Efficient inspection from measurement collection through to report

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Abstract. Ascertaining the integrity of large steel structures such as storage tanks, pipes and vessels is a complex task. Silverwing (UK) Ltd has developed an inspection solution that can inspect, manage, present and generate reports. The inspection data generated from these large assets can be large, requiring gigabytes to even terabytes of storage and meticulous analysis. And while it is normally accepted that more data is always better, the ability to handle, analyse and report findings with vast amounts of information efficiently becomes a challenge. In this paper, examples are given towards illustrating how volumes of information is technically handled and how it can improve the efficiency of the overall inspection process from the measurement gathering stage to the report and how this can benefit the inspection company, asset integrity engineer and asset owner..

1. Introduction

Several inspection standards which cover the maintenance of large assets frequently state that a relatively small collection of sparsely separated spot-measurements are needed to estimate its remaining life or the interval until the next inspection. The inspection of these large assets can be very time consuming and so a balance is normally derived between the time available to conduct the inspection and the level of measurements required to determine its condition. Of course, the inspection time can be reduced by only targeting areas of the asset that are normally associated with corrosion, e.g. the product interface level in a storage tank. The complexity of the inspection of such assets is usually derived from a set of guidelines which the asset owner has adopted. EMMUA 159 [1] is one such guideline and by crude approximation, the recommended number of 10 mm^2 spot-measurements on a 15 m high shell wall of a storage tank 50 m in diameter would cover approximately 0.0012% of its surface. Unless prior information and location of the critical areas of corrosion is available, the likelihood of finding the corrosion is small. The most obvious improvement is to increase the number of spot-measurement, at the cost of time.

The likelihood of locating corrosion on these structures is highly dependent on the non-destructive testing (NDT) approach used. An automated process to collect spot-measurements can improve the positional accuracy but also increases the number of measurements taken over a given area. With a suitable inspection tool setup, the condition of the internal and external surface, along with inclusions, blistering, dis-bonding of internal liners and even cracking[1] can be found. The umbrella of inspection can arguably be divided into two stages, in-field data acquisition followed by reporting. The basis of this process is shown in Figure 1 beginning with the asset in its normal operating state. Once an inspection is deemed necessary, the two stage inspection process begins. Pending the results of the inspection, repair may or may not be necessary before the asset is re-commissioned (or decommissioned). During inspection the data acquisition and reporting stages can repeat several times, dictated by the analysis of the recorded measurements. This is usually a consequence of fine-tuning the inspection tool setup or deciding to hone in on an area of interest.

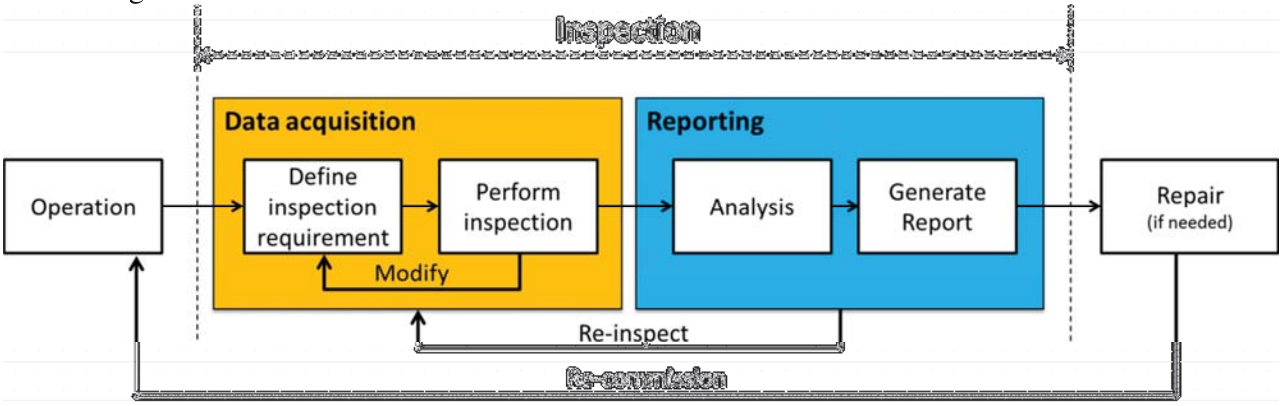

Figure 1: High-level representation of the inspection process

Primarily, focus towards driving the efficiency of the inspection process is given to the data acquisition stage by improving the physical speed of the scanner or by creating arrays of sensors to generate a colour coded 2D (X/Y) map of measurements (C-Scans) with one sweep. It can be argued that the primary goal in this stage is to minimise the operator time in-field and limit the exposure to harsh environments. While such approaches usually result in improved efficiency, little focus is given to the reporting stage. With the ability to capture vast quantities of scan data with the advent of cheap digital storage, the data (or scans) still needs to be labelled, sorted, 'stitched' together, analysed and its key findings consolidated into a final report.

