Low Cost, Full-Field Surface Profiling Tool for Mechanical Damage Evaluation

Final Report

March 3, 2010

Contract No.: DTRT57-09-C-10044
Period of Performance: 09/04/09 to 03/03/10
Reporting Period: 09/04/09 to 03/03/10

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1.0 INTRODUCTION

Gas and oil pipelines are subject to a number of defects or anomalies that can impact fitness for service and potentially compromise the safety of the pipeline. The three major types of anomalies are corrosion, cracks, and mechanical damage. Several analyses of the occurrence of anomalies in pipelines have highlighted mechanical damage (typically from third party excavations) as the most frequent source of leaks and ruptures, either immediately on impact, or after a time delay. The most common types of mechanical damage features are dents, sometimes associated with secondary features such as gouges, external corrosion, or cracks.

It is clearly of great importance to be able to detect mechanical damage as part of regular pipeline assessment activities, so as to allow corrective action before delayed failure can occur. In-line inspection (ILI) is able to detect the presence of dents, but the information obtained is not sufficiently detailed to determine the fitness for service. Excavation at the damage site and subsequent coating removal is thus required in order to inspect the damaged region in a more direct manner. The resulting in-ditch assessment is typically obtained from a caliper measurement that yields the damage depth at a single point as a fraction of the wall thickness. More specialized 3-D laser profiling tools have some ability to determine the actual shape or profile of the damaged region from an external measurement, but they cannot provide an absolute depth measurement (relative to the undamaged pipe surface) and they require a highly trained operator.

It is thus clear that there are at least three gaps in the processes now used to inspect mechanical damage:

1. Advanced techniques used during ILI are still in the development stage and have not been qualified for use;
2. Current in-ditch caliper-based techniques cannot determine the full shape or profile of the damaged region; and
3. 3-D laser profiling tools have the capability of mapping the full profile, but they have certain technical and practical limitations.

It would be highly desirable to have an efficient, inexpensive, external inspection device that could obtain the full depth profile of each damage anomaly. An accurate 2-D depth profile could then be entered into a mechanical model that could calculate stress/strain, and thus provide an accurate assessment of fitness for service.

In this project, Intelligent Optical Systems (IOS) developed an inexpensive, full-field, surface-profiling tool for mechanical damage evaluation based on the processing of a single digital image. Little operator training is required for acquiring the profile data. As shown in Figure 1-1, the tool consists of a consumer camera on a tripod with an external laser or LED line pattern illuminator. The illuminator projects a 1-D or 2-D grid of lines downward onto the damaged region. The camera images this region at an angle, so that the displacement of the line pattern over the damaged region provides a measure of the depth. A software package converts the line pattern from the camera image to a profile of the absolute depth, as measured from the undamaged pipe surface. The depth accuracy is on the order of 0.1 mm. In addition, the shape of the full pipe cross section can be extracted. The local profile of the damaged region, plus the shape of the full pipe cross section, together, provides all information required for mechanical assessment. Thus, our inexpensive, full-field approach overcomes all gaps in the assessment process that are described above.

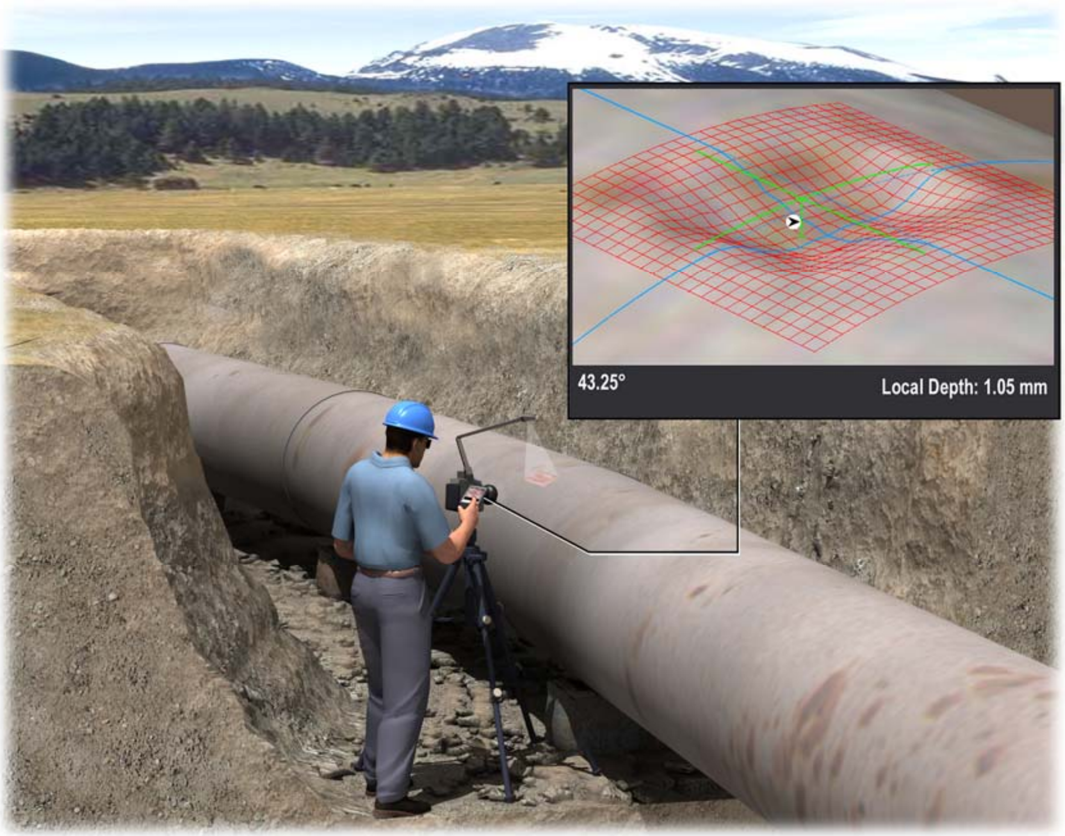


Figure 1-1 A pipeline inspector will be able to capture an image of the illuminated damaged region with a conventional camera. Signal processing will yield the full 2-D depth profile with mm accuracy.

