CREAFORM

THE BENEFITS OF REVERSE ENGINEERING FOR ENSURING PIPELINE INTÉGRITY

Author: Jérôme-Alexandre Lavoie, Product Manager

ABSTRACT

Today, now more than ever before, mounting public concern over pipeline safety has incited many companies to turn to emerging methodologies and technologies to better monitor and assess pipeline degradation. The ultimate goal is to predict the evolution of pipeline degradation so as to deploy preventative measures in a timely fashion—before interventions become too costly and the safety of citizens is compromised.

Reverse engineering is a new tool to help pipeline integrity assessment of complex or combined damages. This paper will describe the various roles reverse engineering plays as well as the different reverse-engineering approaches that can be used for pipeline assessment. This paper will also cover the most suitable 3D technologies—and their distinct advantages—for ensuring optimal assessments.

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INTRODUCTION

Reverse engineering is the process that identifies an object, a device, or a system's technological properties by performing a comprehensive analysis of its structure, functions and operations. In mechanical engineering, this process aims to create a virtual 3D model from an existing physical object in order to duplicate or enhance it.

They are many reasons to use reverse engineering of physical objects. For example, the reverse engineering process will be used if the original design is not supported by sufficient or adequate documentation or if the original CAD model is not appropriate to support modifications and/or standard production methods. In some cases, the original manufacturer no longer exists or manufactures a product—yet some requirements remain for that product. Reverse engineering would then be the ideal solution..

In order to create a 3D model of the object, the object must be measured using 3D scanning technologies (CMM, laser scanners, structured light digitizers, etc.). Once the scanning is completed, it is usually possible to rebuild the 3D model using 3D CAD, CAM, CAE or other software.

HANDYSCAN 3D BY CREAFORM

HandySCAN 3D™ is a handheld scanner manufactured by Creaform. It is a very portable and versatile self-positioning 3D scanner. It uses Creaform's positioning targets to reference its position from the object to scan. This device's main characteristic is its *portability*; it refers directly to the object with targets. It can easily be carried to the object instead of bringing the object to the scanner.

Once the object and the scanner's position have been located with targets, the surface acquisition is completed via the camera. The camera detects laser lines that cross each other and are projected onto the surface. As the surface is swept over by the laser, data is recorded based on the triangulated position. The output file format is a STL file.

STL (stereo-lithography) is a file format native to the stereo-lithography CAD software, widely used in 3D printing and CAD industries. This file format is supported by many other software packages. STL files only contain the surface's geometry of a three-dimensional object without any color, texture or other common CAD model attributes. They also contain a raw unstructured triangulated surface of the unit normal and vertices (ordered by the right-hand rule) using a three-dimensional Cartesian coordinate system.

Using STL files for reverse engineering has several advantages. They can:

- Recognize features intuitively
- Distinguish front and back faces
- Evaluate curvature
- Measure volume
- Accurately measure alignment between scan data
- Be used for visualization and documentation

REVERSE ENGINEERING APPLIED TO PIPELINE INTEGRITY

These days, companies are aware of public concern about pipeline safety and are turning to new technologies to increase public confidence towards pipeline installations. A constant monitoring of the installation is performed with tools capable of detecting anomalies such as loss of wall thickness and mechanical damage and other.

Pipeline integrity assessment is a process that falls under the responsibility of Quality Control (QC) and metrology. As QC is a common process in part manufacturing, pipeline assessment is key in the pipeline integrity management program of asset owner.

Recent technological breakthroughs from Creaform allow easy access to important information, which can help pipeline operators to increase the safety of their networks. Pipecheck™ software, Creaform's proprietary solution for pipeline integrity assessment, is the only software solution on the market to combine the power of reverse engineering and QC methodology for pipeline integrity assessment.

There are several definitions of quality depending on the application. Manufacturing-based definitions associate quality with the conformance of a product to its specifications. QC) is a process that aims to review the quality of all factors involved in the production process and part life cycle.

Metrology is the science of measurement. In metrology, **precision** refers to the dispersion of measurements. The measurement error (the mean) can be close to zero even if the system is very not precise (it nevertheless must have a good trueness). In other words, the less the measurement data is scattered, the more the equipment is precise. A formal definition of precision is: closeness of agreement between indications of measured quantity values obtained by replicate measurements on the same or similar objects and under specified conditions.