The reporting stage is normally underestimated and normally involves a combination of spread sheet, word processing and image manipulation software that can be a process just as time-consuming as the first. This paper examines the efficiency of each of these stages and discusses various forms of gains that can be achieved over both stages of the inspection process.

2. Data Acquisition Stage

There are a myriad of tools available to inspect large areas and perform remote measurements with different inspection instruments, one common form is the deployment of ultrasonic probes. Silverwing (UK) Ltd has an automated inspection tool that is able to perform UT that can cover the vast majority of an assets surface and is able to record millions of spot-measurements, normally referred to as automated UT (AUT). These devices cover relatively small areas and so adjacent scans are conducted in order to cover a larger area. Sometimes the

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[1] Particularly hydrogen induced cracking (HIC) and stress corrosion cracking (SCC).

scans are overlapped to aid alignment (the 'stitching' process) during the reporting stage; a topic discussed towards the end of this paper.

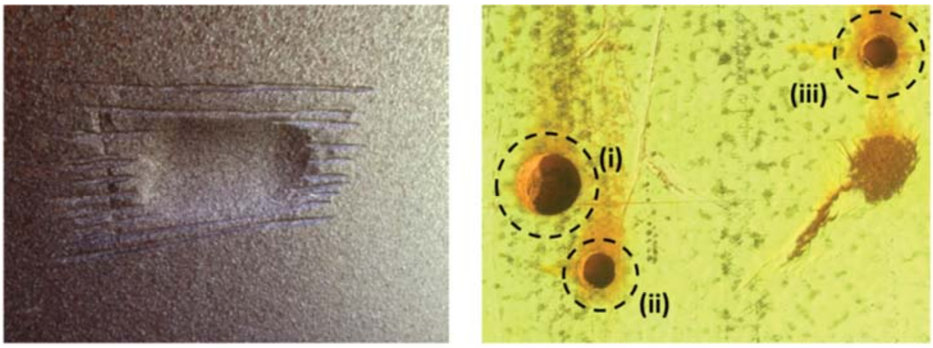
The AUT system offered by Silverwing (UK) Ltd uses an immersion approach that utilises a column of water to couple the sound generated by the probe and the surface under inspection. The water column is contained in a 'probe holder' that is continually fed to overcome water dissipation as the probe travels across the surface. The volume of water lost is subject to changes in the surface of the asset. Even if coated, a breakdown can cause an assets wall to be subjected to the environment, eventually resulting in corrosion. In this section, three small case studies are presented that demonstrate the capability of the AUT approach focusing on the following parameters:

- Water immersion and surface discrimination,
- Scan resolution,
- Amplitude monitoring

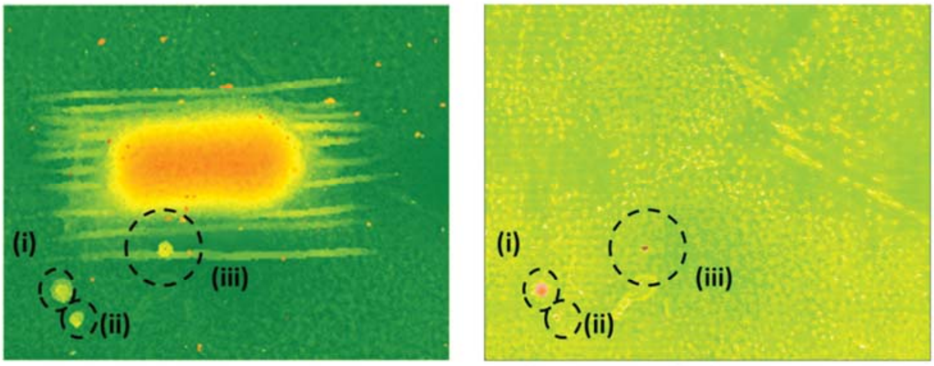
2.1 Water immersion and surface discrimination.

With the water immersion UT approach, there is a distinct advantage as additional information beyond material thickness can be obtained such as the profile of the near-surface. The water column, between the UT probe and near-surface can vary in the presence of flaws or corrosion. Changing the path length of the water causes the surface interface signal of the UT to vary, indicating the presence of near-surface variation. Coupled with traditional back-wall echo measurements and an additional gate fixed to a single point in time on the UT to track the variation of the interface, changes to the water column length can be monitored, indicating the presence of wall loss on internal, external or even on both. An example scan of a section of pipe is shown in Figure 2, illustrating a large artificial flaw on the internal surface (a) and three artificial flaws on the near-surface (b) on which the AUT scanner resides. UT signals from the immersion approach can be seen to contain more information than traditional contact probes. The associated UT thickness map of the flaws shown in Figure 2 (a) and (b) is shown in (c), illustrating a colour coded representation of the thickness of the material. Green relates to the nominal thickness of the pipe, tending from green then yellow through to orange as the material becomes thinner. Peering through the surface of the material with map (c) illustrates the location of the large defect in the centre and also the corresponding defects (i), (ii) and (iii) shown in Figure 2 (b). The near-surface flaws shown in Figure 2 (b) are reported in (d) without the indication of the internal surface flaw illustrating discrimination. Further detail of this approach can be found in [2].

