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Abstract

The objectives of this research project are –

1. To design sensor data fusion algorithms that can synergistically combine defect related information from heterogeneous sensors used in gas pipeline inspection for reliably and accurately predicting the condition of the pipe-wall.
2. To develop efficient data management techniques for signals obtained during multisensor interrogation of a gas pipeline.

During this reporting period, Rowan University designed, developed and exercised algorithms for the effective management of data resulting from multi-sensor interrogation of gas transmission pipelines. Specifically, advanced visualization techniques were employed for immersive, interactive and navigable data representations.

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Executive Summary

The objectives of this research project are:

1. To design sensor data fusion algorithms that can synergistically combine defect related information from heterogeneous sensors used in gas pipeline inspection for reliably and accurately predicting the condition of the pipe-wall.
2. To develop efficient data management techniques for signals obtained during multisensor interrogation of a gas pipeline.

The principal progress during this reporting period involved *Task 5.0 – Recommendations for effective data management*. Following suggestions from the Department of Energy, Rowan has fostered partnerships with local and national utilities, vendors and manufacturers of pipeline inspection systems for arriving at recommendations for effective management of pipeline inspection data.

The principal contributions during this reporting period and the conclusions drawn from the work are listed below:

1. *Research and development partnerships* – Rowan University has established a research partnership with RTD Quality Services, USA based out of Houston, Texas and through their contacts with TransCanada Pipelines. The objective of this partnership is to gain access to field pipeline inspection data and arrive techniques for field-validation of the multi-sensor data fusion algorithms that have been developed as part of this project.
2. *Development of a framework for multi-sensor data visualization in a virtual reality (VR) platform.* An immersive, interactive and navigable VR data fusion environment was defined and created, consisting of (a) graphical data, (b) measurement data, and (c) functional data. The framework was demonstrated using multi-sensor data obtained during the in-line inspection of a section of a gas transmission pipeline. Graphical models of the pipeline components were displayed in addition to MFL / UT inspection signals, neural network predictions of pipeline condition, and the geographic location of the pipeline network

   Results from this research activity formed the basis of Mr. Scott Papson's Master's Thesis, published by Rowan University [1] and will be part of Mr. Justin Bram's Master's Thesis (in progress).

Experimental

The principal progress during this reporting period involved *Task 5.0 – Recommendations for Effective Data Management.* Results from this research activity formed the basis of Mr. Scott Papson's Master's Thesis, published by Rowan University [1] and will be part of Mr. Justin Bram's Master's Thesis (in progress).

Task 5.0 – Recommendations for Effective Data Management

This report describes the use of virtual reality (VR) platforms for effectively managing the voluminous amounts of inspection data that is generated when pipeline sections are interrogated using multiple sensor methods. Virtual reality has emerged as a powerful visualization tool for design, simulation, and analysis in modern complex industrial systems. Virtual reality can be defined as any system that allows a user to have immersion, navigation, and interaction. A fully immersive environment is one in which the user is completely engulfed in the virtual world and sensory input for the real world is completely blocked. Navigation in the virtual world allows the user to move to different regions within the world. Finally, interaction is the user's ability to interact with the data. Interaction allows the user to not only see the data, but manipulate it as well [2]. All of these factors contribute to the main thrust of the virtual environment, presence. Presence in a virtual world is the feeling of an accurate depiction of reality in the virtual environment [3].

The creation of presence in a virtual world serves two main purposes. First, it allows the user to visualize data in true three-dimensional representations. Also, it allows the user to visualize phenomena and data such that additional insight is gained. With full control over the virtual world, the designer can create a world such that the user can gain a perspective that would otherwise be difficult if not impossible to obtain [4]. The creation of the virtual world focuses on component representation and component registration. Components with higher detail will create a greater sense of presence. The tradeoff, however, is that increased detail places more demands on the hardware. If the hardware becomes bogged down the world can lag; the sense of presence will then be lost [5]. Components and data therefore need to be represented with minimum resolution needed for the specific purpose.

VR is a well-suited platform in which the framework can be intended to support not only the integration of data for visual, interactive, and immersive displays, but also provide a method for performing risk analysis. Inside the virtual world, the user could be given the ability to evolve the data over time and create various scenarios. An evolutionary virtual world allows the user to ask "What if…?" The virtual world will then evolve over time as a function of the user inquiry and system data. Using the evolutionary scenario that has unfolded, the user is empowered to more thoroughly analyze the data and draw relevant conclusions. The data integration via VR paradigm is illustrated in Figure 1. Multi-sensor pipeline inspection data is obtained from the following testing methods – magnetic flux leakage (MFL), ultrasonic testing (UT), thermal imaging, and acoustic emission (AE) testing. This data is input into artificial neural nets to classify data signatures, and predict anomaly geometries. CAD models of the pipeline are used for registration of the data. The final component of the virtual world is information obtained from the geographic information system (GIS). The GIS information is used to assess environmental concerns and provide information about the specific location of the pipeline.

