# NIST NeXT: a system for truly simultaneous neutron and X-ray tomography

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# ABSTRACT

Neutrons and X-rays provide excellent complementary, nondestructive probes to understand internal structure of systems across engineering and material science. With its sensitivity to hydrogen, neutrons excel at separating fluids, such as water or oil, from solid and gas phases in three-phase systems whereas X-rays excel at identifying the solid phase. To fully leverage the complementarity of the two methods, the National Institute of Standards and Technology (NIST) has developed the Neutron and X-ray Tomography (NeXT) system which orients a microfocus X-ray generator orthogonally to a reactor sourced thermal neutron beam. This orientation allows for truly simultaneous acquisition of both modalities so that the multi-modal data sets of samples that are evolving with time or undergoing stochastic processes can be directly correlated. The NeXT system has been available for external researchers since 2015 through the NIST Center for Neutron Research user facility program. Significant efforts have resulted in distributable software packages to facilitate image denoising, tomography reconstruction, volume registration, and bivariate histogram segmentation. This paper will give an overview of the NeXT system, explain the process for bivariate histogram segmentation, and provide several examples of use cases for the system.

Keywords: Multimodal imaging, Neutron, X-ray, Tomography, bivariate histogram, volume registration, volume fusion, batteries

# 1. INTRODUCTION

Neutron tomography and X-ray tomography are complementary, penetrating, non-destructive methods to probe the internal structure and composition of materials. The complementarity of the two modalities stems from how the two different particles interact with materials. Neutrons primarily interact with the atomic nucleus through the strong nuclear force while X-rays primarily interact with the electron shell. Correlative studies with neutrons and X-rays, where the two modalities are captured at different times and potentially different facilities, have been conducted across a large range of research areas such as fuel cells [1-2], batteries [3-4], concrete [5], [6], cultural heritage [7-8], building materials [9], and geosciences [10-11], among others.

To fully leverage the complementarity of neutrons and X-rays, in 2015 NIST developed the Neutron and X-ray Tomography (NeXT) system for truly simultaneous neutron and X-ray tomography. Two other systems of this type have been developed at the Institut Laue-Langevin in Grenoble, France [12-13] and the Paul Scherrer Institut in Villigen, Switzerland [14] but the NIST NeXT system remains the only system in the Western Hemisphere. The benefit of truly simultaneous neutron and X-ray tomography is the ability to study dynamic, stochastic, and slowly evolving processes.

NIST has developed analysis tools to support NeXT datasets which include programs for tomography reconstruction, rigid 3D volume registration, and bivariate histogram segmentation. An overview of the NeXT system and analysis software will be discussed here and several examples of how the system can be used will be given.

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# 2. SYSTEM DESCRIPTION

The NeXT system provides truly simultaneous neutron and X-ray tomography by orienting an X-ray tube perpendicular to a thermal neutron beam [15-16]. The system is located on the BT-2 beamline at the NIST Center for Neutron Research (NCNR). It was commissioned in June 2015 and has since seen heavy demand in the NCNR facility user program. An overview of the system is given in Figure 1 which shows the position of NeXT within the neutron imaging facility shielded hutch. Presently, X-rays are produced with an Oxford Instruments UltraBright 90 keV microfocus X-ray tube<sup>1</sup> and future plans include a higher energy and small focal spot X-ray source for users by 2022.

Detectors for both modalities consist of lens coupled cameras to scintillator screens. The scintillators used for both modalities are P43 (i.e. gadolinium oxysulfide doped with terbium,  $Gd_2O_2S$ :Tb, also known as GadOx) and are mounted to a mirror box that redirects the scintillation light 90° to the beam axis. Andor NEO scientific complementary metal oxide semiconductor (sCMOS) cameras are mounted to a linear stage and coupled to the mirror box with light-tight flexible bellows. Nikon Nikkor lenses are attached to the camera and set to the minimum focal distance. The linear stage is used to move the camera to focus the back of the scintillator screen.



Figure 1. Engineering CAD model representation of the NeXT system and where it sits within the shielded experimental hutch (left) and a zoom in of the NeXT system itself with important features labeled (right). The model people in the engineering representation are 183 cm (6 ft) tall for scale.