In Phase I, IOS developed detailed proof-of-principles of the proposed technology, determined precision as a function of lighting and environmental conditions, and determined preliminary software and hardware designs. These designs were evaluated for their feasibility, and techniques that will make an actual system possible for application in the harsh conditions of a pipe evaluation process were selected for further investigation and testing in Phase II. The specific goal during Phase I was to show proof of feasibility using a single line or line pair. Off-line software was used to convert the camera line image into a well-characterized 1-D profile.

2. TECHNICAL APPROACH AND PHASE I RESULTS

The principle of triangulation for surface profiling is well known. The surface is illuminated at one angle and viewed at a different angle. An example of two lines of illumination on a pipe section with deep corrosion pits is shown in Figure 2-1. The proper trigonometric relationships allow extraction of the surface profile from the distorted shape of the line.

There are two ways to implement triangulation for obtaining a surface profile in three dimensions (two surface coordinates and a depth coordinate). Laser profilers scan a small beam across the surface in a line-by-line raster pattern. Depth information is obtained point-by-point using a linear detector array. This laser approach provides high accuracy, but requires sweeping the surface with a scan line and thus requires a long time (measured in hours) for data acquisition and processing, including "stitching" the image data together.

Our approach is also based on triangulation, but uses *a projected linear pattern* and a *simple digital camera* to ***acquire all data in a single snapshot***. Proprietary image processing algorithms are then used to extract the required information in real time.

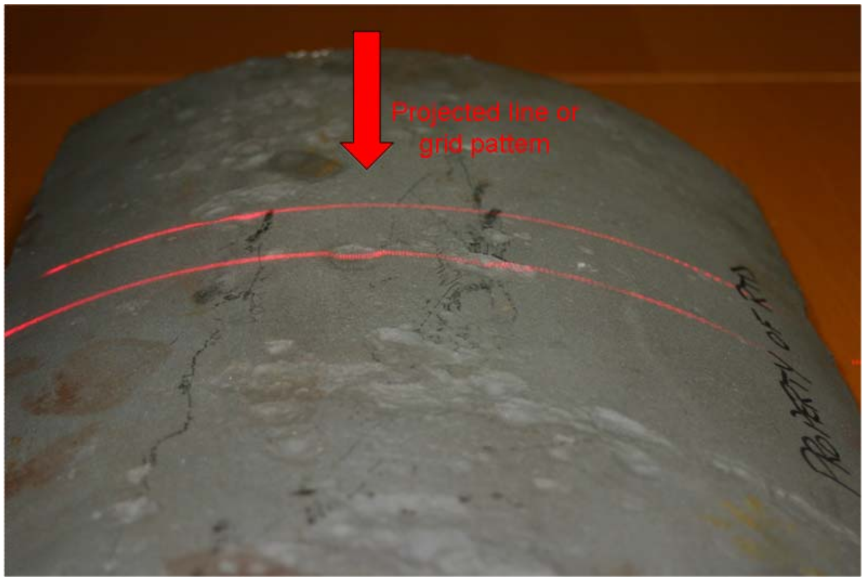


Figure 2-1 Two lines projected onto a corroded pipe section and viewed at a different angle. The distortion of the lines as they pass over corroded regions is clear.

Our approach has several key advantages: (1) we are able to reconstruct the position of the undamaged OD wall of the pipe, so that the depth profile can be referenced to this position; (2) we are able to extract the diameter and shape of the deformed pipe around its full circumference; and (3) our image processing approach has subpixel resolution, thereby increasing the measurement accuracy.

Consider the case introduced above of a dent or corrosion pit illuminated with a single line of light projected perpendicular to the pipe axis and viewed along the axis. An example of this configuration is shown in Figure 2-2(a), in which an LED source projects a line onto a corrosion pit on the outside diameter (OD) of a pipe sample. As before, when viewed at an angle, the line takes on the profile of the curved surface. Our technique uses the measured deflection of the projected line, and an extension of the undeflected line, to measure the depth of the surface feature, and to determine the shape of the distorted pipe. ***Our image-processing algorithmsare able to scale the image taken from any perspective, and project an undistorted OD wall across the line image at the dent, so that a true depth profile can be obtained.***

Figure 2-2(b) shows the Phase I results of the extraction of the shape and diameter of the pipe sample shown in Figure 2-2(a). The extracted 3-D model is shown in Figure 2-2(c). A simple line pattern was projected onto the corroded region of the sample, and projected ellipses were fit to the surface. The numbers near the ellipses are the semiaxis dimensions and the number at the top is the calculated pipe diameter.

2.1 Technical Progress

Our description of progress is tied to each project task, as given below.

Task 1. Determine User Requirements for Mechanical Damage Assessment

The goal of this task was to understand the current state of mechanical damage inspection methods and also the data requirements for the mechanical models used for determining fitness for service. After the program start, we discussed these issues with key individuals and organizations in the industry through phone contacts and through personal meetings. Later, we confirmed these findings at meetings that took place at the PRCI Pipeline Program Research Exchange Meeting in Atlanta in February 2010. IOS presented a talk at that meeting on this project and received many helpful comments and suggestions.

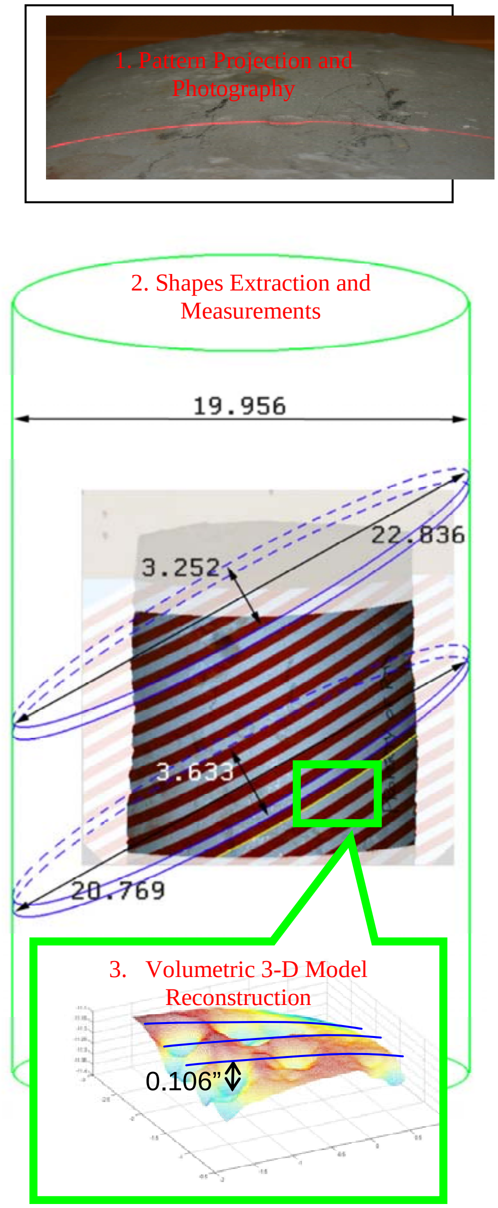


Figure 2-2 (1) Line projected across corrosion pit at its center. On the undistorted surface the line has the shape of an ellipse; (2) example of the extraction of the pipe shape and dimensions from a projected line pattern; (3) extracted 3-D model of the surface provides quantitative damage assessment.