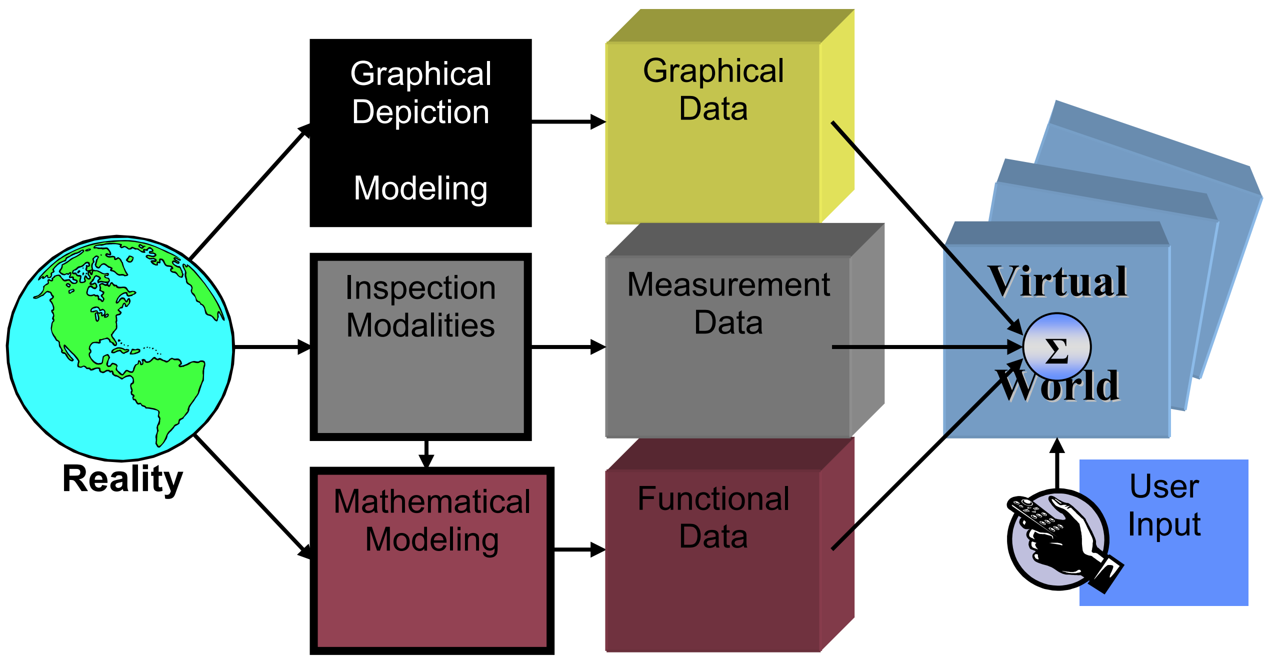


Figure 1: An overview of the data integration process for the NDE of gas transmission pipelines.

There are numerous ways data in a virtual world can be described. The most common methods for categorizing data are dividing it according to its representation in the virtual world or its purpose in the virtual world [6]. For most data integration applications the information can be broken down into three categories - graphical, functional, and measurement. Each category can then have several different representations according to the specific software used and desired results.

Graphical objects are traditionally the basis of a virtual world. The graphical objects in the virtual environment represent objects that exist in the actual environment. In inspection applications the representations would include the object being analyzed and any additional objects that are present in the environment. Graphical objects can be modeled using dimensioned drawings, or created visually using a picture or reference object. Graphical objects must be created with detail suitable to fulfill their role for a specific application.

Measurement data is the raw data obtained from any type of sensor. Multi-sensor data integration focuses on representing each data modality individually and in tandem with the other modalities. Depending on the type of data that is obtained, the measurement data can take on a variety of representations. Each data point collected can be represented using a point representation or glyphs. Interpolation between points can be represented through the use of a color slice. A topological representation can be used to vary the data representation spatially as a function of the value. Three-dimensional surfaces can also be created to represent the true form of the data collected.

For each sensor and each modality of data there may not be only one representation that best fits the data. Each application will have specific visualization needs, and the data representations should be tailored to those needs. Multiple representations of a single type of data are also helpful for a user analyzing complex data sets.