The NEO cameras have 6.5  $\mu$ m square pixels and when coupled to a 1:1 macro lens can obtain a neutron resolution of 20  $\mu$ m, limited by the light bloom from the 20  $\mu$ m GadOx screen used. To overcome this resolution limitation, an infinity corrected macroscope has been developed [17]. This detector uses two Nikon lenses to achieve optical magnification of the scintillation light and amplifies the low light levels produced by GadOx with an image intensifier. The light bloom can be reduced by switching to a 5  $\mu$ m thick GadOx scintillator from the typically used 20  $\mu$ m thick GadOx. Amplification of the scintillation light is required due to the reduction in detector efficiency and stopping power by switching to the thinner screen. With the combination of optical magnification of the scintillator, it is possible to achieve sub-10  $\mu$ m spatial resolution. It will be possible to achieve the sub-10  $\mu$ m neutron

<sup>&</sup>lt;sup>1</sup> Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

resolution with X-ray resolution of 1 µm to 3 µm by combining this neutron detector configuration with the planned X-ray tube upgrade with smaller spot size.

#### 3. VOLUME FUSION TOOLS

The unique utility of the NIST NeXT system is the opportunity for more facile volume segmentation through the use of the bivariate histogram of the neutron and X-ray attenuation coefficients. Following the tomographic cone beam reconstructions on the two modes, the volumes must be registered, which corrects for differences in voxel size, the approximately 90 degree offset of the two volumes in the yaw angle, and small differences in pitch, roll, and arbitrary translations in the three spatial directions. Because the two volumes have different sources of image contrast, the preferred metric for determining the best rigid body registration is found from maximizing the Mattes mutual information statistic [18] rather than finding the maximum of the cross-correlation. To accomplish this, the two volumes are loaded into the computer's random access memory (RAM) and then down-sampled. The down-sampling accomplishes two computational tasks, blurring the volumes which improves the registration through removal of noise and reducing the overall size in memory so that the registration algorithm does not require more RAM than is locally available. It is found that a downsampling size of 5 to 10 (volume reduction of  $5^3$  to  $10^3$ ) yields accurate registration with reasonable computation time (order of minutes). NIST has created a simple graphical user interface (GUI) in Matlab [19] to perform the volume registration process. To speed-up the automatic registration and to improve convergence, the user has the ability to manually register the two volumes. The GUI provides overlays of the two volumes displayed in three orthogonal views. The user is able to adjust values for 3 linear shifts, 3 rotation angles, and scaling. Once the volumes have been coarsely registered, the user initiates the automatic registration. Once the affine translation parameters have been determined, the full volume that is to be moved is reloaded into RAM, the transformation parameters are corrected for the down-sampling, and the affine transformation is applied. The registration process is shown in the Figure 2, where the initial, manual registered and Mattes mutual information rigid body registration are shown in the y-z plane of an alkaline battery.



Figure 2. Successive steps in the volume registration process, starting with the initial volumes (a), manually registered volumes (b), and the automatically registered volumes (c).

Prior to segmentation, it is typically necessary to prepare the volumes with various image filters to improve results. NIST offers tools to optimize basic image filters which include 3D median, unsharp mask, and non-local means filters. Additional filters, such as anisotropic diffusion, total variation, or machine learning based filters, could be used instead. The noise reduction and smoothing offered by this filtering tool can also be applied before registration to improve the

quality of the registration, especially for high spatial resolution scans that can suffer from higher shot noise. The registration program allows the transformation determined with the smoothed dataset to be applied to the unfiltered dataset if desired.



Figure 3. Comparisons of as reconstructed slices (neutron (a), X-ray (c)) and corresponding filtered slices (neutron (b), X-ray (d)) using the presegmentation filtering tool. Filtering tool produces smoother images which produce more accurate automated segmentations. Neutron filter settings: 3D spatial median filter -5 pixel by 5 pixel by 5 pixel, unsharp mask - radius 3 pixel, weight 0.8, threshold 0, non-local means filter -6 pixel by 5 pixel by 5 pixel, unsharp mask - radius 3 pixel, weight 0.8, threshold 0, non-local means filter -6 pixel by 5 pixel by 5 pixel, unsharp mask - radius 3 pixel, weight 0.8, threshold 0, non-local means filter -6 gree of smoothing 0.25.