The individuals contacted included:

- **Mark Piazza (PRCI).** Mark has provided broad industry perspective on the current needs for characterizing mechanical damage.
- **Lynann Clatham (Queens University, Canada).** Lynann has provided perspective regarding current R&D on mechanical damage inspection.
- **Mures Zarea (Gaz de France).** Mures is very active in PRCI. He provided information on the extensive activities at Gaz de France on mechanical damage characterization.
- **John O'Brien (Chevron ETC).** John is also very active in PRCI. He provided information on the characteristics of mechanical damage and on data requirements for mechanical assessment.

- **Aaron Dinovitzer (BMT Fleet Technologies).** BMT has done extensive work on mechanical assessment. Aaron provided a perspective on current activities relating to 3-D profiling, and offered to provide samples.

Task 2. Develop an NC-MDE Software Prototype Package Capable of Validating the Flexibility of the System

We developed an algorithm and software for structural light projection that provides optimal performance. The details of the pattern selection are presented in the Task 3 section of this report. The light pattern that we used (see Figure 2-3) covers the entire surface of the pipe.

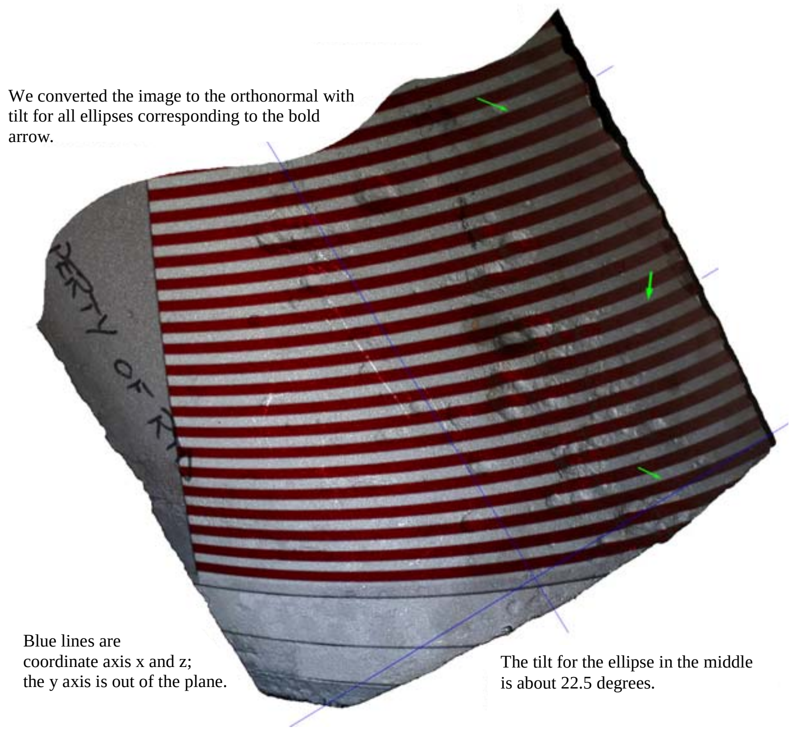
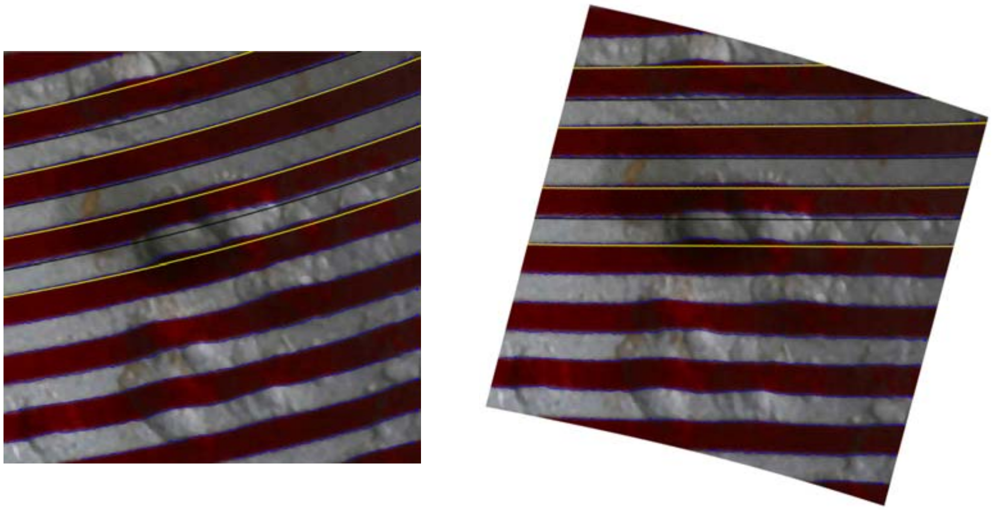


Figure 2-3 Structural light pattern projected on the surface. The curvature of the lines allows the depth of the depressions on the surface of the pipe to be determined.

The curvature of the lines depends not only on the pipe curvature, but also on and pipe, projector, and camera positions. With a fixed camera and light source, one can calculate the depth of the damage by relating the light deviation to the ideal ellipse, and the general shape of the surface (i.e., the diameter of the pipe -- see Figure 2-4). To develop an algorithm and software, we had to develop a mathematical approach on how to interpret/measure the amount of deviation at the surface and compare that value to the ideal ellipse. This approach is described below.



