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# Effective Spatial Parameter Imaging Methodology for Assessing the Current Condition and Serviceability of Monolith Structures of St. Lawrence Seaway Locks

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**Abstract:** Built over 50 years ago, the concrete monoliths of Saint-Lambert, Côte Sainte-Catherine, Lower Beauharnois and Upper Beauharnois Locks of St. Lawrence Seaway are affected by Alkali-Aggregate Reaction (AAR). This reaction causes swelling of the concrete and leads to a progressive loss of lateral clearance in the locks. Critical decisions about the type, scope and time schedule of the required rehabilitation work have to be taken in order to remedy the loss of lateral clearance and insure the passage of large ships. This paper presents a validated methodology for tridimensional imaging of St. Lawrence Seaway Locks with emphasis on novel methods for Spatial Parameter Imaging-SPI$^{TM}$, data integration via multi-source SPI of adjacent monolithic areas, and how the whole process of accurate digitizing and analysis of the locks' monoliths can help in the decision making process for the rehabilitation work to be undertaken. Despite a constantly increased use of HD Laser Scanning (HDS) techniques over the last decade in various stages of an asset life cycle, the imaging of non-physical entities for an accurate physical characterization of the key structures still remains a challenge. Our studies proved the ability to achieve the mm accuracy in both data collection and data processing via a distinct adaptive method for referencing to local datum, and based on implementing consistent indexing and numerical analysis algorithms. All these studies have essentially advanced the existing state of knowledge in both SPI and its application scope for serviceability analysis of seaway locks.

## 1 Introduction

We are introducing hereinafter the concept of Spatial Parameter Imaging-SPI$^{TM}$, in order to define the ability to form visual representations of spatial parameters, i.e. non-physical entities, for the purpose of structural/physical characterization, health diagnosis and monitoring, by means of HD data collection, data mining, data processing, modeling/CAD, and (meta)data graphical management. SPI is quite dissimilar from direct imaging of physical objects, structures and sites, since it generates images through computer simulation of specific spatial parameters, which are not physically existing but are made to appear by specialized algorithms of 'parameter embodying'. SPI also requires much more complex and computationally demanding workflows. Figure 1 illustrates the dissimilarity between direct imaging and SPI performed on a typical lock of St. Lawrence Seaway. SPI is generally used as an essential step of the methodological workflows, which are designed for evaluating the structural health, consistency and serviceability of large structures, and for monitoring their continuous spatial modifications and progressively induced misalignment of the heavy equipment. SPI is successfully applied to solve complex engineering problems and definitely improve the performance in design, manufacturing, construction, operation, maintenance, and QC-QA-QI, in a multitude of industrial domains, such as Aerospace, Heavy

Truck and Automotive, Ship/Maritime Technologies, Turbomachinery, Construction, Architectural Design, Transportation, Roads, Bridges, Viaducts, and Navigation Waterways.