The word **trueness** gives information on the difference between the mean of measurements and the real dimension, regardless of dispersion. In other words, the more the mean of measurements is close to the nominal value, the more the equipment has good trueness. A formal definition of trueness is: closeness of agreement between the average of an infinite number of replicate measured quantity values and reference quantity value.

Accuracy is the conformity between scan data and reality. To evaluate the accuracy of a measuring device, such as a laser scanner, the data acquired with the device should be compared to the data acquired with a more accurate measurement tool (e.g.: a coordinate measuring machine (CMM)). In addition, the measured item must be normalized. A more formal definition of measurement accuracy is: the closeness of agreement between a measured quantity value and a true quantity value.

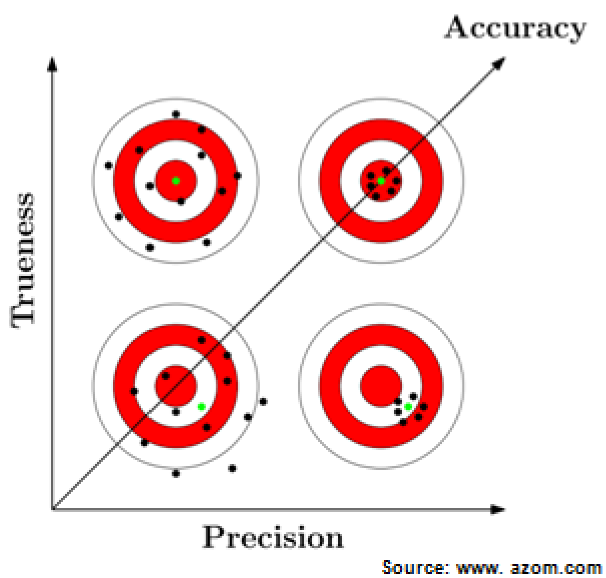

Figure 1: Representation of accuracy, trueness and precision.

Uncertainty is described as the doubt about the validity of a measurement result. A measurement never gives the true value; however, it is the best estimation of it. This way, a measurement is only complete if it is accompanied by a statement of the associated uncertainty. The following figure shows the main sources of uncertainty.

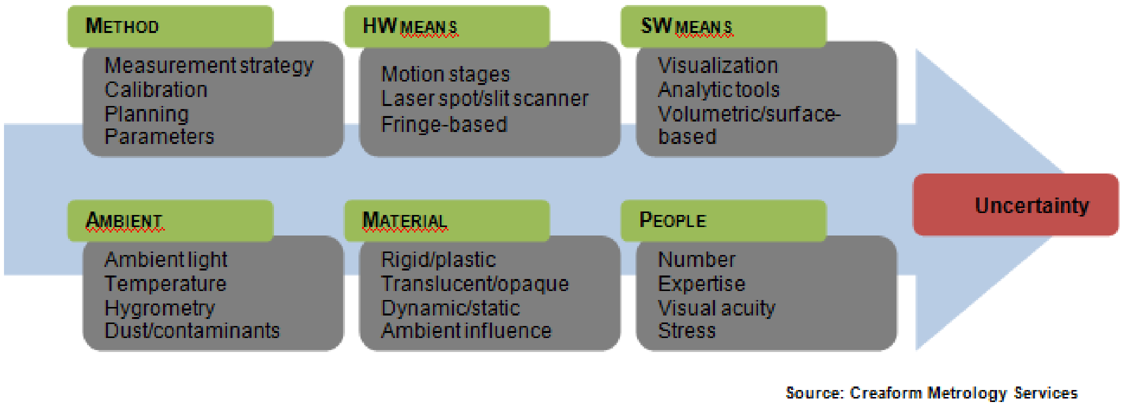

Figure 2: Representation of main sources of uncertainty.

Equipment performance is not the only thing to consider for highest accuracy possible. Due to several potential sources of error, uncertainty is difficult to determine. It is a decisive factor when it is required to make an informed inspection decision.

Applying reverse engineering concept to perform pipeline integrity assessment is an interesting idea when performed properly. There are several existing reverse engineering methods available, but not all of them are suitable for pipeline integrity assessment.