(a) (b)

Figure 2-4 Fitting ellipses to the line allows the general shape of the pipe and depth information to be extracted: (a) We determined ellipses that fit to the surface (yellow lines); then we could unwrap the surface (b) in such a way that the yellow lines become straight. The depression depth (blue line) can then be clearly seen as a deviation from the surface (yellow line).

Depression Depth Measurements from the Surface to the "Ideal" Ellipse

The approach to calculating and measuring the distance (depth) from the surface to the "ideal" ellipse is shown below. The general setup is presented in Figure 2-5. The measurements are based on simply calculating the proportions of the triangle ABC, but to determine the length of the components, we need to provide an additional analysis.

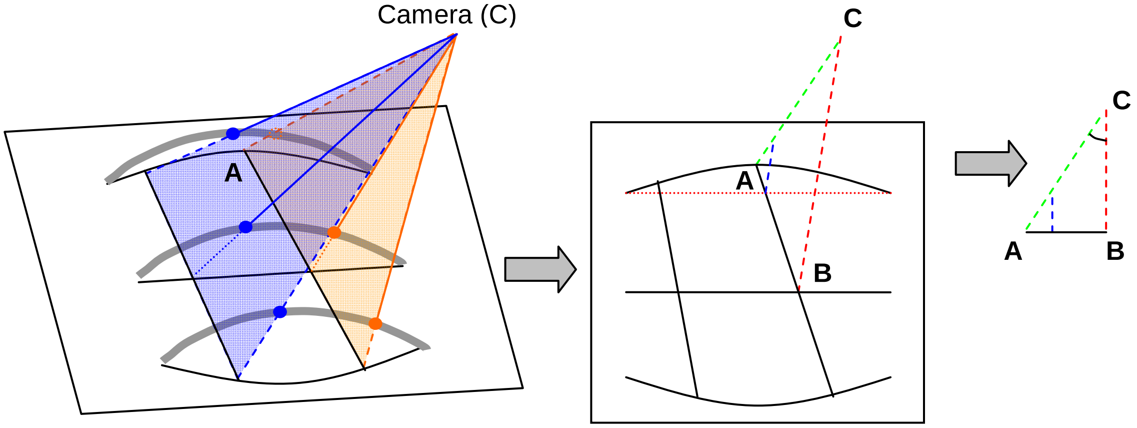


Figure 2-5 Simplified description of the depth measurement procedure. The lines of light on the pipe surface produced by the projector (gray circular lines on the first image) are visible to the camera and appear as ideal ellipses. If the camera lies in the same geometrical plane as the circular line, the ellipse will be visible as a straight line (in the middle); lines to the right or left of the camera geometrical plane will appear as ellipses that bend up (right) or down (left). The curvature of the pipe can be determined using a simple geometrical relationship (ABD triangle). Deviations from the ideal ellipse allow the depth of the depressions to be determined. The distance of the camera from the ideal ellipse line, and the depression surface produce a triangle similar to ABC that can be used to precisely calculate the depression depth.

Based on information extracted from the image, we are able to determine both the ellipse parameters and surface deviation from it (see Figure 2-6). The calculated ellipses and surface deviation lines are presented as a 3-D model in Matlab (see Figure 2-7). Profiles with the parts of the ellipses that represent the idealized surface of the pipe, and the real surfaces of the pipe section, are shown in Figure 2-8.

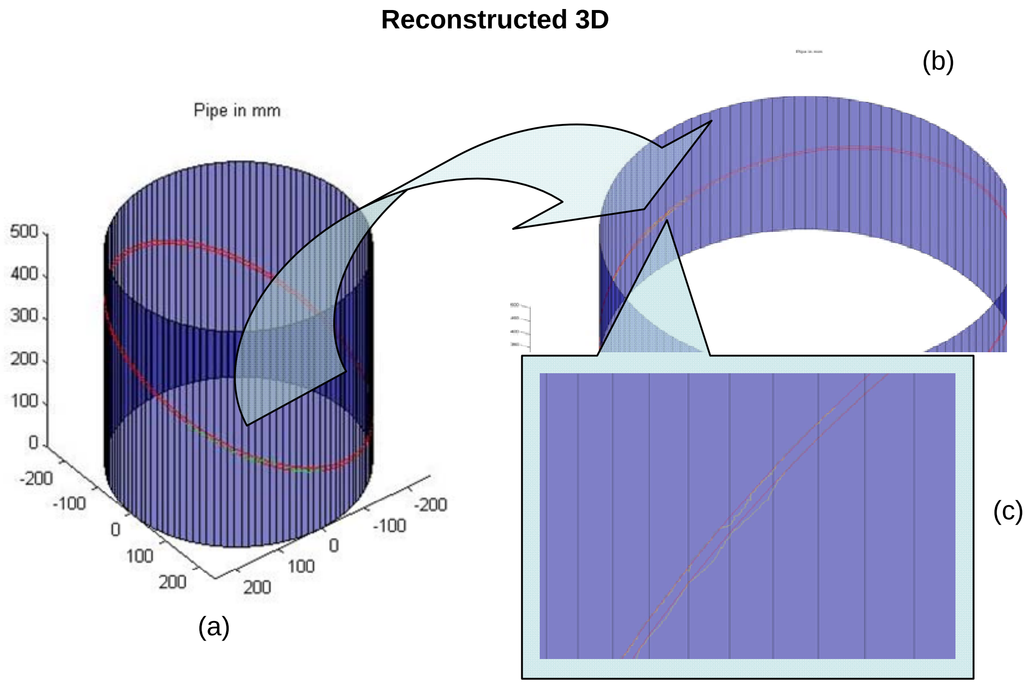


Figure 2-6 Calculated position of the ellipses (red line) at the idealized pipe (blue cylinder): (a) common view, (b) enlarged part on cylinder, and (c) further enlarged part of the surface.