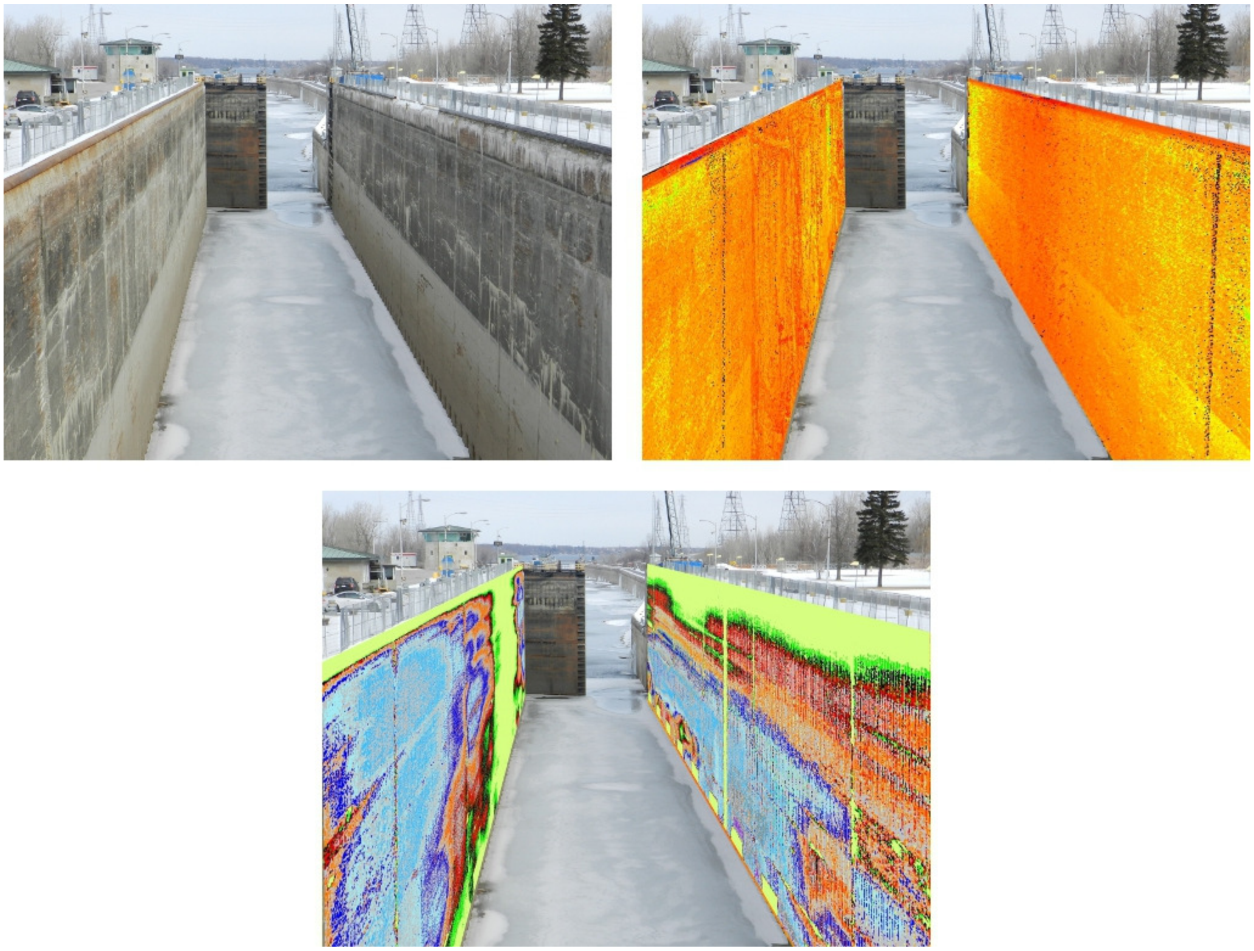


Figure 1: Direct Imaging via HDS (top images) vs. SPI$^{TM}$ (bottom) performed on Upper Beauharnois Lock

Each project/application type requires the creation of specific analysis tools with a high degree of customization. SPI application for seaway locks rehabilitation is an excellent example of how large monolith structures can be digitized, parameterized and analyzed in a short time period, in order to obtain highly useful and usable results that should support critical decisions of seaway locks management.

## 2 Background and Problem Statement

The St. Lawrence Seaway Management's mission is to manage a network of seaway locks in an efficient and safe manner, in respect of the environment. Built over 50 years ago, lock concrete monoliths are affected by AAR, which causes swelling of the concrete and leads to two main categories of problems: i) progressive loss of lateral clearance in the locks, and ii) progressive misalignment of heavy mechanical equipment, such as lock valves and gates. Swelling of the concrete can cause misalignment of some mechanical equipment elements embedded in the concrete, such as drive shafts, hinge assemblies, coin posts and rail beams. St. Lawrence Seaway management put in place remedial programs to correct the misalignment of the mechanical equipment and is monitoring closely the loss of lateral clearance of the lock walls due to AAR. The theoretical distance between the lock walls, as per construction drawings, is 24.384 m or 80 ft. Ships having a maximum beam width of 23.80 m or 78'1'' can transit the seaway. Any loss of lateral clearance may become problematic, particularly in winter conditions. Ice buildup on the lock walls, combined with the loss of lateral clearance can add to the difficulty in operating the locks during winter and may cause delays for the passage of large ships. Figure 2 shows a monolith cross section and illustrates the loss of lateral clearance between the lock walls.

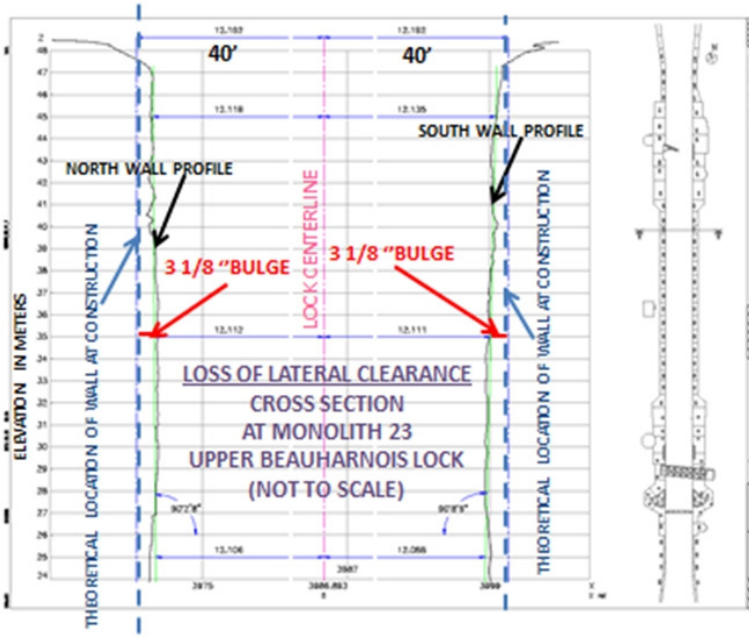


Figure 2: Cross section @ Monolith 23, Upper Beauharnois Lock

St. Lawrence Seaway specialists conduct regular surveys of the lock walls and have installed inverted pendulums, extensometers and crack measuring devices to gather field data and monitor the progress of AAR. Lately, the SPI methodology presented in this paper has been used to assess the serviceability condition of the lock monolith structures. The detailed data collected and processed via SPI are used to monitor the progress of AAR and to make critical decisions about the type, scope and time schedule of required rehabilitation work that have to be taken in order to remedy the loss of lateral clearance and insure the passage of large ships. Typical data collection setups are illustrated in Figure 3. The process of raw data acquisition can be conducted once a lock is de-watered for maintenance work during the winter (LHS image - Upper Beauharnois Lock) or during the navigation season (RHS image - Saint-Lambert Lock), when the data collection sequences are synchronized with the locking cycles due to large vessel passages.

