WHITE PAPER

Non-topographic defects on wet surfaces: an introduction to hyperspectral imaging

SurfConInspect White Paper
Series 2/10

About Us

WHO WE ARE

SurfConInspect (SCI) is a European project funded by the Research Fund for Coal and Steel (RFCS). Our consortium brings together leading steel producers, research institutes, technology developers and innovation experts.

The partners combine industrial expertise, academic knowledge and advanced digital solutions to transform the way steel quality is controlled.

OUR MISSION

The steel industry faces increasing pressure to become more sustainable, efficient and competitive—key goals of the European Green Deal.
Our mission is to enable zero-defect manufacturing in flat steel production by:

- Detecting surface defects earlier and more accurately.
- Reducing waste and improving resource efficiency.
- Supporting operators with advanced visualization tools.
- Providing real-time control actions directly in production lines.

MAIN ACTIVITIES

- Industrial trials in tin-plate and automotive steel production.
- Development of AI-based inspection methods.
- Application of AR for real-time operator support.
- Creation of open datasets to enhance research and industrial collaboration.
- Dissemination of results to industry, research and society through events, publications and digital platforms.

EXPECTED RESULTS

- Zero-defect production through optimized inspection and control.
- Reduced waste and energy consumption, contributing to the
  European Green Deal.
- Higher competitiveness for European steel producers.
- Transferable technologies with potential applications beyond the steel sector.
- Improved working conditions, with operators supported by innovative visualization and decision-making tools.

Executive Summary

Surface quality cannot be fully described through geometry alone. While depth-aware inspection systems have significantly improved the detection and quantification of topographic defects—such as abrasions, dents, and shells—industrial evidence shows that a substantial share of quality-relevant anomalies in any process stage are non-topographic.
These include residual oxides from incomplete scale removal, chemically induced stains, lubricant contamination, and thin films of water or emulsions that alter surface behavior without producing measurable height variations. Especially for process steps after cold-rolling the majority of surface defects appear flat.

Thus, this distinction becomes particularly critical in wet sections of the coating lines, where the presence of liquids fundamentally changes the optical interaction between light and the steel surface. Even micrometric liquid layers can modify reflectance through combined effects of reflection, refraction, and absorption, leading to visual responses that are poorly correlated with the actual material condition. As a result, conventional inspection systems—whether based on 2D intensity imaging or enhanced with 3D topography—may generate ambiguous or misleading signals. In practical terms, this translates into classification uncertainty, where harmless surface conditions can appear critical, and conversely, chemically relevant defects may remain undetected.

The limitation is therefore not a matter of resolution or acquisition speed, but of the underlying measurement dimension. Geometry-based systems capture "how the surface is shaped," but remain largely insensitive to "what the surface is made of" or "how it has been chemically altered." This gap is particularly evident in high-speed pickling operations, where strip speeds, environmental instability, and continuous wetting further reduce the reliability of purely spatial analysis.

Within this context, hyperspectral imaging emerges as a complementary inspection paradigm. Rather than relying on broadband intensity information, hyperspectral systems capture the reflectance of the surface across multiple narrow wavelength bands, enabling the detection of material-dependent spectral variations. Each surface condition—whether clean steel, oxidized material, oil-contaminated areas, or water-covered regions—exhibits a distinct spectral response, often referred to as a spectral fingerprint.

The industrial relevance of this approach lies in its ability to introduce material sensitivity into the inspection process. Instead of inferring defect severity indirectly from visual appearance, the system can directly assess surface composition and condition, even in the presence of optical disturbances caused by liquids.

The objective of this white paper is not to position hyperspectral imaging as a replacement for 3D inspection, but to frame it as a recommended extension. Within the SurfConInspect perspective, the evolution of surface inspection is driven by the integration of complementary data dimensions: geometry for morphological characterization and spectral response for material discrimination. This combined approach enables a more robust, reliable, and physically grounded assessment of surface quality under real industrial conditions.

Beyond geometry: the nature of non-topographic defects

In industrial surface inspection, the distinction between topographic and non-topographic defects is not merely classificatory—it directly defines the observable domain of the inspection technology. Topographic defects are associated with measurable variations in surface height, such as scratches, dents, or indentations. Their severity can be quantified through geometric parameters like depth, width, and spatial distribution, making them well suited for depth-aware inspection systems.