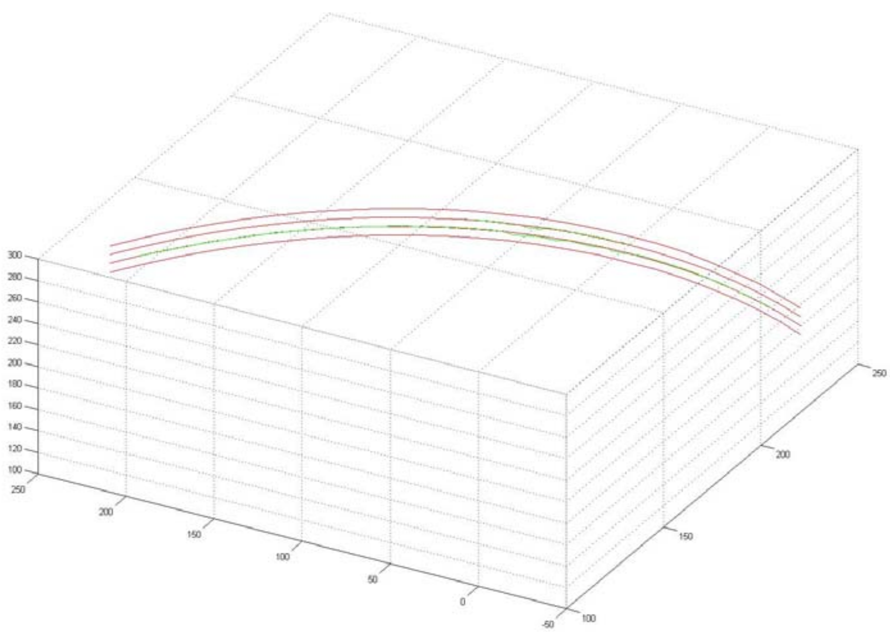


Figure 2-7 The calculated ellipses and surface deviation lines are presented as a 3-D model in Matlab.

The green line is the actual pipe profile; the red line is the ideal shape of the pipe.

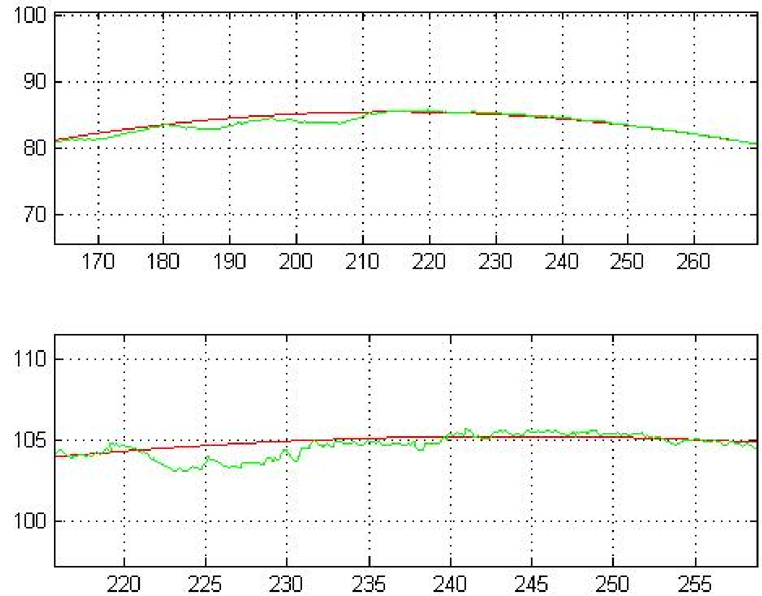


Figure 2-8 Profiles with part of the ellipses that represent the idealized surface of the pipe and the real surface of the pipe section.

Task 3. Perform Proof of Principle Tests on Real Damaged Samples

While we were developing our own hardware for the acquisition of profile data, we had a representative from a commercial 3D profiling instrument company come to IOS and demonstrate one of their laser-based systems. We provided a pipe sample with deep corrosion pits for scanning. They completed the scan, and made a 3-D model of the pipe section (see Figure 2-9). We "printed" this model and made a replica of the pipe section, using a 3-D printer.

The important thing that we observed during the demonstration is that this company's technique has no way to reproduce the undamaged surface in order to obtain the absolute depth of the surface feature, unless they scan the entire pipe circumference. In our approach, we can reproduce the undamaged surface by scanning only a limited area around the dent. The other important advantage we have is that we can obtain the surface profile using a few snapshots from a digital camera, while the laser profilers require a considerable scan time, a trained operator, and a lot of number crunching to obtain the profile.

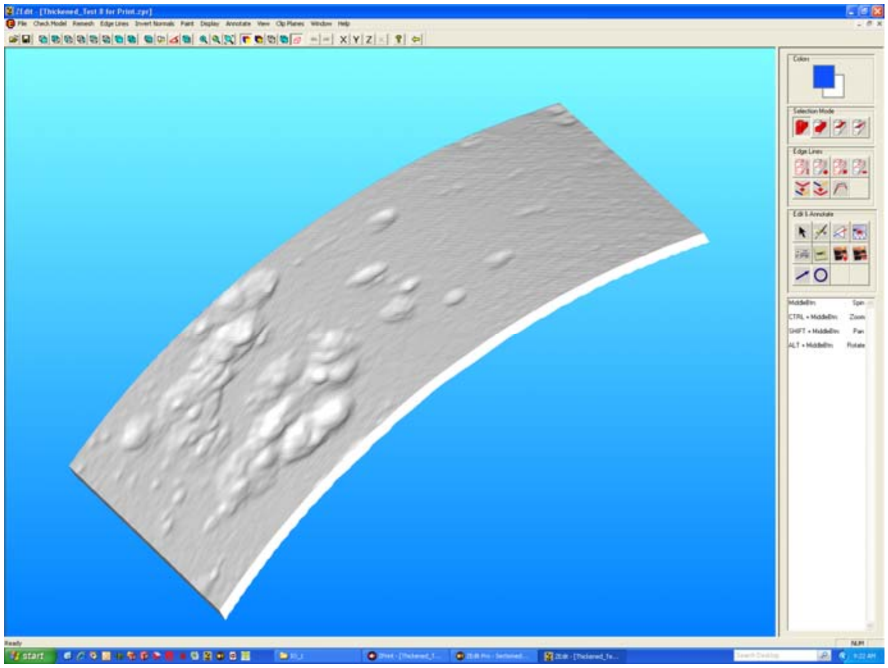


Figure 2-9 Solid model of corroded pipe section.

We developed software and evaluated software performance based on several patterns of light. The first light pattern evaluation was based on multiple, thin, parallel lines (see Figure 2-10).