Figure 3: Typical Data Collection Setups on St. Lawrence Seaway Locks

## 3 Methodological Workflow

The main steps, tasks and outcomes of a typical methodological workflow used to assess the monoliths of a seaway lock are presented in Figure 4 below.

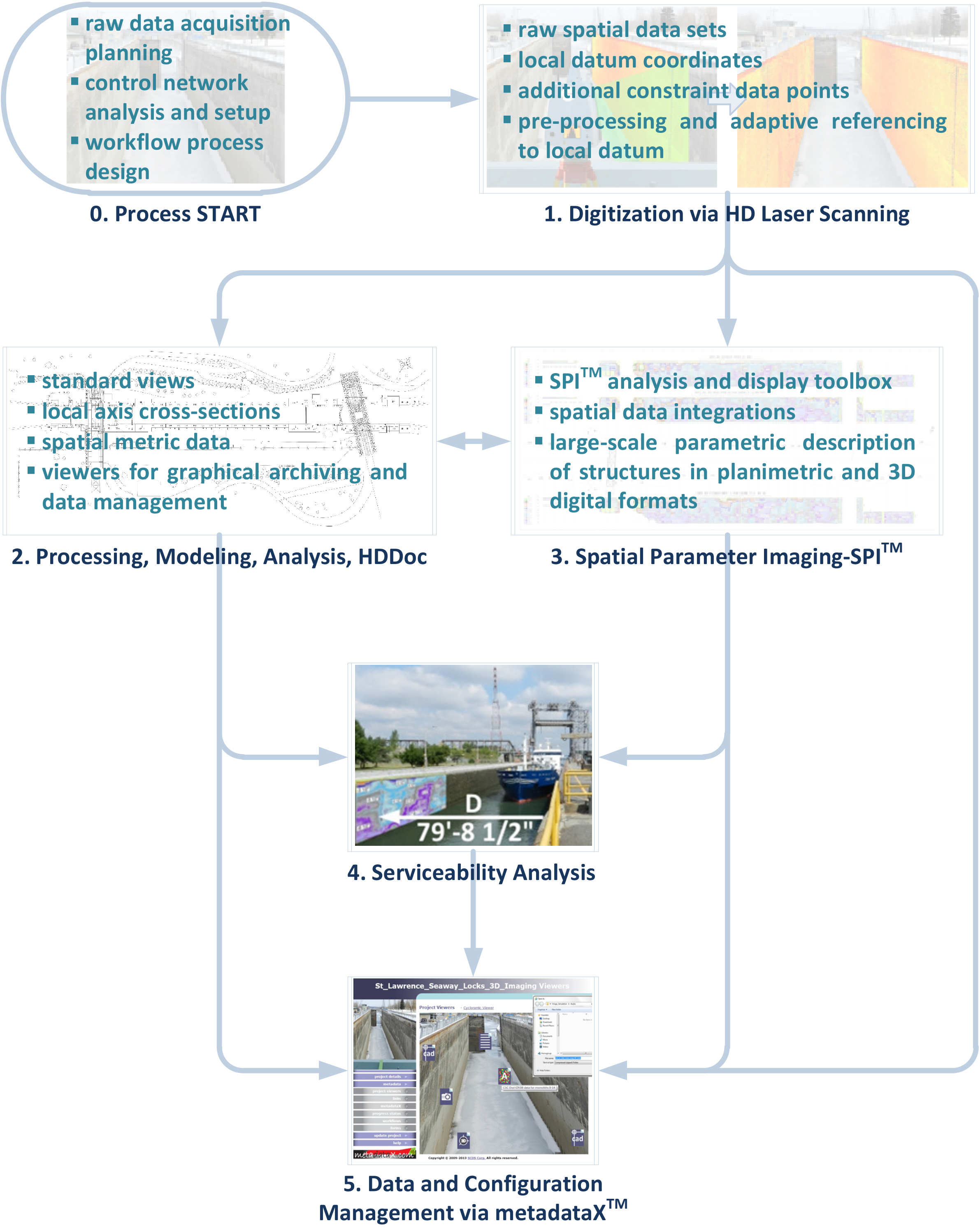


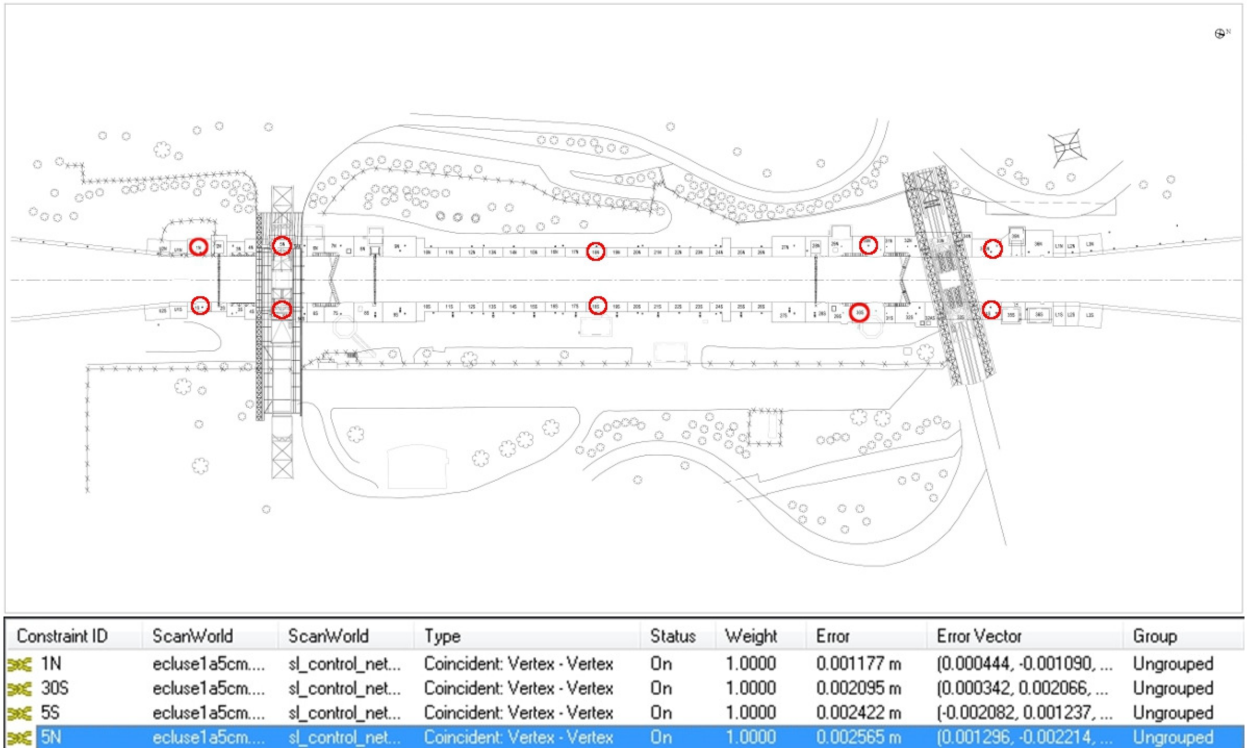
Figure 4: Typical Workflow for Assessing the Monolith Structures

### 3.1 Step 1: On-Site Data Collection through Digitization via HDS

The On-Site Data Collection process produces high quality raw data. The spatial data sets come in the form of a tridimensional Cloud of Points (CoP), which is a very dense collection of hundreds of millions of accurate xyz coordinates complemented with reflected pulse intensity and/or color information (code). A CoP becomes a HD digital description/representation of any solid object or site, e.g., seaway lock monoliths and associated structures/equipment. Although commonly regarded as trivial, HDS offers a spatial data collection platform generating input data opportunities for the development of other digital imaging techniques, analysis tools, and experts systems. Consequently, we will particularly emphasize the technological aspects beyond the traditional data collection, i.e. the adaptive methods for CoP referencing to local datum, multi-source data integration, and digital transformations of globally referenced CoP.

#### 3.1.1 Adaptive Method for CoP Referencing to Local Datum

As distances between opposite monoliths are computed along x-axis, which is quasi-perpendicular to most vertical monolith surfaces, the $err_X$ (x-component of referencing error vector) values are essential to distance computations. The