While discrimination is a major benefit there are other parameters to consider with the immersion approach. Along with crystal frequency of the probe plays an important part in the definition of the thickness measurement, the probes focal length is a parameter to consider. With the immersion approach, the focal point is a combination of the path length of the water column and the thickness of material being inspected. Depending on the requirement, the focal point can be chosen to focus on the internal surface to look for flaws or in the centre of the material to observe laminations or inclusions.



a) Artificial discontinuity (internal surface)   b) Artificial discontinuities (near-surface)



c) Thickness UT C-Scan of the large internal artificial defect (a) and three near-surface flat bottom discontinuities

d) Water-path 'fixed' gate UT C-Scan showing the same three near-surface flat bottom discontinuities

Figure 2: Example internal and external flaws and their associated top surface and material thickness maps via UT.

2.2 Scan resolution.

A raster scanning AUT system allows the resolution of spot-measurements to be tailored. Each spot-measurement is typically defined by a square area such as 10 mm x 10 mm and even down to high-resolutions of 0.5 mm x 0.5 mm or less. The choice in resolution is a compromise between the time available to conduct the inspection and the largest discontinuity that the asset owner is willing to miss. When planning the inspection, risks are calculated based on many other factors including, the already mentioned asset history, the assets location (environment), information about neighbouring assets, the timeliness to get the asset back in-service and the approach used to perform the inspection. Some efficiency gain can be achieved by first scanning the majority of an assets surface at a coarse resolution, for example 20 mm x 20 mm or 50 mm x 50 mm. From these scans, corrections to the inspection requirement may then follow based on unforeseen circumstances or located areas of interest with a more detailed inspection, e.g. re-scanning areas of interest a second time at a higher resolution. To illustrate the potential danger of this approach, an AUT inspection has been conducted with a set of artificial defects and their corresponding C-Scans are shown in Figure 3. In this example, the data acquisition has been repeated with four different resolutions starting with a coarse resolution of 50 mm x 50 mm in (a) and increasing the resolution down to 1 mm x 1mm in (d). It is clear that from the pixelated representation in (a), the increased resolution improves the definition and shape representation of the defects. It is also apparent that the two smaller circular defects and diagonal grind marks shown in (c) and (d) are missing in (a) and only partially represented in (c). Based on the defects illustrated in this example, scan (b) represents the minimal resolution necessary to find the defects. Even so, this is again a compromise as the shape of the diagonal grinds could be misinterpreted as individual narrow defects, only at higher resolutions are their shapes identified.

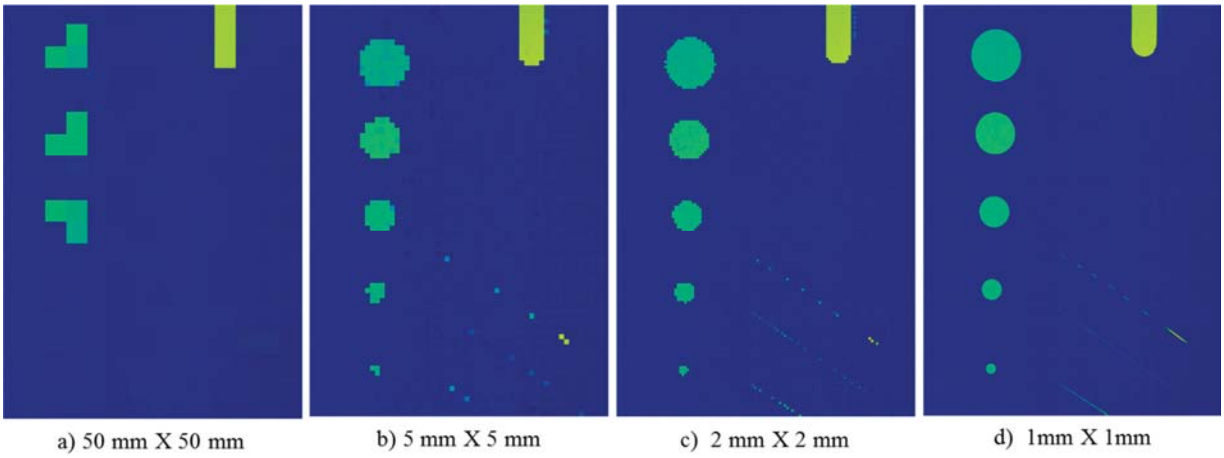

a) 50 mm X 50 mm b) 5 mm X 5 mm c) 2 mm X 2 mm d) 1mm X 1mm

Figure 3: C-Scans of a set of artificial defects at four different resolutions. Notice that as the resolution decreases towards 50mm x 50mm, a number of smaller discontinuities have been missed.