Using the registered and optionally filtered volumes, one can calculate the bivariate histogram to perform material phase segmentation. Currently, NIST has developed a region of interest (ROI) based bivariate histogram segmentation, wherein a user can draw arbitrary polygons over portions of the bivariate histogram. The user can assign a label and a color to these voxels which are then removed from the displayed bivariate histogram. Additionally, the user can view the segmentation process on an arbitrary medial, axial, or sagittal plane. In order to speed-up the display update, it is preferred to perform the interactive bivariate histogram segmentation and component update display on down-sampled volumes, and the user

can choose the sampling rate, again a down-sampling of 5 to 10 provides sufficient resolution and speeds computation and update times. ROIs can be merged, edited, and deleted. Any portion of the bivariate histogram that is not tiled by an ROI is considered its own material phase, labeled as "not identified". Upon completion of identifying all material phases, the segmentation proceeds using the full resolution volumes. Binary masks are written to disk, as well, slices are saved using the color chosen for each phase. The histogram with final ROI polygons and a legend identifying the color with the user-defined phase label is produced, as shown in Figure 4.



Figure 4. The bivariate histogram (left) of the alkaline battery. Yellow, green, and magenta polygons on histogram are the corresponding regions of interest for the colorized segmented slice shown on the right. Black polygons correspond to regions of interest not shown in this specific slice of the battery. Color legend shown in the top right.

# 4. EXAMPLE CASES

#### 4.1 Alkaline AAA Battery

Alkaline batteries are a mature technology that is ubiquitous in everyday life, however these batteries can still benefit from improvements to capacity and shelf life. NeXT can be used to probe the chemical reactions within the battery and potential physical damage during discharge. As shown in Table 1, neutrons can easily detect water, an important reaction component, and the polymer separator (assumed to be polyvinyl alcohol) while X-rays can detect the change in the anode active material from zinc to zinc oxide and physical damage, such as cracking, in the cathode.

Figure 5 shows the contrast differences between neutrons and X-rays for alkaline batteries. The polymer separator layer and anode electrolyte gel are clearly visible in the neutron slices (Figure 5a and 5c) while being difficult to discern in the corresponding X-ray slices. The X-rays perform better at identifying the anode current collector spike, i.e. the bright circle in the center of the battery in Figure 5b, and the anode active material. The datasets shown in Figure 5 were acquired at 9  $\mu$ m pixel pitch and required three separate scans to acquire the entire length of the battery. Each section of the battery was reconstructed independently and the three volumes for each modality were stitched together into single volumes using Dragonfly [20]. After stitching, the (1400 x 1200 x 5000) pixel neutron and X-ray volumes were registered, filtered, and segmented with the NIST tools described above. The tools are capable of handling large volumes if enough RAM is available on the analysis machine. This work was performed on a machine with 128 GB of RAM. The results of the segmentation are shown in Figure 5e with the colorized slice that corresponds to Figures 5c and 5d. After the segmentation was completed further work was done to isolate various components that segmented together, such as the stainless steel shell and the zinc anode material, from each other. This work was completed with a combination of functions in ImageJ Fiji [21] and Dragonfly. The final segmentation is given in a partial cutaway view of the 3D visualization in Dragonfly in Figure 5f.

	1.8 Å neutron [cm <sup>-1</sup> ]	45 keV X-ray [cm <sup>-1</sup> ]	Density [g cm <sup>-3</sup> ]
MnO <sub>2</sub> (charged)	0.834	7.691	5.03
Mn <sub>2</sub> O <sub>3</sub> (discharged)	0.748	7.475	4.50
Zinc (charged)	0.345	27.660	7.14
ZnO (discharged)	0.393	17.704	5.61
stainless steel	1.205	20.323	7.87
potassium hydroxide	2.043	1.806	2.10
polyvinyl alcohol	5.609	0.264	1.19
H <sub>2</sub> O	5.647	0.243	1.00

Table 1. Calculated neutron and X-ray attenuation coefficients and density for alkaline battery materials. Attenuation coefficients calculated with [22-23].



Figure 5. Axial neutron slice through the AAA alkaline battery (a), corresponding axial X-ray slice through the battery (b), vertical neutron slice through battery (c), corresponding vertical X-ray slice through battery (d), the colorized vertical slice produced in the bivariate histogram segmentation tool (e), and 3D visualization of segmentation produced in Dragonfly [20] (f). Legend for (f): magenta – stainless steel, red – manganese cathode, yellow – separator, green – electrolyte, blue – zinc anode, cyan – anode current collector, grey – gasket.