Non-topographic defects, by contrast, are governed by variations in material composition, chemical state, or surface condition, often without introducing any detectable change in geometry. After cold rolling, this class of defects is particularly relevant and often dominant from a quality perspective. Typical examples include residual oxides resulting from incomplete scale removal, chemical stains generated by reaction by-products, oil or lubricant residues originating from upstream processes, and thin films of water or emulsions that persist across wet sections of the line. Surface contamination layers—sometimes only a few micrometres thick—further contribute to this category, altering the functional properties of the steel without affecting its morphology.

What makes these defects industrially critical is their direct impact on downstream processing. Even in the absence of visible or measurable geometric anomalies, non-topographic defects can compromise coating adhesion, reduce corrosion resistance, and negatively affect forming performance. In high-quality steel applications, where surface condition directly influences product reliability, these effects are often more significant than purely geometric imperfections.

The challenge is further amplified in wet environments. Thin liquid films—whether water, oil, or mixed emulsions—introduce an additional layer of complexity by modifying the optical response of the surface. These films alter reflectance characteristics through changes in refractive index and absorption behavior, effectively masking the underlying material condition. As a result, surfaces with fundamentally different chemical states may appear visually similar, while uniform surfaces may exhibit apparent irregularities purely due to liquid-induced optical effects.

Under these conditions, geometry-based inspection methods encounter intrinsic limitations. Even when high-resolution 3D systems are deployed, the absence of measurable height variation means that non-topographic defects remain largely invisible to depth-driven analysis. The inspection problem therefore shifts from one of geometric detection to one of material discrimination—a transition that requires moving beyond morphology and into the domain of surface-sensitive measurement.

Inspection in wet environments: optical challenges

The inspection of steel surfaces in wet environments is fundamentally constrained by the way light interacts with liquid-covered metallic surfaces. Unlike dry conditions, where reflectance is primarily governed by the intrinsic properties of the steel, the presence of water, oil, or emulsions introduces an additional optical layer that alters the propagation of light before it reaches the sensor.

When illumination interacts with a wet surface, multiple physical phenomena occur simultaneously. A portion of the incident light is reflected at the liquid–air interface, while another portion penetrates the liquid layer and undergoes refraction. Within the film, absorption may take place depending on the chemical composition and thickness of the liquid, and scattering effects are influenced both by the roughness of the underlying steel and by inhomogeneities within the liquid itself. These combined effects create a complex optical response that is no longer directly representative of the steel surface alone, but of a composite system formed by steel, liquid layer, and illumination geometry.

From an operational perspective, even micrometric variations in film thickness can lead to significant changes in apparent brightness and contrast. This has several practical consequences in inspection systems deployed on pickling lines. Underlying defects may become partially or completely obscured due to attenuation or diffusion of light within the liquid layer. Conversely, purely optical artefacts—such as reflections or interference patterns—may generate features that resemble defects despite the absence of any physical or chemical anomaly on the steel.

In addition, the presence of liquids can lead to contrast inversions, where areas that would normally appear darker become brighter, or vice versa, depending on viewing angle and illumination conditions. This effect is particularly problematic in high-speed industrial setups, where acquisition geometry cannot be dynamically adjusted for each surface condition. As a result, classification models based on grayscale intensity or texture may interpret liquid-induced variations as geometric irregularities, leading to false positives.

A critical aspect to consider is that these optical effects are largely decoupled from defect severity. A small, harmless water droplet can produce a strong specular reflection and dominate the visual signal, while a thin but chemically significant contamination layer may induce only subtle spectral variations that remain undetected in conventional imaging. This mismatch between visual prominence and industrial relevance is one of the core limitations of intensity-based inspection in wet environments.

In such scenarios, inspection approaches relying exclusively on spatial descriptors—such as shape, edges, and texture—are inherently insufficient. They operate on the assumption that visual patterns correspond to physical structures, an assumption that breaks down in the presence of liquid-mediated optical distortion. The inspection problem therefore shifts from identifying geometric features to disentangling optical effects from material properties, highlighting the need for sensing modalities capable of accessing information beyond spatial appearance.

Hyperspectral imaging: from intensity to spectral response

Hyperspectral imaging represents a fundamental shift in industrial vision systems, moving from intensity-based observation to wavelength-resolved analysis. In conventional imaging, each pixel encodes a single value—typically grayscale intensity or RGB information—resulting from the integration of reflected light over a broad spectral range. In contrast, hyperspectral systems decompose this signal into multiple narrow wavelength bands, effectively capturing a reflectance spectrum for every point on the surface.