Ideally, if the inspection equipment were able to perform the inspection at the same speed regardless of resolution then the smallest resolution would be chosen as digital storage is available at relatively low cost. Negating phased array type systems, traditional AUT systems normally comprise of a single transducer that is driven in a raster manner to generate the C-Scan images. As the resolution increases, the number of samples required per second increases as do the number of raster sweeps. This gives an exponential style increase of time required to scan as a function of resolution. To illustrate this, the time taken to perform a 1 m scan with a 600 mm wide sweep for different resolutions using the Silverwing AUT system is shown in Figure 4. At a high resolution of 0.5 mm, the time taken to conduct a scan is approximately 144 minutes. This time decays in an exponential manner as the resolution decreases and down to 1 minute for a resolution of 50 mm. For the corresponding defects, the smallest diameter that could be found as from a choice of scan resolutions is represented by the logarithmic style plots. The red plot depicts the absolute smallest defect diameter that could be found for a given resolution and is based on the Nyquist sampling rate which states that the sampling rate must be two times higher than the highest frequency to observe. In this context, the highest frequency relates to the smallest defect diameter. Under this sampling theorem, the smallest defect that could be reliably observed at a 0.5 mm resolution is 1mm, at 2 mm it would be a diameter of 4 and so on; double the chosen resolution. This is also under the assumption that these defects are flat-bottom. Another condition is that the Nyquist sampling rate applies to period signals, not discontinuous ones like defects and so to obtain a reasonable estimate of a defect size a typical engineering ‘rule-of-thumb’ approximation of the sampling resolution should be 10 times that of defect diameter that needs to be located and profiled. This is illustrated by the green profile in Figure 4 and clearly demonstrates the impact that scan resolution can have on the ability of AUT.

However, there are other parameters that can be considered to aid the efficiency. One considers the beam spread at the focal point of the UT probe. Depending on the focal spot, the beam spread can cover an area in the region of mm^2 and so scan resolutions that are higher than the focal point can be considered excessive[2].

Another compromise relates to perform data acquisition with a coarse resolution to first locate defects, followed by higher resolution scans of located defects in order to size them. One caveat with this approach is that the coarse resolution chosen must, at the very minimum adhere to Nyquist sampling rate.

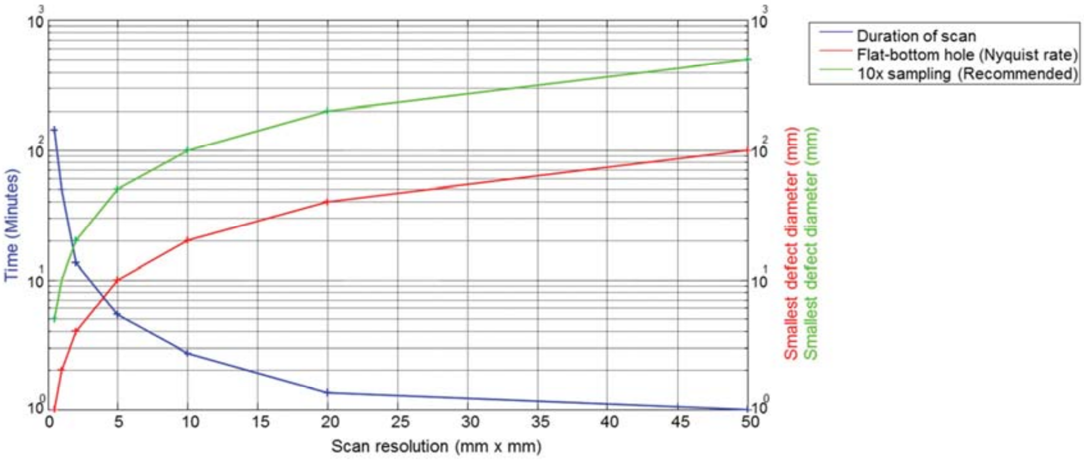


Figure 4: The time required to perform a scan at a variety of resolutions (blue). The diameter of defect that can be located at a given resolution is also shown, one adhering to the Nyqusit sampling rate and the other based on a recommended 'rule-of-thumb' sampling rate of 10.