Parametric Reverse Engineering

This method for reverse engineering is also known as "design intent." The main goal of using such techniques is to understand how the object was conceived. Some software programs are dedicated to this application. They include actual conception tools with typical geometrical shapes. Basically, the workflow consists of analyzing the several parts composing the object and creating similar features, as one would do in CAD software (extrusion, revolution, geometries, etc.) to match its global shape.

The physical object or a scanned 3D model is made up of approximate shapes. Therefore, an object conceived in this reverse engineering process is never the exact copy of the reference. As it is composed of perfect conception features, it is always slightly different. The reference and the reverse engineering model need to be compared to each other in order to evaluate their relative deviations. If the deviations are too high and the tolerance is not respected, modifications may have to be applied to solve the problem.

Freeform Reverse Engineering

With this method, the idea is not to understand the conception of an object, but only to create a surface with the exact same shape. Using such techniques, it is possible to efficiently extract accurate freeform surfaces from the shape of 3D scanned objects. Freeform surfaces range anywhere from the shape of a rock formation to the body of a car. In these cases, the STL model is used as a reference to build NURBS based on the surface.

For this application, the scan surface needs to be as perfect as possible. Therefore, we can distinguish two main steps for freeform reverse engineering: mesh preparation/optimization and the actual surface reconstruction. These two stages are strongly linked; a thorough preparation will ease the surface construction.

The mesh optimization sometimes involves multiple steps, including: alignments, manifold, hole filling, assembly combination (merge operations), decimation, etc. All of these concepts are highly proscribed when performing quality control since they can modify the surface condition. The NURBS (Non-uniform rational B-spline) model to build will therefore be performed on the direct output of the acquisition software.

Creaform's Innovation

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Creaform's breakthrough comes from the development of a hybrid technique between the two approaches described above. When applied to pipeline integrity assessment, especially for material loss located at the bottom of mechanical damage defects, Creaform's approach enables the extraction and extension of dent curvatures over corroded areas. This approach requires the understanding of the dent shape prior to any material loss—without surface optimization operations. Using the HandySCAN 700, powered by the *TRUaccuracy*™ technology, and powerful surface fitting methods, Pipecheck software offers a simple workflow to accurately measure corrosion depths at the bottom of a dent.

The dent shape prior to corrosion is extracted using the surface of the dent. This surface is user-defined: Pipecheck uses the dent surface area and removes what the user manually defined as the corroded surface. These steps are performed manually to allow the user total control over the exact area that is considered corroded.

