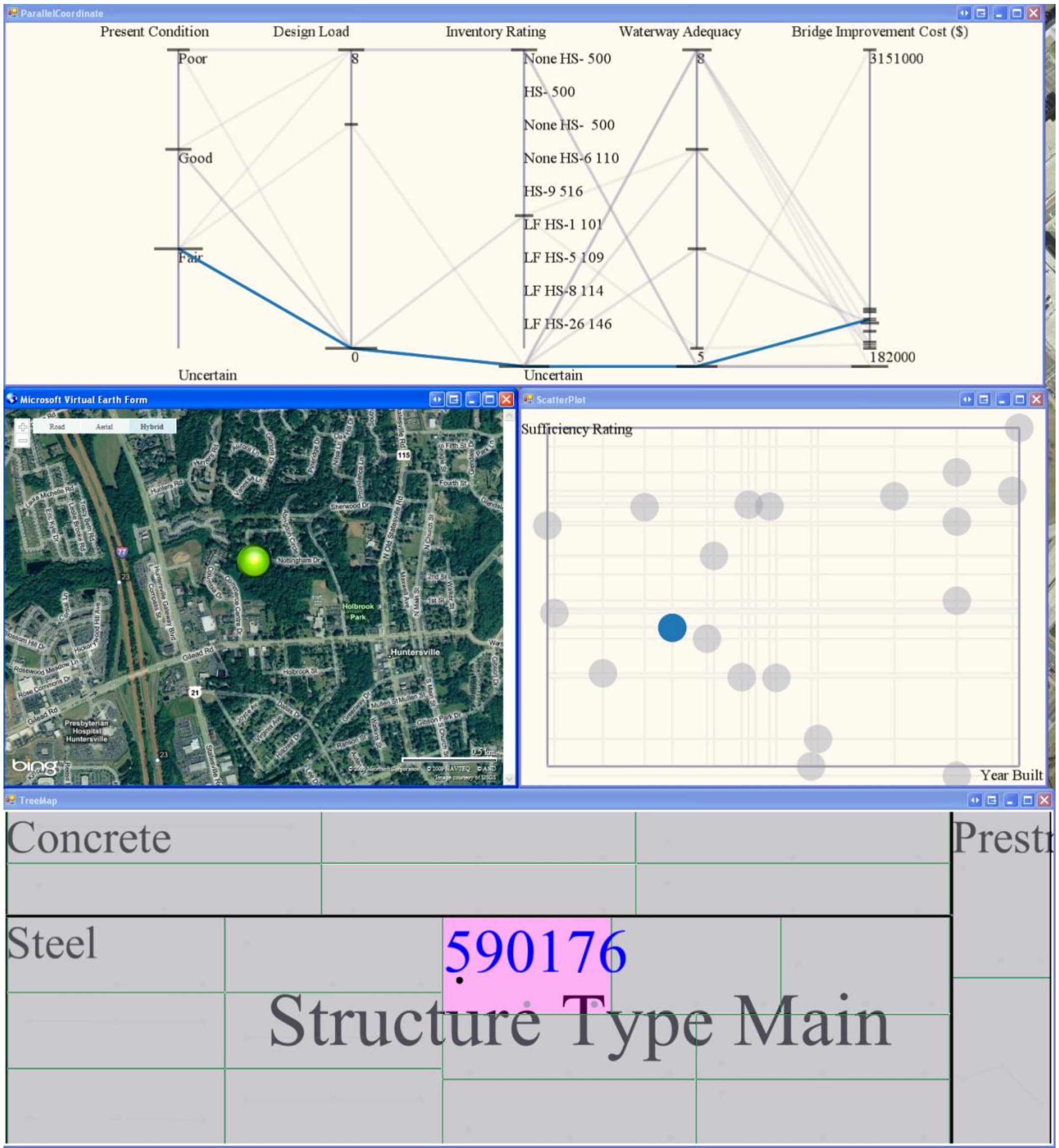
590706
5/22/2006
Poor
0
HiRes For: Bridge590706
Controls
Flyover

590176


ParallelCoordinate
Present Condition
Design Load
Inventory Rating
Waterway Adequacy
Bridge Improvement Cost ($)
Poor
Good
Fair
Uncertain
8
0
None HS- 500
HS- 500
None HS- 500
None HS-6 110
HS-9 516
LF HS-1 101
LF HS-5 109
LF HS-8 114
LF HS-26 146
Uncertain
8
5
3151000
182000
Microsoft Virtual Earth Form
Road
Aerial
Hybrid
Huntersville
bing
ScatterPlot
Sufficiency Rating
Year Built
TreeMap
Concrete
Prestr
Steel
590176
Structure Type Main


Bridge Detail View For: 590176
File
Edit
Tools
Windows
Recall Bridge
590176
Span
Span
LIDAR
Sensor
General
Hi-Res. (Available)
ImageCAT
etc.
Deck
Superstructure
Substructure
Channel & Channel Protection
Bridge Number
Inspection Date
Present Condition
Maintenance
Sufficiency Rating
Status
590176
6/11/2007
Fair
12
43.3
Structurally Defici...
590176
590176
HiRes For: Bridge590176
Controls
Flyover

Appendix C. List of Acronyms and Symbols

AADT	Annual Average Daily Traffic
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ASCE	America Society of Civil Engineering
BMS	Bridge Management System
CBA	Cost Benefit Analysis
CBR	Cost-Benefit Ratio
CDOT	Charlotte Department of Transportation
CRS	Commercial Remote Sensing
DEM	Digital Elevation Model
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPR	Ground penetrating radar
GPS	Global Positioning System
GSM	Global System for Mobile communications
HBRRP	Highway Bridge Replacement and Rehabilitation Program
HPS	High Performance Steel
HTF	Highway Trust Fund
IRSV	Integrated Remote Sensing and Visualization
ISTEA	Intermodal Surface Transportation Efficiency Act
LaDAR	Laser Detection and ranging
LiBE	LiDAR Bridge Evaluation
LiDAR	Light Detection and Ranging
NBI	National Bridge Inventory
NBIP	National Bridge Inventory Program
NBIS	National Bridge Inspection Standards
NCDOT	North Carolina Department of Transportation
NDE	Non-Destructive Evaluation
NDI	Non-Destructive Inspection
NPV	Net Present Value
NSTIFC	National Surface Transportation Infrastructure Financing Commission
PC	Prestressed Concrete
RC	Reinforced Concrete
RITA	Research Innovative Technology Administration (RITA)
SBRP	Special Bridge Replacement Program
SHM	Structure Health Monitoring
STIP	State Transportation Improvement Program
SAR	Synthetic Aperture Radar
SI	Spatial Information
TIP	Transportation Improvement Program
UNCC	University of North Carolina at Charlotte

USDOT US Department of Transportation