2.3 Amplitude monitoring

Traditionally, AUT systems are utilised to determine the condition of an assets structure by measuring its thickness by configuring a set of gates over a UT signal. These gates can have several functions, they can measure the flank of each echo (the first point which crosses the gate in time), the time at which the peak amplitude of the echo is located or from a fixed position in time (as shown earlier to discriminate near-surface flaws). A gate can also be used to monitor the amplitude of a given echo. This can provide further information about the condition of the asset by indicating regions of poor reflectors caused by the sound scattering. As the amplitude of these echoes is a function of the reflecting UT signal, then the edges of defects and those with low amplitudes that make gate measurements difficult can be clearly shown on the corresponding C-Scan. Monitoring the amplitude of an echo can also be used to assess the condition of an internal rubber bonded liner. In the region of a bonded area, the acoustic impedance is less and so the sound travels through asset material, into the adhesive bond and into the liner, absorbing the sound energy and limiting the amount of reflection. The interface between the internal of an assets surface and an un-bonded area has higher acoustic impedance, thus giving a reflection with higher amplitude. The discrimination of a bonded and un-bonded area with AUT and an amplitude gate configuration is shown in Figure 5. This is a C-Scan of an area of a 16 mm nominal thickness pipe with an internal rubber coating 11 mm thick. The bonded area of rubber is identified by the low amplitude signals, shown here by the red region. The corresponding un-bonded are is shown with higher amplitudes in yellow. The

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[2] Note that the profile of the beam spread is not flat and so the measurement may result error.

aim here would be to locate any regions of high amplitude (yellow) in the bonded areas and identify regions where the lining or glue had perished. It is also interesting to see additional information in this scan by the location of the glue overspill area. As the liner was applied, the bonded area was pressed on top of some adhesive at such pressure, the remainder of the glue was forced out the side, resulting in the overspill area. This is made visible by the trace at the edge of the glue, shown here in red, which also causes the amplitude to drop based on the refraction and scattering of sound.

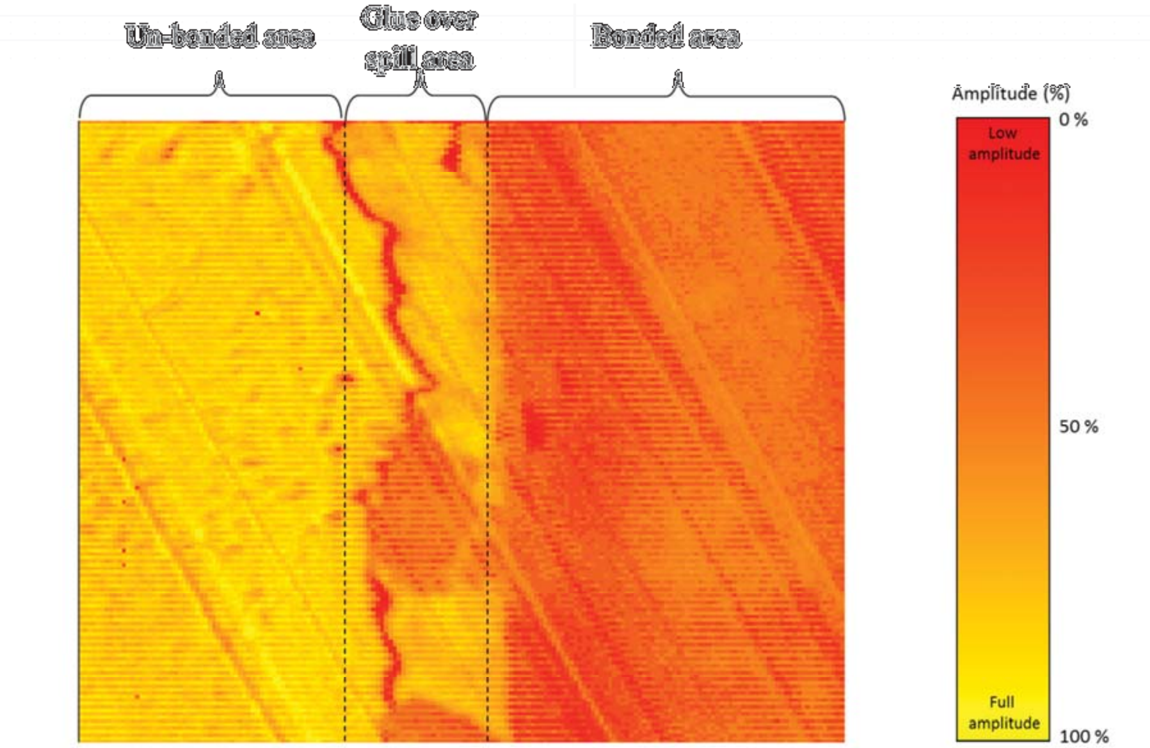


Figure 5: Amplitude map of a back-wall echo showing bonded, un-bonded and glue line of an internal rubber liner in the internal surface of a pipe.

The case studies of the three parameters presented here demonstrates advantages of the AUT approach and considerations when planning the inspection. Efficiency in the form of time can be chosen at the cost of likelihood of locating a defect in the data acquisition stage. Then next section discusses potential efficiency gains at the reporting stage.