adaptive method for CoP referencing took into consideration a control network that is configured in such a way to allow the minimization of $err_X$. This error reduction is corroborated with a highly accurate dual-axis/tilting compensation at any time during the data collection. Figure 5 shows an example of control network configuration, where control points that coincide with local datum points associated with certain monoliths lead to an optimized CoP referencing, where $err_X$ varies within [0.34, 2.08] mm, along the monolith walls, between upper and lower gates. The $err_X$ variance guarantees the computed distance errors within the same interval. However there are two other sources influencing the total errors, as follows: i) errors of local datum surveying, which are within the same range as CoP referencing, and ii) errors due to required or imposed digital transformations of CoP, which are dependent on the governing equation arguments and functional inputs, as demonstrated in § 3.1.3.



| Constraint ID | ScanWorld | ScanWorld | Type | Status | Weight | Error | Error Vector | Group |
|---|---|---|---|---|---|---|---|---|
| 1N | ecluse1a5cm.... | sl_control_net... | Coincident: Vertex - Vertex | On | 1.0000 | 0.001177 m | (0.000444, -0.001090, ... | Ungrouped |
| 30S | ecluse1a5cm.... | sl_control_net... | Coincident: Vertex - Vertex | On | 1.0000 | 0.002095 m | (0.000342, 0.002066, ... | Ungrouped |
| 5S | ecluse1a5cm.... | sl_control_net... | Coincident: Vertex - Vertex | On | 1.0000 | 0.002422 m | (-0.002082, 0.001237, ... | Ungrouped |
| 5N | ecluse1a5cm.... | sl_control_net... | Coincident: Vertex - Vertex | On | 1.0000 | 0.002565 m | (0.001296, -0.002214, ... | Ungrouped |