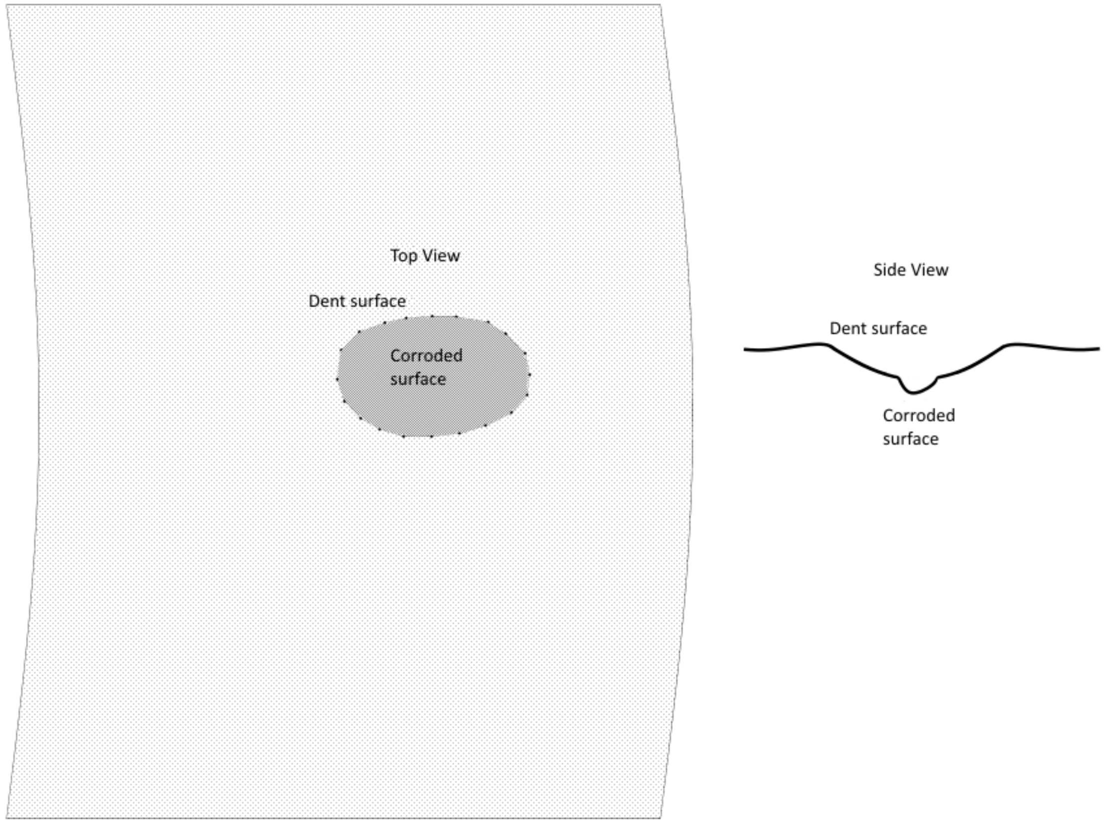


Figure 3: Overall dent surface and corroded region representation

Creaform's research and development team have considered many different methods for the extrapolation of the material that falls under the corrosion damage. Considering the pros and cons for each was an important part of the final decision to go for NURBS. Some extrapolation techniques gave surfaces that were too rigid. For instance, looking for the weighted mean of the edge of the corrosion and using that as the central point of the extrapolation gave a surface that was too flat with no assurance of continuity along the edges.

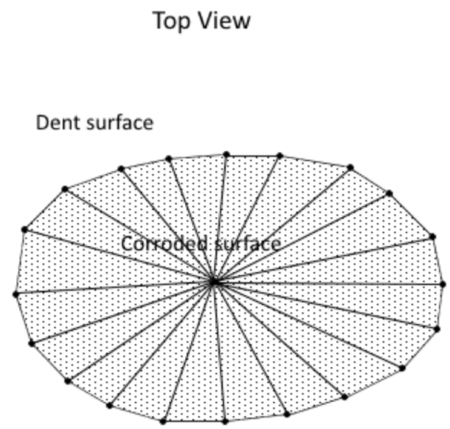


Figure 4: Material extension using a weighted mean

A second approach was to consider simple curve fitting using the main directions of the pipe surface. The curves could be done in both directions independently and each would have continuity along the edges. However, for this approach to reconcile the two directions to form a single surface, interactions were needed between the curves; using a simple mean of the two surfaces meant possibly losing some of the continuity in one direction or another. It was better to consider parametric surfaces which would naturally make the two directions interact.

Therefore, looking into parametric surfaces, two options seemed more interesting: Coon patches and NURBS surfaces. Using a grid that follows the main directions of the pipe, it's possible to define parametric curves that follow the edges of the corrosion patches. The curves can be used to define four independent surfaces. The Coon patch is the interpolation of all four curves with the necessary continuity in all directions.

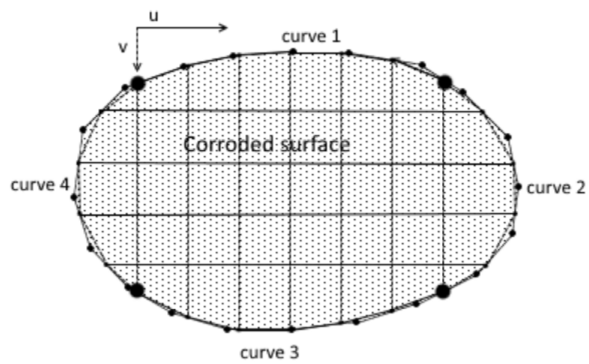


Figure 5: Parametric curves resulting in a Coon patch

The main drawback of using Coon patches is that this technique focuses on the boundary information and the first derivatives of these boundaries. Therefore, the overall dent surface information is ignored, which can lead to inaccurate reconstruction. NURBS surface techniques using the dent surface surrounding the corrosion damage ensure continuity throughout the entire interpolated surface. This technique brought the best results during the validation technique.