Functional components are representations of processed or calculated data. Analyzing raw data is not usually sufficient in most inspection applications. Neural nets or other algorithms can be used to help classify certain areas within the data sets. Components (the graphical objects) can be identified or flagged such that only the areas of interest are analyzed. Evolutionary algorithms can be designed to predict how the current state of the world might evolve over time for a given set of parameters. Analysis using first principles or finite element analysis can also be used to see how measured data compares to theoretical data. Like the measured data, each type of functional data representation will have a representation consistent with the purpose of that data.

Graphical Data

Graphical data represents the objects being investigated and the environment in which those objects exist. For this application there are two types of graphical objects being integrated, pipeline components and GIS information. The component models represent the object being investigated and the GIS data conveys information about the environment of the pipeline

There are a number of base graphical objects to represent a pipeline. These include a section of pipe, flange, weld, sleeve, t-section, check valve, ball valve, anchor, and anomalies (crack, pit, etc.). Each component can be modeled using a CAD program. The library of modeled components can then be assembled to create the pipeline that is being inspected. Drawings of the pipeline system can be used to manual piece together the various library components to make an increasingly complex network of pipes. Automated assembly algorithms can also be constructed to allow construction of the pipeline network in the virtual world. The library can also have multiple detail levels for each component. Using lower detail allows for the creation of expansive pipeline networks. When an area of interest is identified, a subsection of the network can be subsequently generated using the components with finer details.

The geographic information system can give a great deal of information about the location of the pipeline network. The GIS can give information about the topography, land usage, location of rivers, roads, buildings, etc. This information can be integrated into the virtual environment such that the user can gain insight into the location details of the pipeline. Under certain conditions remediation measures are determined based on the location of the pipe in question. Integrating GIS information into the virtual environment allows the user to have not only physical location, but additional sociologic information.

Functional Data

Functional data can be obtained through any type of mathematical model. For this application the functional data is a function of the measured data. Using the data gathered, artificial neural nets can be used to classify the data signatures. The category labels for the output of the neural net are the library components for the graphical library. ANN predictions can be used in two different ways. The predictions can be used to assist in visually classifying the signatures and searching for anomalies within the data collected; also, the predictions can be used to construct a pipeline network. For each neural net prediction the corresponding component piece can be obtained from the graphic library and appended onto the network. This predicted network can be easily compared to the actual network.

If an anomaly is present ANNs can be used to further classify the depth and geometry of the anomaly. Using multiple modalities of data, predictions can be made on the size and shape of an anomaly. This information can be represented in the virtual world, and used to help assess the pipeline integrity.

Measurement Data

Measurement data has been collected using a variety of NDE methods including magnetic flux leakage (MFL), ultrasonic testing (UT), thermal imaging, acoustic emission (AE), and thermal imaging.

Results

Task 5.0 – Recommendations for Effective Data Management

The following worlds were created to implement the procedure as described in the previous section. The Fakespace ImmersaDesk R2, a semi-immersive display system, was the projection system used. The system includes head tracking and a tracked navigation wand. VRCO's vGeo software was used to create the virtual worlds and drive the display system.

Graphical

First, a component library was created. The library included a pipeline anchor, check valve, ball valve, T-section, tap, weld, sleeve, flange, and straight length of pipe. The graphical components were modeled and assembled using SolidWorks. All models were converted to virtual reality modeling language (VRML) files and imported into vGeo. Figure 4 shows three sections of a pipeline network, each having a different set of components.

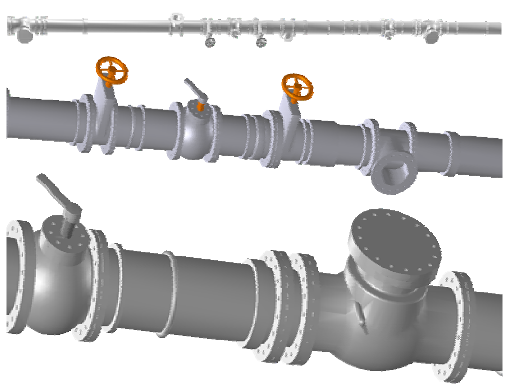


Figure 2: Pipeline sections that are composed of various library components.

Although this particular assembly was done prior to integration, it is possible to import each piece individually and create the pipeline network interactively.

ESRI's AcrMap was used to obtain certain geographical features. The software generates two-dimensional maps that can be extruded to a third dimension using ESRI's add-on package, 3-D Analyst. Files can then be imported into the virtual world as VRML files. Alternately, two-dimensional pictures can be imported into the virtual reality system. A third dimension, if desired, can then be extrapolated within vGeo. When GIS data is imported as a VRML file, the entire file is one group of data. When imported separately, each portion of data can be turned on and off in the immersive display.