Figure 5: Optimized Referencing of CoP to Local Datum Between Upper and Lower Gates (1N to 30S) of Saint-Lambert Lock

### 3.1.2 Multi-Source Data Integration

Under the multi-source data integration scenario, CoP data are originated by distinct sources, e.g., HDS and side-imaging sonar, providing different data accuracies and qualities. The side-imaging sonar provides much lower accuracy than HDS, and is traditionally used to evaluate/quantify the required dredging of the seaway channel for sediment removal and for preserving the design grade of the channel bottom. Although CoP data format, aspect and patterns are apparently similar, significantly different accuracies generate parametric inconsistencies when the multi-source sets of data are integrated together, via either cross-sectional comparative analysis or SPI processing (discussed in § 3.3). Even though integrating HDS and sonar-based digitization processes has been considered potentially suitable, especially during the seaway operational periods, when the monoliths are partially submerged, the jointly referenced raw data corroborated with the SPI integration results (illustrated in Figure 9) proved that the combined HDS-sonar imaging is practically inappropriate for monolith parameterization, since the sonar imaging cannot meet the mm accuracy requirement, which is critical to SPI quality, performance and usability. HDS remains the best solution for achieving the required raw data and SPI accuracies.

### 3.1.3 Digital Transformations of Globally Referenced CoP's

The monoliths and their associated structures and equipment form an anisotropic system, which deform and become internally stressed due to prescribed loading conditions induced predominantly by thermal expansion. Thermal expansion (+ve or -ve) is assumed linear and determining linear displacements of local points. Any local point displacement (DISP) due to a thermal gradient is computed by interpolating the DISP underlying function over known test cases (control points) onto the CoP spatial domain.

The governing equation establishing the coordinate (COORD) transformations between two distinct stress conditions (C1, C2) can be formulated in terms of the DISP function (fDISP), which is extrapolated (extrap) on the variations (OFFSET) of control (CTRL) points over the COORD domain ([ ]), as follows:

[1] $\mathrm{COORD}_{C2}$ = $\mathrm{COORD}_{C1}$ + COORD_OFFSET =
= $\mathrm{COORD}_{C1}$ + interp1D(fDISP, COORD[ ], method, extrap) =
= $\mathrm{COORD}_{C1}$ + interp1D(COORD_CTRL, COORD_CTRL_OFFSET, $\mathrm{COORD}_{C1}$, method, extrap)

'interp1D' defines one-dimensional data interpolation method or table lookup for nonuniformly spaced and unordered data. As the governing equation is applicable to raw data sets, in order to reduce the computational effort in parametric estimates, yet conserving the accuracy, we adaptively applied the transformation equation to those pre-defined grids used for distance calculation too. The coordinate 'gridding' is realized via CoP indexing, which also facilitates the computational optimization through memory pre-allocation for vectors and matrices, optimized element access on large multidimensional arrays, code vectorization and accelerated computation methods. The CoP coordinate transformations between different stress conditions proved that $\mathrm{OFFSET}_Y$ and $\mathrm{OFFSET}_Z$ have negligible influence on opposite monolith distance charts and cannot determine relevant changes of dominant color areas on monolith (YZ) plane. Contrariwise, $\mathrm{OFFSET}_X$ is critical to parametric computations and could determine significant changes in distance mapping, as illustrated in § 3.3.

### 3.2 Step 2: Processing, Modeling, Analysis, HDDoc

This workflow step provides: i) metric data for current and any future planning/design of rehabilitation work, ii) accurate HD documentation including relevant information on both external and internal features, drawings, plans, planimetric maps and cross-sections, as illustrated in Figures 2 and 5, iii) inputs to numerical analyses and coordinate transformations (§ 3.1.3), iv) inputs to tridimensional SPI mapping (§ 3.3), v) inputs to serviceability analysis (§ 3.4), and, finally, vi) inputs for creating the viewers used for graphical archiving and data management (§ 3.5).

### 3.3 Step 3: Spatial Parameter Imaging-$\mathrm{SPI}^{TM}$

Despite an increased development of 3D imaging techniques for large industrial equipment and structures, the imaging of parameters that characterize and are critical to structural serviceability still remains an issue. This must be addressed specifically, as each category of application imposes its specific set of spatial parameters that must be quantified for accurate physical characterization of key structures, which are often severely affected by various environment factors determining parametric modifications. The methodological workflow for tridimensional imaging of large structures includes novel methods for SPI and specific data integrations, which are based on consistent numerical and theoretical fundaments, and digital simulations of real conditions. The SPI toolbox includes script-driven functions and routines for geometric primitive regression, CoP indexing, error compensation and accuracy improvement, monolith parameterization, and color mapping. The geometric regression is used for both extracting physical primitives from scattered data, e.g., vertices, lines and patches to be used as additional constraints, and for creating virtual primitives to be used as references in the parameter computation, e.g., lock C/P (central plane). The sequential execution of SPI functions gives a complete parametric description of the lock monoliths and provides valuable information for serviceability analysis and assessment studies, as shown in Figures 6 and 7.