3. Reporting stage

A popular term used at present is ‘big data’ (see [3]) and is used to illustrate the challenge of sorting and analysing vast quantities of data in a timely manner. While there is no unique solution, attempts to analyse such vast quantities have been tackled through enhanced data mining algorithms, faster computing hardware, parallel processing and cloud computing that leverages all the latter with large computational clusters. This is a challenge across many institutions including sciences, medicine and surveillance and of course NDT, both periodic inspection and condition monitoring. In the context of periodic inspection, large volumes of data generated by AUT present additional and unique challenges. Along with the normal timeliness to analyse and reporting findings, data is normally obtained in isolated locations and can make cloud computing unsuitable due to poor or non-existent internet connection. This restricts the 'big data' problem and so analysis of inspection measurements is normally conducted on a desktop or portable computing platform. To exemplify the quantity of data that can be involved in a periodic inspection, the number of measurements that can be obtained from a full coverage inspection of a tank shell, 50 m diameter storage tank and 15 m high, scanned at a high resolution of 1 mm x 1mm would result in around 4,825 GB (gigabytes) of UT data. Naturally, the coarser the resolution, the less data, decaying exponentially as the resolution decreases.

Following on from the basic inspection process shown in Figure 1, and interlace it with the concept of 'big data', it is proposed that the typical size of data obtained at each stage can be divided into four levels. A hierarchical view of this concept is shown in Figure 6 and demonstrates the levels of data during the inspection, from data collection to the ultimate '1 bit' question, is the asset fit-for-service (yes or no)? Gigabytes or perhaps even terabytes (TB) of data would be recorded at the source during the 'data capturing' stage, this is considered to be the largest data set and is represented by level 1 in Figure 6. Ideally at this level, it can be argued that the more useful data captured at this stage, the better the analysis and report can be, at the cost of the 'big data' conundrum. It is therefore necessary to reduce the data to a manageable size by filtering out and locating regions of interest. This is normally done post-data gathering during the off-line reporting stage and leads into level 2 of the data hierarchy in Figure 6. The interaction between the bottom two levels normally constitutes the most time-consuming of the entire hierarchy as scans are normally examined one at a time, cross-checking measurements and build a picture of the asset through a combination of word processing and spread sheet tools. Once the regions of interest have been identified, now brought to a more manageable amount of data in the region of megabytes (MB), more detailed analysis can begin. Statistics of these regions resides in the third tier which describes defects and flaws of most interest to help determine the condition of the asset. Now the dataset is typically numbering in hundreds of kilobytes (KB) to tens of MB. Statistical analysis in level 3 can then lead to the ultimate question, a binary answer at the peak of the data hierarchy, is the asset fit for service?

The key difficulty illustrated here is the ability to iteratively (and rationally) reduce the data down to a manageable form; between levels 1 and 2 is presumed to be the most time-consuming analysis because the sheer volume of data that must be examined. While this hierarchy is by no means an exhaustive breakdown, it does aim to illustrate the typical process from data capture through to the analysis and reporting which has multi-levels of analysis in order to distil the data to relevant answers.

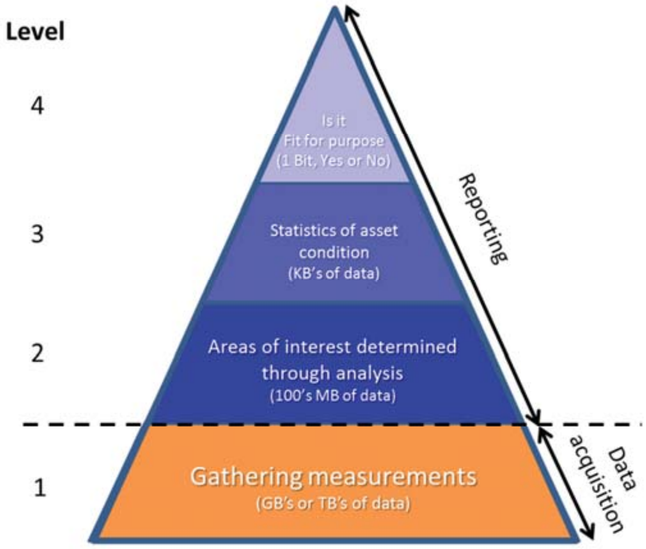


Figure 6: Basic hierarchy of data sizes and the route to the ultimate question, is the asset fit for purpose?

In the context of the AUT approach, and to expedite the move between levels 1 and 2 of the data hierarchy in Figure 6, Silverwing (UK) Ltd has developed a proprietary stitching, analysis and reporting software tool called CMAP. CMAP is able to automatically (or manually) arrange the scans to provide an overall map of the asset with tools to perform level 2 and level 3 analysis including further annotation, culminating in a customisable report. With typical desktop computing capability and advanced processing functions, the inspector is able to determine areas of interest quickly by simply scrolling through the overall view of the asset in real-time.