# 4.2 Lithium Ion 10180 Battery

Lithium ion batteries are critical to current tech evolution in devices such as electric cars, cell phones, and other portable electronics. It is critical to understand the degradation modes and capacity fade with cycling to improve performance and lengthen useable life. A limitation to the adaption of lithium ion battery electric vehicles is the time required to recharge the batteries. Extreme fast charging, achieving 100 % charge in 6 min to 10 min, can produce recharge times comparable with the time it takes to refill a gasoline powered car. This extreme fast charging degrades the battery and causes a reduction in capacity over time and number of cycles by irreversibly plating lithium in the battery. Neutrons have good sensitivity to natural lithium due to the significantly high absorption cross-section of  $^{6}$ Li, shown in Table 2, giving neutrons the ability to track lithium transport and plating inside commercial batteries. It can be difficult to separate natural lithium for polymer materials used for the separator. By increasing the fraction of  $^{6}$ Li in the lithium used for the battery, it is possible to increase the attenuation of the material or it is possible to deuterate or fluorinate the polymers to make them more transparent to neutrons.

Figure 6 shows the contrast differences between neutrons and X-rays along with the segmentation results using the NIST segmentation tool. The battery shown is a Li-NiMnCoO 10180 jelly roll battery. The 10180 size was chosen as it would fit in the entire field-of-view for the 9 µm pixel pitch detector configuration, thus avoiding the need for multiple scans as seen with the AAA battery example. With the recent availability of new cameras with larger imaging arrays, it will be possible to achieve higher resolution and/or scan larger batteries, such as the industry standard 18650. With charge cycling it would be possible to track the lithium transport between electrodes with the boundaries identified with the X-ray volume.

	1.8 Å neutron	45 keV X-ray	Density
	[cm <sup>-1</sup> ]	[cm <sup>-1</sup> ]	[g cm <sup>-3</sup> ]
NiMnCoO	0.608	6.955	2.31
copper	1.003	31.342	8.96
aluminum	0.104	1.206	2.70
graphite	0.599	0.421	2.15
Li (natural)	3.333	0.081	0.53
<sup>6</sup> Li (enriched)	50.362	0.081	0.53
Polyethylene	6.579	0.195	0.90
stainless steel	1.205	20.323	7.87

Table 2. Calculated neutron and X-ray attenuation coefficients and density for lithium-ion battery materials. Attenuation coefficients calculated with [22-23].



Figure 6. Vertical neutron slice through lithium ion battery (a), corresponding X-ray slice (b), corresponding colorized image from the bivariate histogram segmentation tool (c), and 3D visualization of the segmentation of the battery produced in Dragonfly. Legend for 3D visualization: orange – electrolyte, graphite and separator layers, magenta – copper current collector and NiMnCoO electrode, grey – stainless steel case, red – gasket.

#### 4.3 Material Evolution in Concrete

Understanding of the degradation modes concrete goes through and how to mitigate these processes is critical to improving and extending the operational lifetime of critical infrastructure such as highways, bridges, dams, and power plants [24-25]. Failure of modern concrete can occur from freeze-thaw cycles in colder climates, alkali-silica reaction (ASR) [26], delayed ettringite formation (DEF) [27], and corrosion of the steel reinforcements. NeXT offers a volumetric nondestructive analysis that can track the evolution of damage in concrete. Figure 7a and 7b give a side-by-side comparison of what each modality can see in concrete. This particular specimen had iodine added to the water when mixed to provide enhanced contrast between the cement paste and the aggregates, another contrast enhancing option is barite [28]. As can be seen in Table 3, the X-ray attenuation coefficients for cement paste and sand is very small necessitating the use of a contrast enhancer.

Tracking of damage is possible as NeXT provides truly simultaneous tomography so that the data from the two modalities can be exactly correlated in time. To capture the formation of damage, concrete specimens can be imaged in a time sequence with each scan separated by weeks or months. Neutrons have good contrast for the damaging phases, such as water, ASR gel, and ettringite, while X-rays provide detail on fracturing that can be difficult to see with neutrons. Correlating the fractures with the potentially highly mobile degradation phases, the extent and evolution of the damage can be tracked. Combining the two modalities provides greater constituent identification within the specimen as shown in the segmented image and 3D image in Figure 7c and 7d, respectively. The concrete sample in Figure 7 was poured and cured in a 25 mm by 25 mm by 150 mm prism and core drilled to remove the sample. A 7 mm core drill was used. The scan was obtained with a 9 µm pixel pitch and took 12 hours to complete.

	1.8 Å neutron [cm <sup>-1</sup> ]	45 keV X-ray [cm <sup>-1</sup> ]	Density [g cm <sup>-3</sup> ]
Cement paste	1.890	1.087	1.79
Sand (SiO <sub>2</sub> )	0.287	0.997	2.65
Limestone	0.280	1.447	2.16
ettringite	4.759	0.895	1.80
ASR gel	1.621	0.374	1.18
H <sub>2</sub> O	5.647	0.243	1.00
Ca(OH) <sub>2</sub>	3.169	1.839	2.21

Table 3. Calculated neutron and X-ray attenuation coefficients and density for concrete materials. Attenuation coefficients calculated with [22-23].