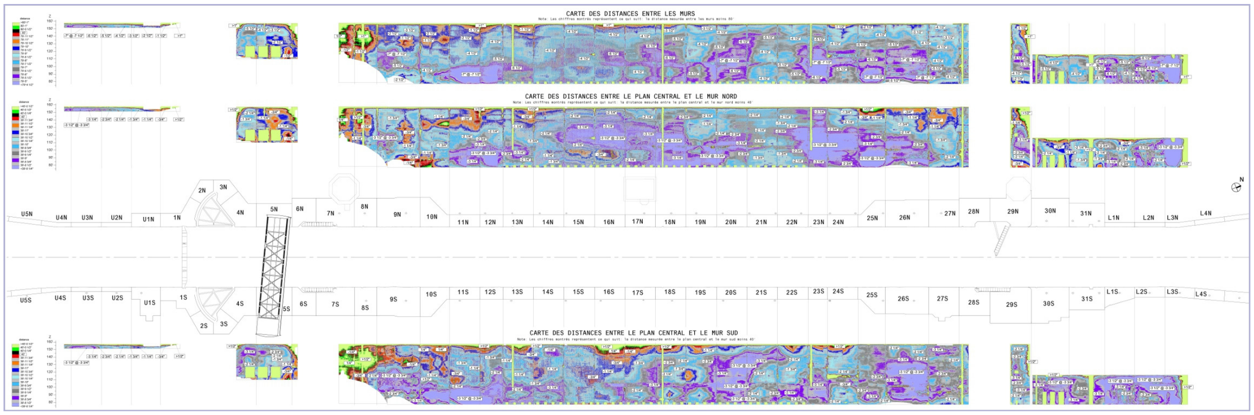


Figure 6: Full-Scale SPI$^{TM}$ of Upper Beauharnois Lock

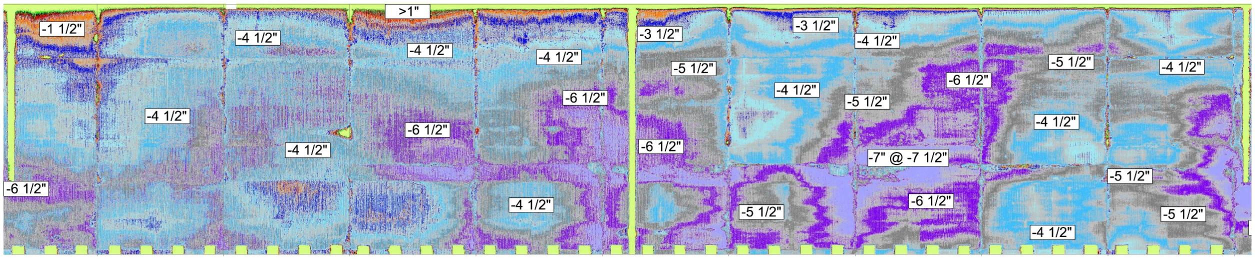


Figure 7: SPI$^{TM}$ Section Displaying Total Distances $\Delta$'s along Monoliths 13-22 of Upper Beauharnois Lock

The SPI results can also be presented in spatial format, within simplified 3D digital models of the monoliths, as illustrated in Figure 8. Half Distance (D/2, from C/P to opposite monoliths) charts are placed over monoliths, while the Total Distance (D) chart is placed onto C/P. The SPI charts are generated on distinct monolith sections (groups of adjacent monoliths), which are resized appropriately to maximize the image resolution, then captured as snapshots of small (individual monolith size or smaller) areas, and finally stitched together automatically, using a reliable tool for controlled creation and editing of snapshot collages. SPI process allows for creation of high definition, full-scale documentation (generically called HDDoc), as presented in Figure 6, with a characteristic size of 72,000 px (W) x 21,600 px (H), affording a CAD drawing of 120 in. x 36 in. @ 600 DPI.

Accuracy of computed C/P is critical to SPI consistency and correctness. Any individual source of data collection is treated separately. Linear regression is performed over the whole XY domain of the quasi-vertical CoP that is 'attached' to monoliths. When performing multi-source data integration, C/P is also used as benchmark for data compatibility and integration consistency. In other words, when attempting to integrate HDS with any differently sourced data, C/P's are computed independently for each data source and, if they are found dissimilar, the integration becomes inapplicable. The C/P Δ's and resulted outcome of multi-source SPI integration are shown in Figure 9.