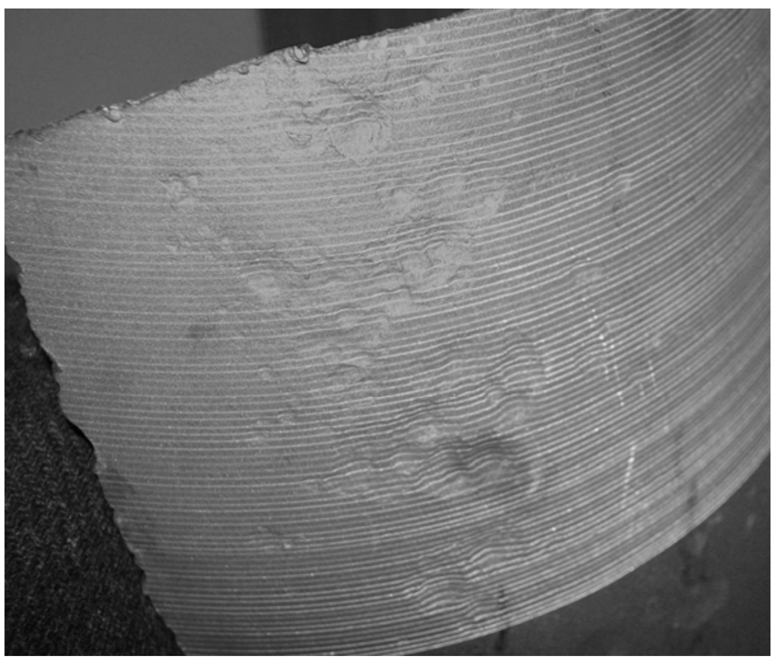


Figure 2-10 Illumination by thin, parallel lines.

We tried to use available image processing algorithms, including IOS proprietary algorithms, to extract each individual line automatically. However, the extracted lines sometimes were cut at the surface due to color and intensity variations, or even were connected to the wrong rows. Better illumination contrast would enable better automated acquisition of the lines.

We also tried a checkerboard pattern, as shown in Figure 2-11. This time the projector was bright enough to produce significant differences in color. The resulting extracted shapes are shown with significant magnification. We are now able to precisely map the pattern lines, and produce the desirable measurement precision (Figure 2-12). However, the checkerboard pattern generated instabilities, at the corners, that would affect performance.

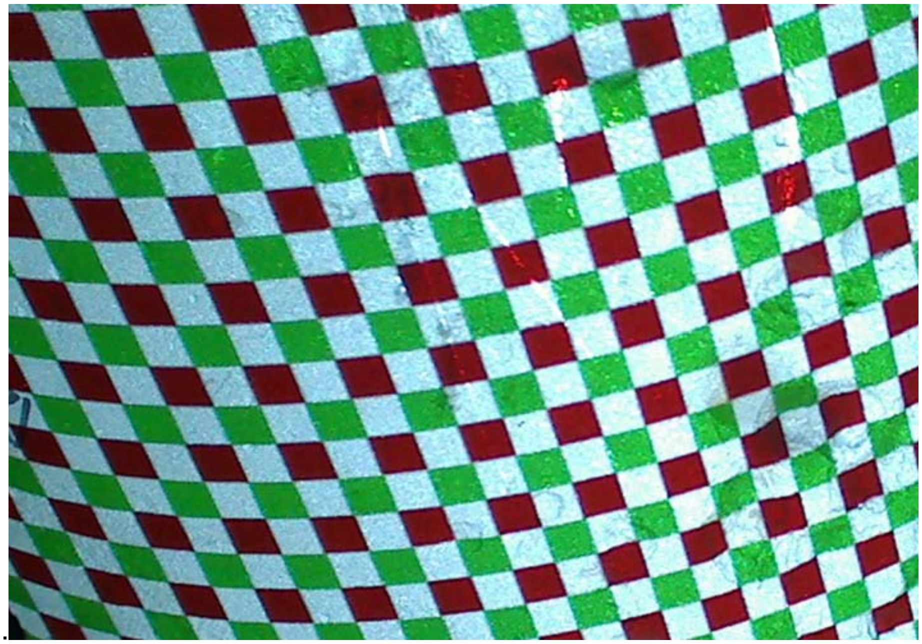


Figure 2-11 Illumination by a checkerboard pattern.

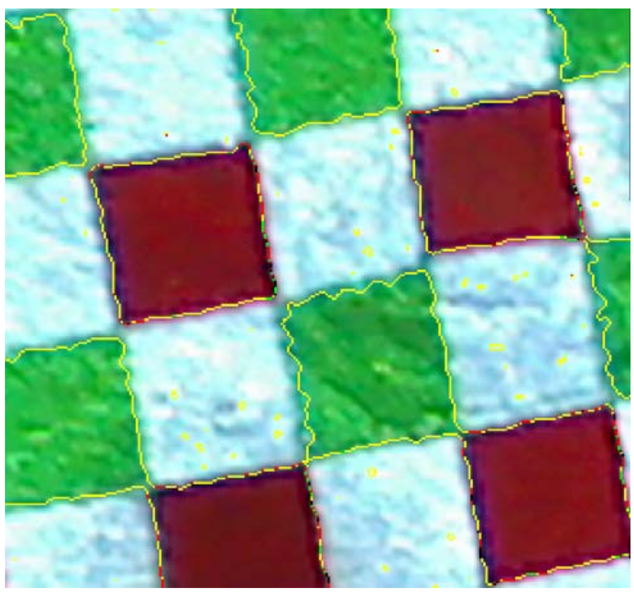


Figure 2-12 Result of the checkerboard pattern processing. The yellow lines are the extracted shape.

Finally, we produced a thick line pattern (see Figure 2-13, left) that yielded much more manageable lines, as shown in Figure 2-13 (right). The thick line pattern allows us to produce a reliable pattern of extracted lines (see Figure 2-14) from both sides of the line. The integrity of the extracted lines is much easier to verify.