Figure 7. Concrete as viewed with neutrons (a), and X-rays (b). Segmentation results obtained with the NIST segmentation tool and a 3D partial cutaway visualization of the segmentation in Dragonfly. Color legend: magenta – aggregates and sand, yellow – cement paste, gray – voids.

# 5. CONCLUSIONS

The NIST NeXT system provides truly simultaneous neutron and X-ray tomography by orienting an X-ray source perpendicular to a neutron beam. The complementarity of the two penetrating probes can be applied to a vast range of research topics in engineering and material science, among others. By capturing both modalities simultaneously, it is possible to directly correlate the two complementary modes when the sample is undergoing a stochastic process or slowly evolving in time. NIST has developed several tools to fully leverage the capability of the NeXT system. A rigid volume registration program corrects for the 90° offset of the beams and any other arbitrary translation or rotation. Denoising and smoothing is performed to improve the quality of the segmentations and registrations in the case of noisier data. Finally, the bivariate histogram segmentation program provides a straightforward method for segmentation of the multimodal data through the selection of regions of interest on the 2D histogram. The power of these tools is shown with three example cases.

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#### REFERENCES

- [1] I. Manke *et al.*, "Investigation of water evolution and transport in fuel cells with high resolution synchrotron x-ray radiography," *Appl. Phys. Lett.*, vol. 90, no. 17, p. 174105, Apr. 2007, doi: 10.1063/1.2731440.
- [2] X. Peng *et al.*, "Using operando techniques to understand and design high performance and stable alkaline membrane fuel cells," *Nat. Commun.*, vol. 11, no. 1, pp. 1–10, Dec. 2020, doi: 10.1038/s41467-020-17370-7.
- [3] R. F. Ziesche *et al.*, "4D imaging of lithium-batteries using correlative neutron and X-ray tomography with a virtual unrolling technique," *Nat. Commun.*, vol. 11, no. 1, pp. 1–11, Dec. 2020, doi: 10.1038/s41467-019-13943-3.
- [4] I. Manke *et al.*, "In situ investigation of the discharge of alkaline Zn-Mn O2 batteries with synchrotron x-ray and neutron tomographies," *Appl. Phys. Lett.*, vol. 90, no. 21, p. 214102, May 2007, doi: 10.1063/1.2742283.
- [5] D. P. Bentz *et al.*, "Influence of substrate moisture state and roughness on interface microstructure and bond strength: Slant shear vs. pull-off testing," *Cem. Concr. Compos.*, vol. 87, 2018, doi: 10.1016/j.cemconcomp.2017.12.005.
- [6] E. Roubin, E. Andò, and S. Roux, "The colours of concrete as seen by X-rays and neutrons," *Cem. Concr. Compos.*, vol. 104, p. 103336, Nov. 2019, doi: 10.1016/j.cemconcomp.2019.103336.
- [7] R. Livingston, A. O'Connor, J. LaManna, H. Chen-Mayer, and D. Turkoglu, "Investigation of a simulated Chinese jade and bronze dagger-axe by neutron radiography and prompt gamma activation analysis," J. Archaeol. Sci. Reports, vol. 21, 2018, doi: 10.1016/j.jasrep.2018.06.011.
- [8] R. Triolo et al., "Combined Application of X-Ray and Neutron Imaging Techniques to Wood Materials," Conserv. Sci. Cult. Herit., vol. 10, p. 16, 2010, doi: 10.6092/issn.1973-9494/2322.
- [9] J. Dewanckele *et al.*, "Neutron radiography and X-ray computed tomography for quantifying weathering and water uptake processes inside porous limestone used as building material," *Mater. Charact.*, vol. 88, pp. 86–99, 2014, doi: http://dx.doi.org/10.1016/j.matchar.2013.12.007.
- [10] E. Perfect *et al.*, "Neutron imaging of hydrogen-rich fluids in geomaterials and engineered porous media: A review," *Earth-Science Rev.*, vol. 129, 2014, doi: 10.1016/j.earscirev.2013.11.012.
- [11] M. Zambrano, F. Hameed, K. Anders, L. Mancini, and E. Tondi, "Implementation of Dynamic Neutron Radiography and Integrated X-Ray and Neutron Tomography in Porous Carbonate Reservoir Rocks," *Front. Earth Sci.*, vol. 7, p. 329, Dec. 2019, doi: 10.3389/feart.2019.00329.
- [12] A. Tengattini, D. Atkins, B. Giroud, E. Andò, J. Beaucour, and G. Viggiani, "NeXT-Grenoble, a novel facility for Neutron and X-ray Tomography in Grenoble," in *Proceedings of the 3rd International Conference on Tomography of Materials and Structures, Lund, Sweden*, 2017, pp. 26–30.
- [13] A. Tengattini et al., "NeXT-Grenoble, the Neutron and X-ray tomograph in Grenoble," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 968, p. 163939, Jul. 2020, doi: 10.1016/J.NIMA.2020.163939.
- [14] A. P. Kaestner *et al.*, "Bimodal Imaging at ICON Using Neutrons and X-rays," in *Physics Procedia*, Jan. 2017, vol. 88, pp. 314–321, doi: 10.1016/j.phpro.2017.06.043.
- [15] J. M. Lamanna, D. S. Hussey, E. Baltic, and D. L. Jacobson, "Neutron and X-ray Tomography (NeXT) system for simultaneous, dual modality tomography," *Rev. Sci. Instrum.*, vol. 88, no. 11, 2017, doi: 10.1063/1.4989642.
- [16] J. M. LaManna, D. S. Hussey, E. Baltic, and D. L. Jacobson, "Improving material identification by combining xray and neutron tomography," in *Proceedings of SPIE - The International Society for Optical Engineering*, 2017, vol. 10391, doi: 10.1117/12.2274443.
- [17] D. S. Hussey, J. M. LaManna, E. Baltic, and D. L. Jacobson, "Neutron imaging detector with 2 μm spatial resolution based on event reconstruction of neutron capture in gadolinium oxysulfide scintillators," *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 866, 2017, doi: 10.1016/j.nima.2017.05.035.
- [18] D. Mattes, D. R. Haynor, H. Vesselle, T. K. Lewellyn, and W. Eubank, "Non-rigid multimodality image registration," in *Medical Imaging 2001: Image Processing*, 2001, vol. 4322, no. July 2001, pp. 1609–1620, doi:

10.1117/12.431046.

- [19] The Mathworks Inc, "MATLAB R2019b." Natick, Massachusetts.
- [20] Objects Research Systems Inc, "Dragonfly." Montreal, Canada, [Online]. Available: http://www.theobjects.com/dragonfly.
- [21] J. Schindelin *et al.*, "Fiji: An open-source platform for biological-image analysis," *Nature Methods*, vol. 9, no. 7. Nature Publishing Group, pp. 676–682, Jul. 28, 2012, doi: 10.1038/nmeth.2019.
- [22] M. J. Berger *et al.*, "NIST Standard Reference Database 8 (XGAM)." NIST, PML, Radiation Physics Division, 2010, doi: https://dx.doi.org/10.18434/T48G6X.
- [23] "Neutron Activation and Scattering Calculator." https://www.ncnr.nist.gov/resources/activation/ (accessed Aug. 31, 2020).
- [24] 2013 Report Card for America's Infrastructure. American Society of Civil Engineers, 2013.
- [25] J. J. Biernacki *et al.*, "Cements in the 21st century: Challenges, perspectives, and opportunities," *J. Am. Ceram. Soc.*, vol. 100, no. 7, pp. 2746–2773, Jul. 2017, doi: 10.1111/JACE.14948@10.1111/(ISSN)1551-2916.MSAT18.
- [26] A. Mohammadi, E. Ghiasvand, and M. Nili, "Relation between mechanical properties of concrete and alkalisilica reaction (ASR); a review," *Construction and Building Materials*, vol. 258. Elsevier Ltd, p. 119567, Oct. 20, 2020, doi: 10.1016/j.conbuildmat.2020.119567.
- [27] A. Pavoine, X. Brunetaud, and L. Divet, "The impact of cement parameters on Delayed Ettringite Formation," *Cem. Concr. Compos.*, vol. 34, no. 4, pp. 521–528, Apr. 2012, doi: 10.1016/j.cemconcomp.2011.11.012.
- [28] P. Carrara *et al.*, "Improved mesoscale segmentation of concrete from 3D X-ray images using contrast enhancers," *Cem. Concr. Compos.*, vol. 93, pp. 30–42, 2018, doi: https://doi.org/10.1016/j.cemconcomp.2018.06.014.