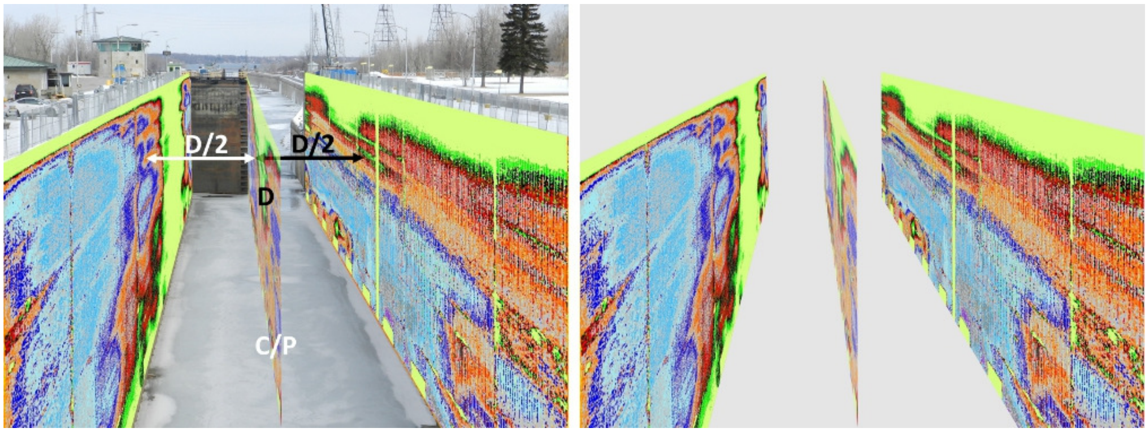


Figure 8: SPI$^{TM}$ Charts Fused into Lock's Simplified 3D Model

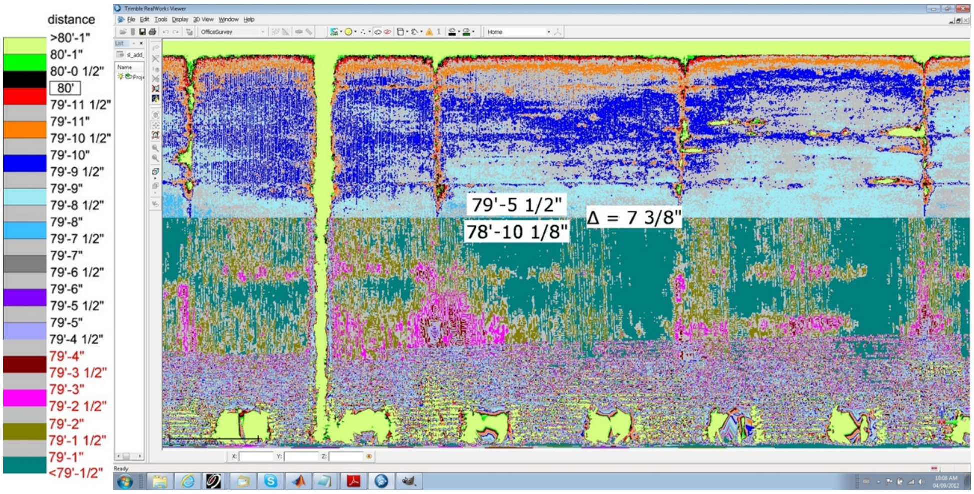
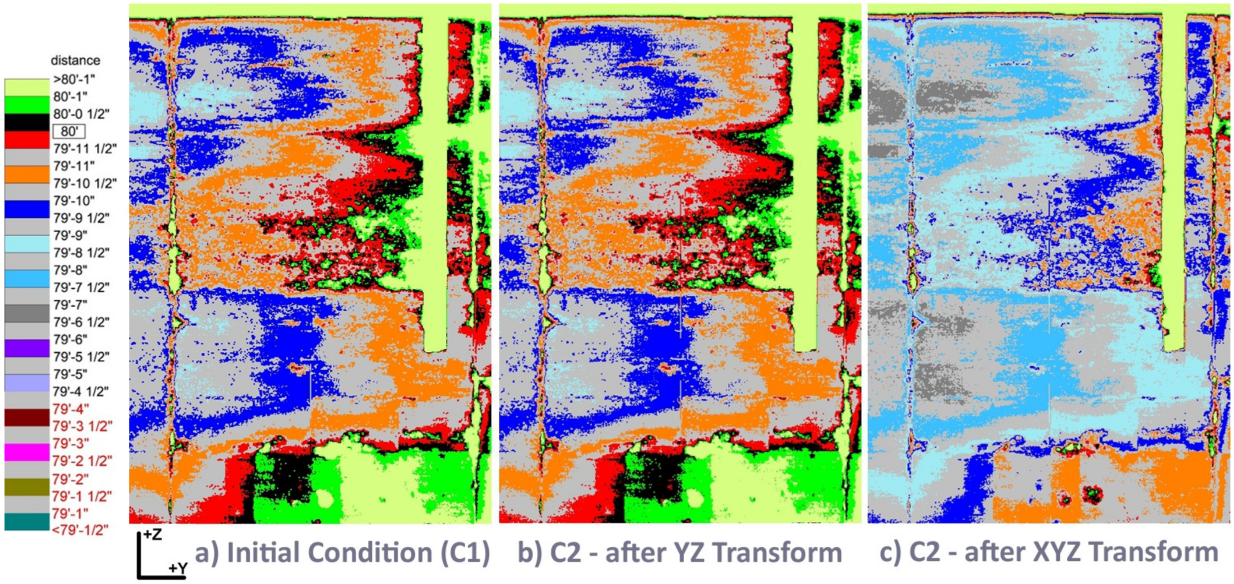


Figure 9: Inconsistencies and Distance Function Discontinuities of Multi-Source SPI$^{TM}$ Integration (C/P $\Delta_X$ between 22 mm and 130 mm, over 500 m along lock's longitudinal axis)

The SPI of CoP coordinate transformation is illustrated in Figure 10. As expected and stated previously in § 3.1.3, while observing a negligible influence of the monolith-planar (YZ) transformation (Figure 10b), we nevertheless noticed a significant contribution of $OFFSET_X$ (Figure 10c), which actually reveals the magnitude of the concrete swelling variation due to CoP spatial transformation.