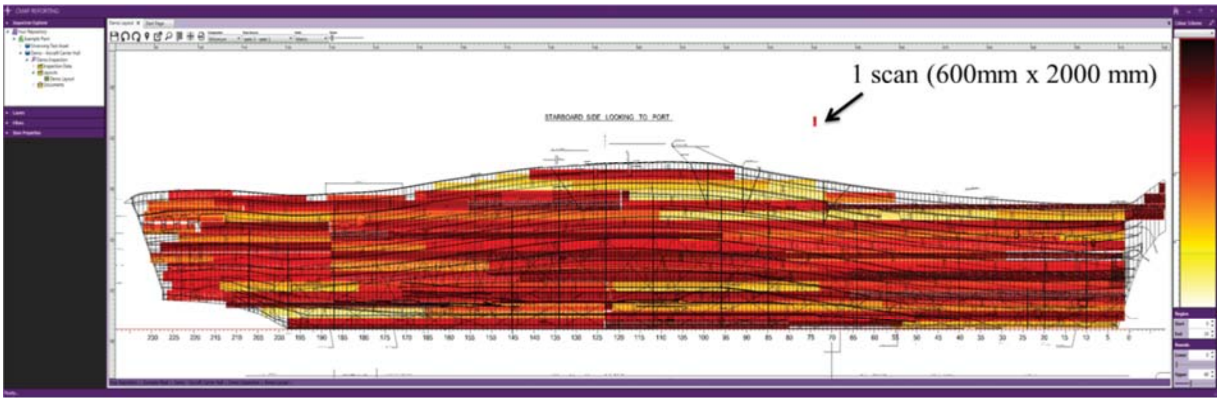


Figure 7: Side view of a ship hull of over 230 m in length tiled with over 6000 scans using the CMAP software. For demonstrate the scale of this dataset, a typical scan of 600 mm by 2000 mm is shown. Note that the data presented is for illustraion only and is not indicative of its condition.

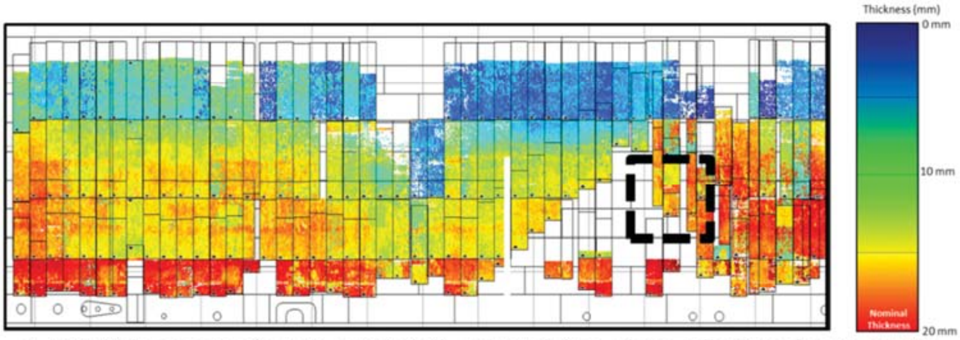
Figure 7 illustrates the ability of CMAP to handle vast quantities of data by tiling 6000 AUT scans, 600 mm by 2000 mm onto a CAD drawing of a 230 m long ship hull. The volume of data to create this map equates to around 3000 GB. Several technical challenges have been overcome to achieve the presentation of such a large dataset. The CMAP system first produces multiple levels of details (LOD) of each C-Scan, where each level corresponds to a different zoom level. The LOD approach adopted here is similar to that used to present detailed geographical maps at different levels of zoom, with higher detail at high zoom and lower detail when larger areas are shown. For each LOD, the data is downscaled using a minimum function (or maximum – depending on the type of measurement is of interest) applied over adjacent measurements to ensure that even a very low LOD (when zoomed out), the data presented on-screen shows the minimum (or maximum) measurements. This approach can sometimes reveal patterns over large areas that would otherwise be difficult or exceedingly time-consuming to achieve manually.

The LOD maps and any associated inspection data, such as the raw A-Scans, are compressed and stored in a bespoke file system, while associated inspection metadata such as the scan position, size and rotation is stored in a database. This allows data and associated scans to be queried rapidly to provide real-time interactivity.

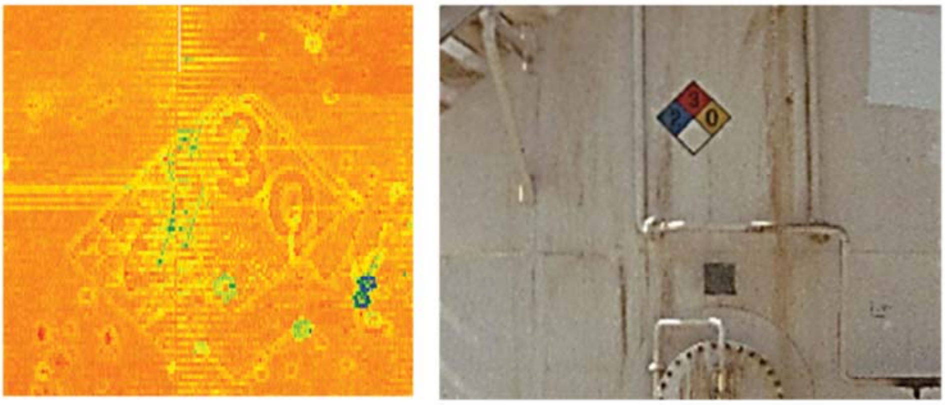
Figure 8 (a) shows low LOD's of a large set of data recorded from an inspection of a storage tank shell while a higher LOD of (a) is shown in (b). The colour of the scans in (a) represents the material thickness from thin to thick corresponding to colours blue, through to yellow and then red. As mentioned in section 2, a variety of gates can be added onto the UT, for example, by using four gates, the thickness (as shown in (a)), near-surface profile and amplitude variation of the echoes will result in three separate C-Scan maps. This would increase time necessary to investigate all three C-Scan maps if the data were arranged and analysed manually but this can be achieved automatically by simply choosing which C-Scan to present, without the need to re-organise the raw data. As such, further investigation of the tank shell AUT shown in