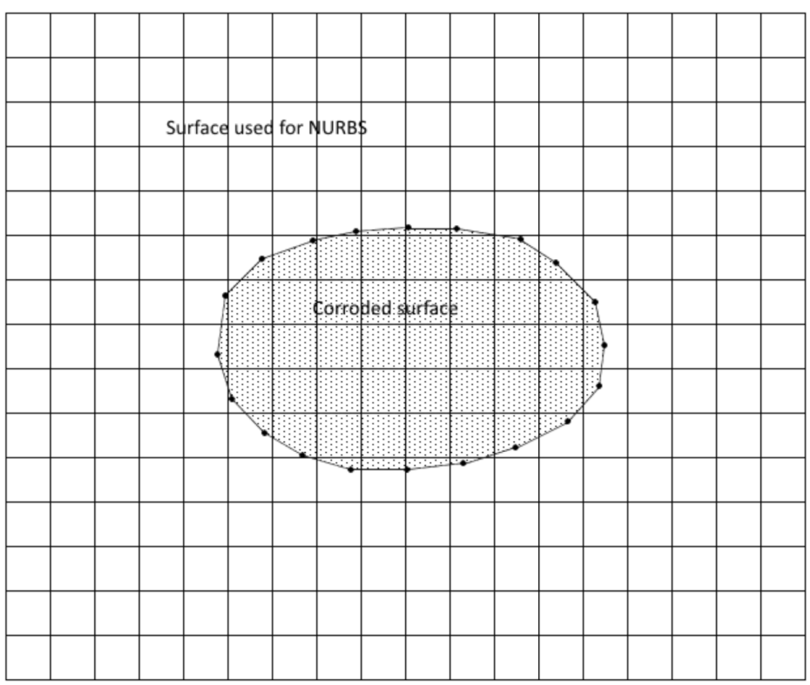


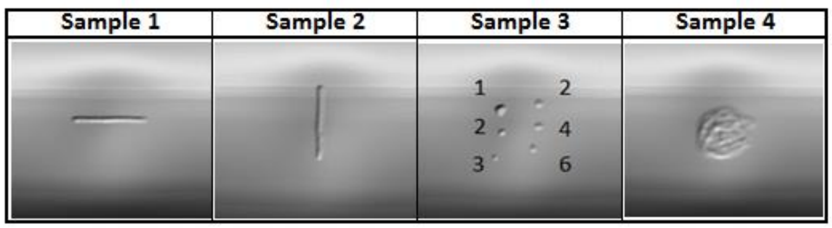
Figure 6: NURBS surface reconstructed from the overall dent area without information from the corroded area.

CASE STUDY: FILL HOLES VS NURBS SURFACES

This section presents the comparison results between the two methods previously mentioned: Coon patches (usually associated with hole filling methods) and NURBS surfaces. The idea was to study both methods' reaction and thus determining their accuracy when reconstructing a surface. When applying these approaches to NDT, specifically to corrosion analysis inside a dent, we focussed on how accurately the deepest corrosion point can be extracted. Using four different samples, two specific analyses were processed: one comparing the deepest corrosion points found and one determining how human error influences each method's accuracy. Prior to these analyses, a data set was created following these steps:

a. Different corrosion patterns were numerically created on a real dent surface scanned by a HandySCAN 3D.

Table 1: Sample data with corrosion



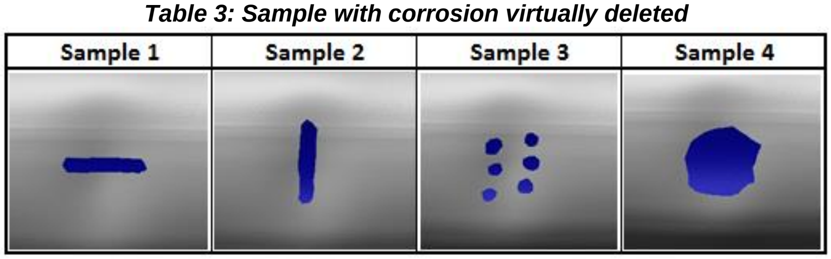
b. Nominal deepest corrosion points were found in each sample by creating a deviation analysis from the original surface without corrosion. For *Sample 3*, a deepest point for each of the six corrosion pits was found.