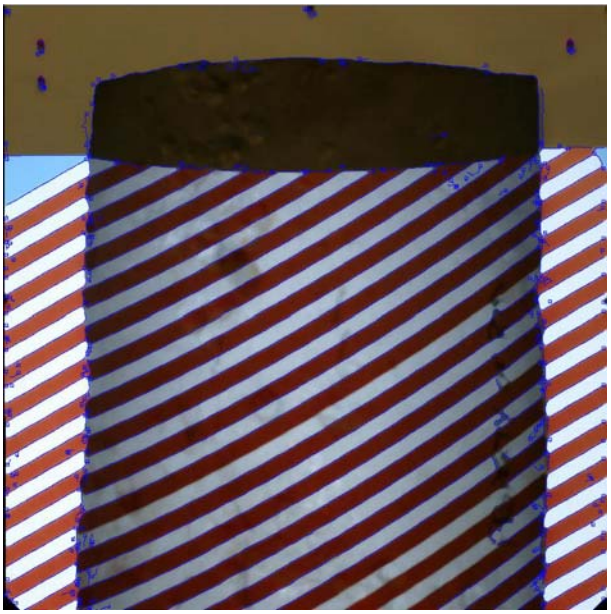
 

Figure 2-13 Illumination by pattern of thick lines (left), with the extracted lines shown in blue (right).

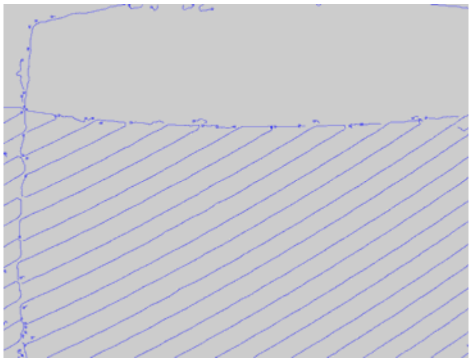


Figure 2-14 The extracted lines only.

Task 4. Develop Schematic Design of Phase II Prototype

We developed the main principles of the Phase II prototype design. The system will be capable of collecting multiple lines of scan using just one digital photograph, and could provide a complete dense 3-D scan with several photographs. The system will consist of a camera and a micro-projector (or light pattern source) rigidly fixed to each other. The projector, which will be placed at an angle to the pipe, will produce a line pattern on the pipe surface.

The projected pattern can be used to calculate not only the depth and shape of the depressions, but also the ideal shape of the pipe surface, as shown in Figure 2-15.

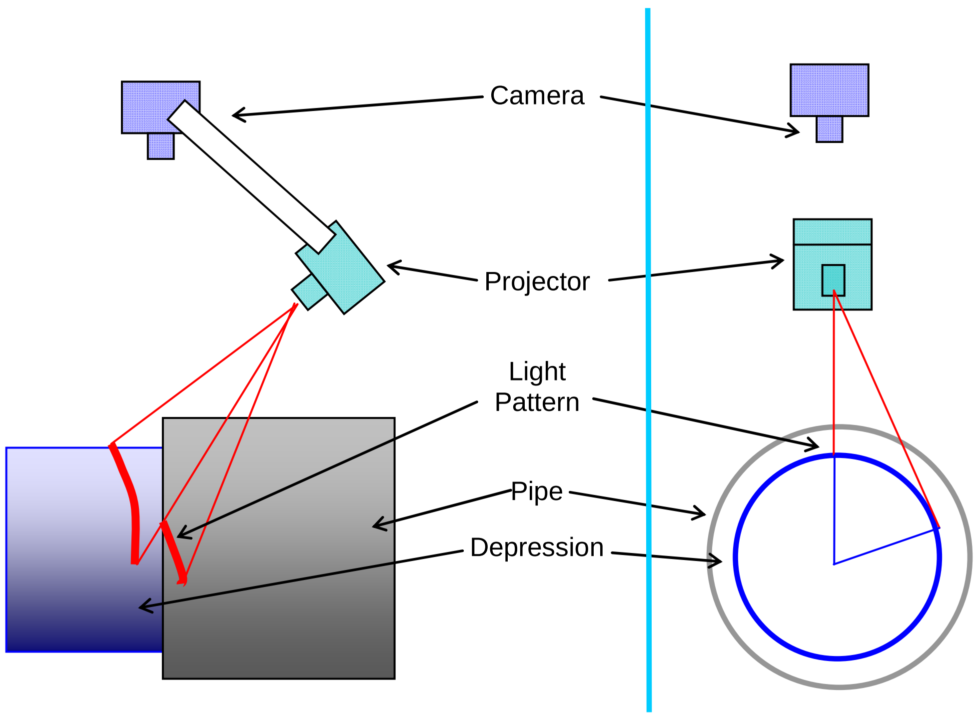


Figure 2-15 Schematic drawing of the Phase II prototype system.

In the case of a dent or depression at the pipe surface (see Figure 2-16), the line will shift from position A to C at the dent. Shift |AB| can be extracted using a photo camera and a projector. Let's assume that the camera is directed along z, the normal to the surface. The projector and the camera lie in the same xOz plane. If the projector's beam angle is known, then the depth |CB| can be calculated using the simple formula |CB|=|AB|*tan CAB.

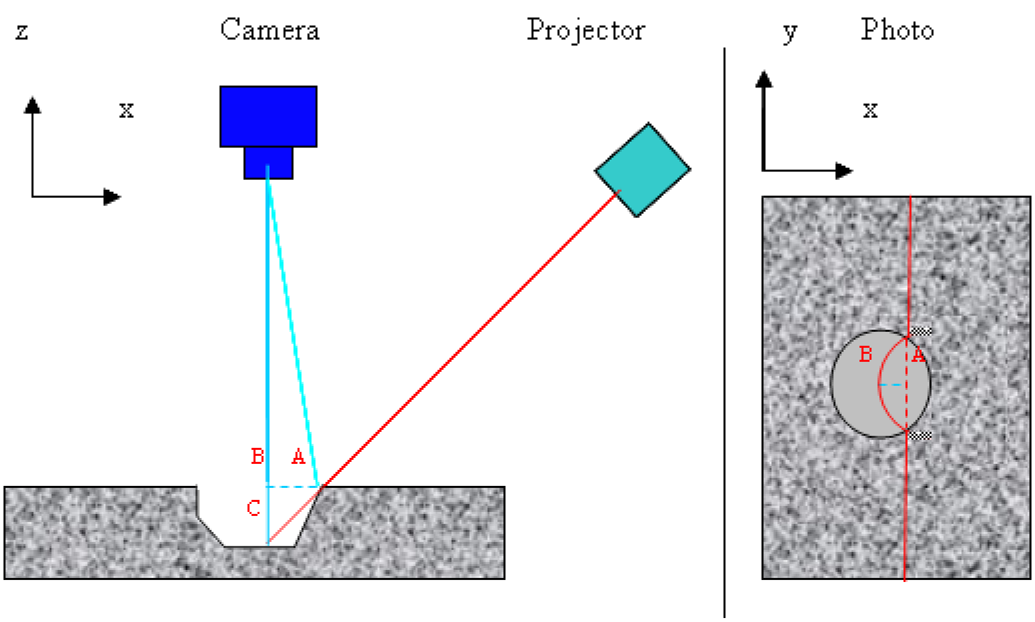


Figure 2-16 Depth extraction.