Measurement and Functional

A suite of test specimens was created in order to obtain the NDE signatures from the various testing modalities. The specimens were tested using MFL, UT and thermal imaging – these have been described in previous reports. The results of the measurements were then integrated using virtual reality. The figures below show the results obtained using each of the testing methods.

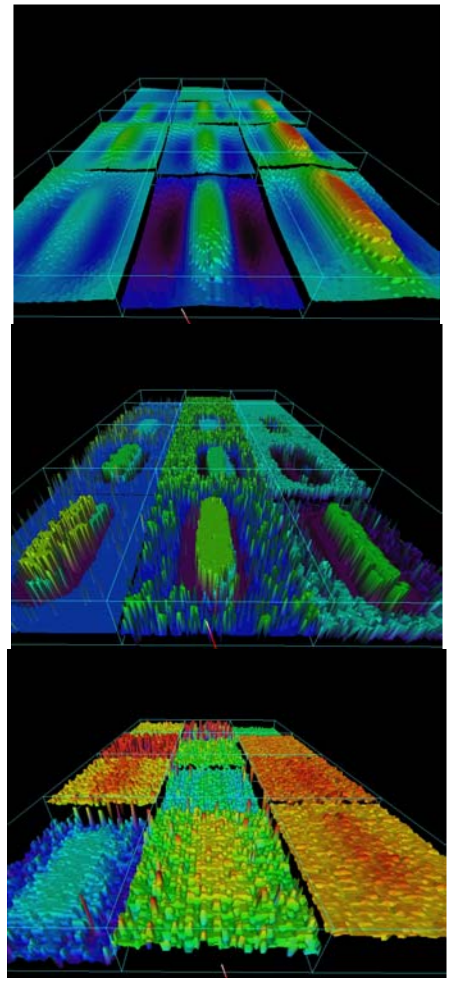


Figure 3: MFL, UT, and thermal images from the inspection of corrosion pits displayed in VR.

MFL flux data for the pipe section depicted in Figure 2 was obtained from a pig with 83 sensors around the circumference. The complete set of data for each sensor is represented by one column of data; the measurement of all 83 sensors for a particular distance measurement is represented by each row. This tabular data was then projected onto an irregularly shaped grid. After the circumferential grid was constructed, the grid was distended proportional to the magnitude of the flux observed at each sensor. This is illustrated in Figure 4.

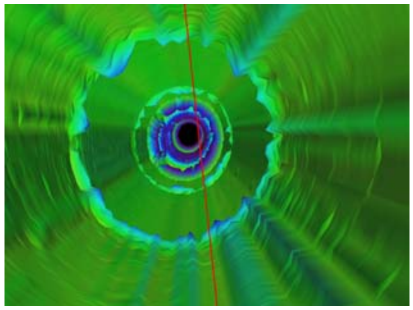


Figure 4: MFL pigging data inside a pipeline.

This information was also fed into a neural network. The ANN classified the flux signatures as one of the component model pieces. The classification results can simply be overlaid onto of the actual flux data. Figure 5 illustrates the integration of the measured data and the predicted classification result.

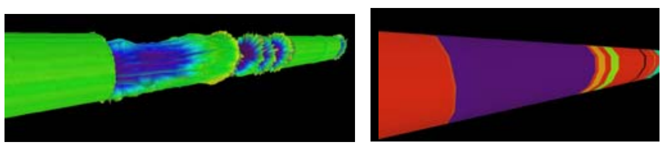
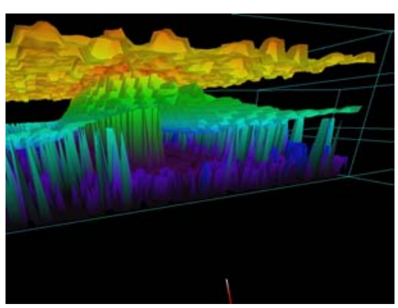
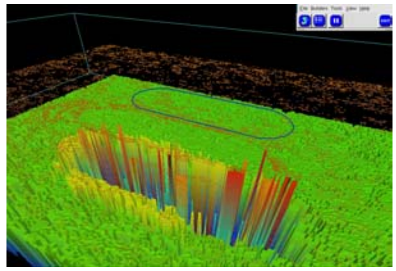


Figure 5: MFL image obtained from a section of pipe and the corresponding color-coded neural net classifications.