Table 2: Nominal deepest corrosion points for each sample

Samples	**Sample 1**	**Sample 2**	**Sample 3**						**Sample 4**
Deepest point	-2.195	-2.316	-4.088	-1.668	-1.406	-1.62	-0.972	-1.415	-3.465

c. Corrosion was selected and virtually deleted, thereby leaving a hole to be filled by each method.

Table 3: Sample with corrosion virtually deleted



Analysis 1 – Deviations of deepest corrosion points for each method

Steps:

a. Dent surfaces were recreated from the samples with holes (corrosion deleted) using each method. For Method 1 (Fill holes/Coon technique), three major different software programs were used.
b. Deepest corrosion points were measured by creating a deviation analysis between samples with corrosion and surfaces created by each method.
c. Deviations were computed based on the nominal deepest points that were found earlier.

When comparing deviations, the NURBS Patches approach was better 6 times out of 8 on normal corrosion patterns. When less accurate, the NURBS Patches method slightly overestimated the corrosion depths, giving a deeper measurement and thus creating a more conservative reading. This behavior is better for NDT applications; when it is always advisable to underestimate the pipeline's remaining strength, rather than overestimate it. NURBS Surfaces stability was also better: its mean deviation being almost twice more accurate than the other approach. For abnormal corrosion shapes, where the corroded area is very large in proportion to the dent surface, such as *Sample 4*, no method was accurate. It was impossible to determine the exact mechanical damage shape prior to any corrosion.

NURBS Patches:

- More accurate 6 out of 8 times
- Average deviation is 0.019 mm compared to 0.031 mm

Table 4: Deviation (mm) of deepest corrosion points measurements for each method

Samples	**1**	**2**	**3-1**	**3-2**	**3-3**	**3-4**	**3-5**	**3-6**	**3-7**
Method 1 : Coon Patches									
Software 1	0.004	0.072	-0.050	0.032	0.039	-0.012	0.032	-0.040	1.541
Software 2	-0.037	0.036	-0.018	0.056	0.058	0.027	0.022	-0.034	0.965
Software 3	0.000	0.002	0.014	0.039	0.036	0.031	-0.008	-0.041	2.011
Mean	0.014	0.037	0.027	0.042	0.044	0.023	0.021	0.038	1.506
Method 2 : NURBS Surfaces									
Pipecheck	-0.006	0.010	0.008	0.038	0.016	-0.003	-0.026	-0.045	2.367

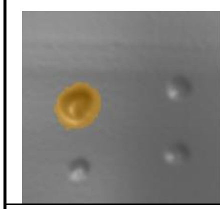
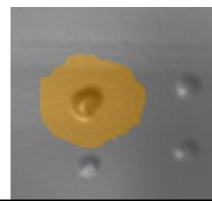
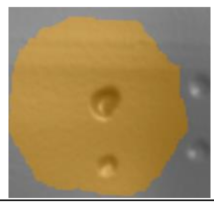
Analysis 2 – Determining how human error influences each method

In this second analysis, the hypothesis is that human error—and therefore corrosion selection and deletion—will influence the accuracy of the methods. On the deepest corrosion pit of *Sample 3*, three different selections from smaller to larger were deleted.

This replicates some inaccurate selections made by the user, were larger selection passed the corrosion should lead to larger deviations.

Results indicate that both methods are affected by the selection, since the deviations get larger on inaccurate *Selection 2 & 3*. The interesting fact is that the NURBS Surfaces approach is much less affected by human error; its mean deviation on the three different selections was more than twice better (0.035 mm VS 0.080 mm).

Table 5: Deviation (mm) of deepest corrosion points measurements for each selection and method

Selection 1	Selection 2	Selection 3
		
Method 1 : Coon Patches		
0.027	0.139	-0.075
Method 2 : NURBS surfaces		
0.008	0.069	0.028

CONCLUSION

As part of a comprehensive continuous improvement process, pipeline integrity assessment has become mandatory for the industry. Reverse engineering can play an important role in this process when done properly. Development and the appearance of 3D technologies on the market have definitely made available the use of this practice in the pipeline industry. Although often seen as complicated, reverse engineering is now greatly facilitated by the use of Creaform's 3D accurate and reliable technologies and software.