### 3.4 Step 4: Serviceability Analysis

Serviceability analysis refers to evaluating the performance of monolith structures under normal service conditions and is concerned with the structure uses and/or occupancy. Monolith serviceability is generally evaluated by quantifying the concrete swelling, deflections, displacements, cracking, and concrete surface deterioration and damages due to freeze-thaw cycles, vessel impacts and other monolith contaminations. All these effects might interrupt the seaway lock use and operations but do not usually involve structural failure, i.e. the monoliths might still be structurally sound but unfit. By gathering comprehensive data and information, such as raw data CoP's, CAD drawings, plans, planimetric maps, cross-sections and SPI charts, and by implementing effective processing tools for accurate estimates of the parameters that define the serviceability limit, the presented methodology has proven to be highly useful to the structural serviceability characterization.



a) Initial Condition (C1) b) C2 - after YZ Transform c) C2 - after XYZ Transform

Figure 10: Digital Transformations of Globally Referenced CoP's; Simulation of Control DISP Influence on a Limited Scope of Côte Sainte-Catherine Lock

### 3.5 Step 5: Data Management and Configuration Management via metadataX$^{TM}$ Manager

Initially, the (meta)data manager has been developed to fill the gap in the intuitive graphical visualization and management of spatial data originated by 3D Imaging systems. Such systems generate large data sets that are typically assembled across multiple repositories, over a project life cycle. The challenge was to provide a consistent platform for data archiving, organizing, versioning, maintenance, and monitoring, to support the publishing and deployment of scientific/technical data, and to facilitate the data access by any level of engineering, management and technical support. The data manager is an open-source, universally adaptable (meta)data-based system for viewing, graphical management and configuration management of any project data type. There were two major technological benefits of using it within St. Lawrence Seaway projects, as follows: i) any sort of 3D imaging or SPI output can easily become a specialized viewer for graphical data management, actually a highly visual storage system driven by a simple and effective mechanism for graphical data archiving and versioning control, and ii) the comparative analyses performed for monitoring purposes, on any spatial data sets that are collected and/or processed at any time during a seaway lock life cycle, will be effectively facilitated.

## 4 Conclusions, Upcoming Developments and Recommendations

This paper presents a comprehensive methodology for assessing the current condition and serviceability of monolith structures of any seaway lock. The proposed methodology has been developed, consolidated and validated for an effective end-to-end processing, including data capture, spatial parameterization, and elaboration of HD documentation, which provided quite useful metric data for both current and future planning, design and construction activities, and supported the decision making process for the rehabilitation work to be undertaken.

The essential aspect of the validation process was related to the monolith parameterization accuracy, which was ensured by a highly accurate data acquisition via HDS, and by consistent geometric transformations, numerical regressions and numerical analysis methods used in parametric (distance) computation. The ability to achieve the mm accuracy in both data collection and data processing, via a distinct approach of referencing to local datum and based on a coherent CoP indexing, was fundamental to the correctness of the SPI process, which represents the core of the serviceability analysis.

The whole process of HD documentation creation, from non-intrusive and highly accurate HDS to highly accurate SPI charts production, provides the finest tridimensional (yzPar) information in planimetric (2D) format and makes SPI so meaningful for serviceability assessment. Furthermore, the recurrent application of this methodology to any monolith or series of monoliths, in conformity with a predefined monitoring schedule, will provide the parametric data sets for predictive modeling and simulation, which are advanced steps in serviceability analysis.

By providing detailed data and information for monitoring the AAR progress, and by aiding to make critical decisions about the type, scope and time schedule of the required remedying work, the methodology documented hereinbefore essentially advanced the existing state of knowledge in both SPI and its application scope for seaway locks rehabilitation.

The experts involved in the design, development and validation of SPI tools recommend the upgrading of assessment capacities by performing and integrating a complete Thermal/Subsurface Imaging of all monoliths along the lock. The thermal analysis images can be exported and referenced to seaway lock CAD models, potentially in any format, either monolith chart or tridimensional. The Infrared Thermal Scanning would just be a fast and effective way of investigation, which can be used to detect and map the moisture areas and energy losses, two major causes for structural decay. It can also complement the surveying tools, testing techniques and SPI methods that are currently used to monitor the AAR progress. Another suggestion concerns the SPI performing opportunity and application scope. Although this paper is principally dedicated to the analysis of AAR direct effects on monoliths, there are other motivations, either independent of or indirectly related to AAR, of applying SPI to evaluate the serviceability of seaway locks, as follows: i) the progressive misalignment of heavy mechanical equipment, such as lock valves and lock gates, ii) the misalignment due to concrete swelling affecting mechanical equipment elements embedded in the concrete, such as drive shafts, hinge assemblies, coin posts and rail beams, and iii) the deteriorations/damages of lock structures caused by icing & freeze-thaw cycles, and by vessel impacts. Many of these structures are more than 50 years old, have concrete bases partially underwater, have experienced varying degrees of damages and require more than regular repairs. This rationale makes the SPI application extremely useful to any seaway lock, regardless the AAR occurrence and impact. The large-scale SPI chart (Figure 6) can become a 'digital identification mark' of any seaway lock.

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