Integration

There are an infinite number of combinations that can be used to represent the various data modalities in a virtual world. In order to view the MFL, UT, and thermal imaging data, color mapped topologies were used. The data from Figure 3 was displayed together to investigate the three data sets at the same time. Figure 6 shows how the aggregate data is integrated.





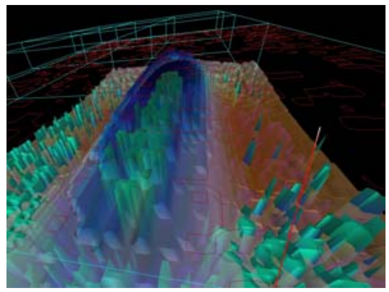


Figure 6: Various representations of MFL, UT, and thermal data sets integrated in a virtual world.

Contour slices can also be used instead of surface representations to analyze the data. Graphical representations can also be used for reference. Figure 6 shows UT data surface, a thermal contour, and a graphical contour used for reference; also a UT topology, a MFL transparent topology and a thermal contour. The same integration procedures used on the test specimen data was used on the component MFL data. A pipeline network was created and the MFL data was superimposed onto it. Figure 7 illustrates the integration for these two data types.

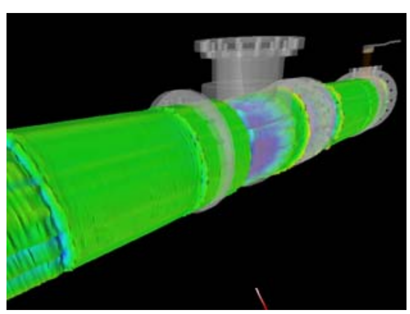


Figure 7: MFL data registered onto the graphical pipe representation.

Similarly, a pipeline network was created using less detailed components to save graphical memory. The pipeline network was then registered inside of a virtual world. The location information was conveyed through a grid, topography, and simulated GIS data. The integrated world is shown in Figure 8.

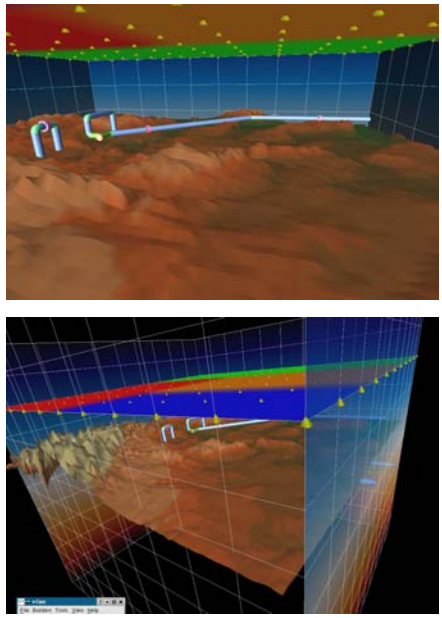


Figure 8: A view of an integrated environment for a pipeline network.

Conclusion

The principal progress during this reporting period involved *Task 5.0 – Recommendations for Effective Data Management*.

In collaboration with instrument manufacturers and pipeline inspection companies, virtual reality platforms were investigated as a mechanism for data management. The principal contributions during this reporting period and the conclusions drawn from the work are listed below:

1. *Research and development partnerships* – Rowan University has established a research partnership with RTD Quality Services, USA based out of Houston, Texas and through their contacts with TransCanada Pipelines. Attempts were made to obtain field inspection data – a sufficient quantity was not available for a comprehensive field validation of the methods developed as part of this research project.
2. *Development of a framework for multi-sensor data visualization in a virtual reality (VR) platform.* An immersive, interactive and navigable VR data fusion environment was defined and created, consisting of (a) graphical data, (b) measurement data, and (c) functional data. The framework was demonstrated using multi-sensor data obtained during the in-line inspection of a section of a gas transmission pipeline. Graphical models of the pipeline components were displayed in addition to MFL / UT inspection signals, neural network predictions of pipeline condition, and the geographic location of the pipeline network. The technique allows the inspection vendor to rapidly sift through hundreds of miles of pipeline inspection data and zero-in on features of interest and suggest appropriate remediation measures, if required.

   Virtual reality environments show considerable promise for the integration of multi-sensor data. The system allows a user to rapidly sift through large and complex data sets to isolate features of interest. Additionally, the VR environment has the ability to evolve as a function of both system data and user input. The use of data integration and evolution empowers the user to evaluate scenarios to make informed decisions.

References

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List of Acronyms and Abbreviations

AE Acoustic emission

ANN Artificial Neural Network

MFL Magnetic flux leakage

MLP Multilayer perceptron

UT Ultrasonic testing

VR Virtual Reality