This transition is not merely an increase in data volume, but a change in the nature of the information acquired. Instead of describing how bright a surface appears under a given illumination, hyperspectral inspection characterizes how that surface interacts with light across different wavelengths. This interaction is intrinsically linked to material properties and therefore provides direct access to information that is invisible to conventional imaging systems.

From a physical standpoint, the spectral response of a surface is determined by several interrelated factors. Chemical composition and molecular structure define how specific wavelengths are absorbed or reflected. Surface oxidation alters electronic and optical properties, leading to measurable spectral variations. The presence of contaminants—such as oils, residues, or reaction by-products—introduces additional absorption features, while the thickness and composition of liquid films modulate the spectral response through combined effects of absorption and interference.

By sampling reflectance across a sufficiently dense set of wavelengths, hyperspectral systems generate a high-dimensional data representation in which each pixel is associated with a spectral vector rather than a single intensity value. This enables the differentiation of surface conditions that may appear identical in conventional images but exhibit distinct spectral signatures.

In industrial coating-line applications, hyperspectral acquisition is typically constrained to selected spectral ranges where material-dependent variations are most pronounced and technically accessible. These ranges often span from the visible to the near-infrared region, balancing sensitivity to relevant surface phenomena with practical considerations such as illumination stability, sensor robustness, and acquisition speed. The choice of spectral bands is therefore not arbitrary, but driven by the need to maximize discriminative power under real production conditions.

The key outcome of this approach is a transition from purely spatial analysis to material-sensitive inspection. Surface characterization is no longer inferred indirectly from visual appearance, but derived from measurable, wavelength-dependent behavior. This provides the foundation for addressing non-topographic defects in environments where geometry and intensity alone fail to deliver reliable information.

The concept of the spectral fingerprint

The notion of a spectral fingerprint lies at the core of hyperspectral inspection and represents the transition from visual interpretation to physically grounded material identification. A spectral fingerprint can be understood as the unique reflectance profile that a material or surface condition exhibits when observed across multiple wavelengths. Rather than relying on how a surface appears under a specific lighting condition, the inspection system evaluates how it interacts with light over a defined spectral range.

In industrial steel processing, this concept becomes particularly powerful because many surface conditions that are indistinguishable in conventional imaging reveal clear differences when observed spectrally. For instance, water films exhibit characteristic absorption features in specific near-infrared regions, driven by molecular vibrational modes. Oil layers, although visually similar to water under certain conditions, produce a different spectral modulation due to their distinct chemical composition. Likewise, oxidized steel surfaces show reflectance behaviors that deviate from those of clean metallic substrates, reflecting changes in surface chemistry and electronic structure.

A critical aspect is that these differences are not necessarily accompanied by any measurable geometric variation. From a topographic perspective, a clean surface and a chemically altered one may be identical. However, their spectral signatures remain distinct and stable enough to be identified, provided that the acquisition system captures the relevant wavelength bands with sufficient resolution and signal-to-noise ratio.

By leveraging these spectral fingerprints, hyperspectral inspection systems can move beyond indirect inference and directly classify surface conditions based on material properties. This enables reliable differentiation between water and oil films, which is essential in wet production environments where both are commonly present and visually ambiguous. It also allows the detection of thin chemical residues or contamination layers that would otherwise remain invisible in grayscale or RGB imaging. Furthermore, variations in oxidation state—often critical for downstream processes such as coating—can be identified through subtle but consistent spectral shifts.

The value of the spectral fingerprint lies in its material sensitivity. It provides an additional analytical dimension that complements spatial information, enabling inspection systems to distinguish between surfaces that look similar but behave differently in production. This shift—from appearance-based to property-based inspection—is a key step toward more reliable and physically meaningful surface quality assessment.

Complementarity with 3D inspection

3D inspection addresses one of the central limitations of conventional vision systems by resolving geometric ambiguity. Through depth measurement, it enables the quantification of defect morphology—capturing parameters such as height variation, depth, and spatial extent—and allows defects to be assessed in terms of their physical impact on the material. This represents a major advancement over purely intensity-based approaches, particularly for topographic defects that directly affect downstream performance.