Figure 8 (a) revealed a clear pattern of the NFPA sticker on the tank wall, including the associated codes and is a consequence of attenuation on the back-wall echo. A corresponding image of the sticker is shown in Figure 8 (c)

Another concern during analysis is overlapping scans. Typically, adjacent AUT scans are overlapped by 10's of mm to minimise the risk of missing regions of a surface. This can however present a challenge during the analysis as measurements may be different between adjacent scans, over the same region. This can be perhaps due to varying reflection characteristics or positioning of measurements from coarse scans. Searching for the minimum measurement between overlapped areas of two or more scans can be a time-consuming process. The CMAP automates this process when scans are overlapped and presents this in a visual manner. When the layout is drawn the scan data is first rendered into a composite image that represents the visible area of the view on the display. The locations where scans overlap, rather than using a conventional overlapping approach (technically referred to as Z-order) where the topmost scan hides the one beneath, a minimum or maximum comparison is made and used to automatically determine which measurement is to be shown in the final output. The composite image is then processed further through a variety of filter stages to allow the data to be modified prior to display.



a) AUT thickness map of a storage tank shell, generated from a large collection of scans. Notice the stair shape on the right of the map, indicating an uninspected area with the AUT.



b) Stitched amplitude measurments from the Region highlighted in (a)

c) Corresponding sticker shown in amplitude map shown in (b)inspection

Figure 8: Example of a tank shell with suitably positioned C-Scans. The highlighted region is shown in higher detail to reveal a more detailed view of the shells condition, along with an outline of a sticker found with the RMS system. An image of the physical sticker is also shown.

This allows data to be modified without altering the original source data, offering security and traceability for future audits. Finally, the filtered data is passed through a colourise filter via a colour lookup table. This image is then drawn to the screen and can be overlaid with annotations, photographs, CAD and other metadata. With modern day computer and graphics acceleration hardware, the described processes can be run at a pace to allow real-time feedback to the user when zooming the view, altering filter parameters or modifying the colour palette to look for patterns in the data; an automated pattern extraction feature aims to be integrated into a future release of CMAP. The analysis tools available aims to reduce the quantity of data, in essence, navigating between levels 2 and 3 of the data hierarchy in Figure 6. Between levels 3 and 4 of the hierarchy, the statistics and areas of interest are examined further with the aim to summarise the condition of the asset. At this level calculations befitting to the application need to be performed, for example those described in EEMUA [1] or API [4] guidelines can be used to estimate the condition of components of a storage tank. At present, this would be conducted manually, but it is anticipated that CMAP will be able to perform such calculations automatically, directly from the recorded measurements.

Automating as much of the data hierarchy path as much possible is a key value of CMAP as it currently able to handle the vast amounts of data indicated in this paper. The overall aim is to reduce the burden to the user of manually sorting, stitching, comparing measurement data and producing the report. Importantly, using such automation, the many days of data collection and report generation can be greatly reduced into just a few hours. This lends more time for detailed analysis instead of the mundane tasks associated with data manipulation.

4. Conclusion

Efficiency of the inspection process is always improving, usually through faster scanning equipment. It then follows that faster scanning can result in more data and while it is generally accepted that more useful data can reveal further details about an assets integrity, more data can also lead to challenges downstream during the analysis and reporting stage. In this paper both sides of the argument have been addressed, the first being able to obtain more asset information through extra gates and the surface location of defect without impacting on efficiency or tailoring the time taken to inspect by adjusting scan resolutions. The second describes and attempts to create an awareness of the time consuming analysis and reporting stage that is sometimes overlooked. Various concepts in the form of a data volume hierarchy illustrate the need to reduce it to a manageable level to improve efficiency at this stage. The CMAP software tool created by Silverwing (UK) Ltd attempts to minimise the level of manual data handling by automating the data sorting and manipulation to give more time to concentrate on and perform suitable analysis. Future enhancements to CMAP aim to include manual components of the inspection process such as real-time API calculations to ascertain the asset condition in a consistent and efficient manner.

5. Acknowledgments

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