Based on the image extraction results, we are able to evaluate the precision of the depth extraction. Theoretically, the extracted depth precision is limited by the camera resolution, or pixel pitch. The sensor pitch ranges from 2.3 micron pixels (on a Canon S70 point-and-shoot consumer camera) to 8.2 micron pixel (on a large sensor such as that in a Canon 1D Mark II DSLR camera). If we use a camera with a regular lens, the size of the object is reduced at the sensor chip. However, with a common macro lens typically used in professional photography, we could obtain a magnification of 1:1 to even 1:20 at the sensor. Even in the case of a 0.1 magnification (~240 mm × 360 mm FOV) and a 7.6 micron pixel pitch, the system will have a depth precision of better than 100 microns.

To produce a dense depth map, we generated several images when the pattern was shifted normal to the line a known distance (see Figure 2-17). We generated multiple images to generate a dense depth map similar to the laser-based distance measurement map.

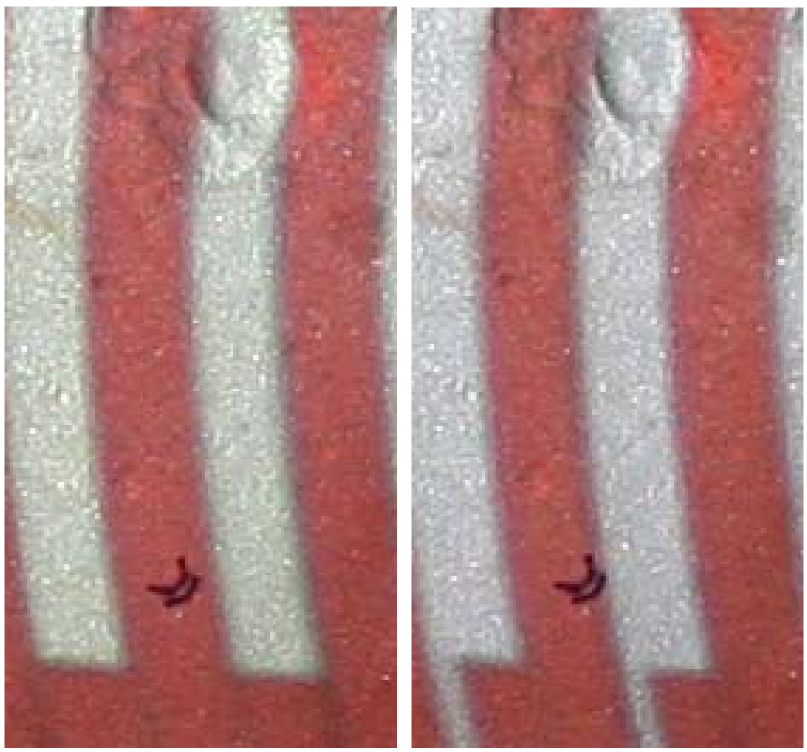


Figure 2-17 The pattern in two photographs automatically shifted using the Matlab software.

The processing of these images allowed us to produce a dense 3D representation of the depression (see Figure 2-18) that is competitive with laser based measurement systems.

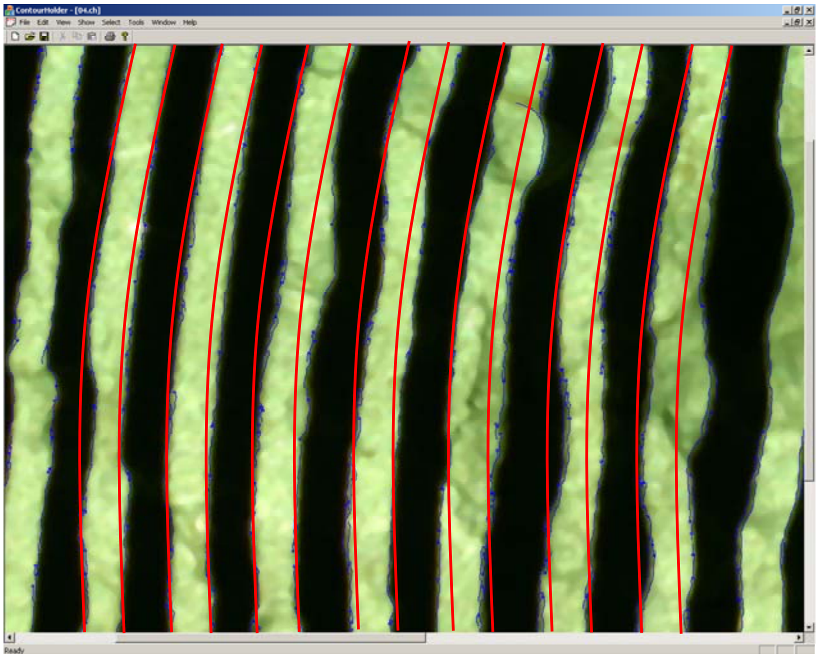


Figure 2-18 Extracted elliptical contours and lines for dense depth map calculation.

Task 5. Explore Commercial Potential

The discussions with industry leaders reviewed in Task 1 above also covered issues of commercialization.

The first step in commercialization is to demonstrate the technical capabilities of our proposed camera-based damage profiling tool to the broadest possible segments of the pipeline community and to gain their acceptance. We are in discussions with PRCI aimed at developing a small PRCI-funded project to demonstrate our system on damaged pipes in the Houston area.

Normally, ILI and external inspection is performed by large inspection contractors, who own and operate their own tools. These organizations are the logical first customers for early versions of our profiling tool. As the price reduces to the approximate level of $50,000, we expect that a much broader market will develop that could include the pipeline operators themselves. Outside the pipeline community we expect applications for inspection of process piping in chemical and petrochemical plants, as well as power plants. If we can apply our technique to the inspection of external corrosion, the market will expand further.

Beyond the pipeline community, we will investigate the application of our inspection tool to the assessment of critical infrastructure, including bridges and tunnels.