Hyperspectral inspection operates along a different, yet equally critical dimension. Rather than focusing on shape, it characterizes the material state of the surface by analyzing wavelength-dependent reflectance. In doing so, it resolves what can be defined as material ambiguity: the inability of geometric or visual systems to distinguish between surfaces that are morphologically similar but chemically or compositionally different.

These two approaches are therefore complementary by design, not alternative solutions to the same problem. 3D inspection provides access to geometric information, enabling the system to answer questions related to defect severity in terms of physical deformation. Hyperspectral inspection, in parallel, provides material-sensitive information, enabling the identification of surface conditions that do not manifest through measurable geometry but are nonetheless critical for product quality.

This complementarity becomes particularly evident in pickling-line environments, where both types of ambiguity frequently coexist. A surface may appear geometrically flat and therefore acceptable from a topographic standpoint, yet be affected by residual oxides, or chemical contamination that compromise subsequent processes such as coating or forming. Conversely, a geometrically significant defect—clearly detectable through depth measurement—may be partially or completely masked in optical imaging due to the presence of water or emulsions, leading to reduced visibility or misclassification if only intensity-based methods are used.

By integrating geometric and spectral information, inspection systems can overcome these limitations and achieve a more complete representation of surface quality. Geometry provides a physically grounded measure of deformation, while spectral data introduces sensitivity to composition and surface condition. The combined analysis enables not only more accurate detection, but also more reliable classification, as each defect can be evaluated across both its morphological and material dimensions.

It is important to emphasize that hyperspectral imaging does not replace geometric inspection. Depth measurement remains essential for quantifying topographic defects and for assessing their mechanical relevance. What hyperspectral imaging adds is an additional layer of interpretation, extending inspection capabilities into domains where geometry alone is insufficient. In this sense, the evolution of industrial surface inspection is not a shift from one technology to another, but a convergence toward multi-modal systems capable of capturing the full complexity of real production conditions.

Industrial constraints and practical considerations

The deployment of hyperspectral imaging in production environments must be evaluated against the realities of continuous steel production, where inspection systems are required to operate under conditions that are far removed from controlled laboratory settings. Strip speeds are typically high and varous, imposing strict constraints on acquisition time and exposure stability. At the same time, mechanical vibrations from rollers and transport systems introduce dynamic disturbances that can affect both spatial alignment and spectral consistency during data capture.

Environmental factors further complicate the scenario. Illumination conditions are inherently variable due to reflections and process-induced changes in surface wetness. Splashing liquids and vapors—often containing aggressive chemical agents—can interfere with both the optical path and the integrity of sensor components. These conditions are not incidental but intrinsic to the pickling process, and any inspection technology must be designed to operate reliably within them rather than attempting to eliminate them.

Within this context, the key requirement for hyperspectral systems is not maximum spectral resolution, but stability and repeatability of the acquired signal. The system must ensure that spectral variations correspond to actual changes in surface condition rather than to fluctuations in acquisition parameters. This places emphasis on robust optical design, controlled illumination strategies, and calibration approaches capable of compensating for environmental variability.

Another critical aspect concerns data management. Hyperspectral imaging inherently produces high-dimensional datasets, where each pixel contains a full spectral vector. In a high-speed production line, this translates into a substantial data throughput that must be processed in real time. The challenge is therefore not only acquisition, but also the extraction of meaningful features within the time constraints imposed by the process. This requires the implementation of efficient dimensionality reduction techniques and targeted spectral feature selection, focusing on the wavelength bands that carry the highest discriminative value for the defects of interest.

It is important to recognize that the objective in industrial applications is fundamentally different from that of laboratory spectroscopy. The goal is not to reconstruct detailed spectral profiles with scientific precision, but to achieve a level of material discrimination that is sufficiently accurate, robust, and fast to support operational decision-making. In this sense, hyperspectral inspection in flat-steel production lines must be understood as an engineering compromise: a balance between spectral richness and system reliability, between analytical depth and real-time performance.

Only by addressing these constraints can hyperspectral imaging move from a promising analytical technique to a viable industrial tool, capable of delivering consistent value under the demanding conditions of steel production.

The SurfConInspect perspective

Within the SurfConInspect project, hyperspectral imaging is positioned as a complementary technological pillar that extends the capabilities of surface inspection rather than replacing it. Building on the foundation established in WP1, where 3D inspection enables reliable quantification of surface geometry, the project investigates how spectral information can be introduced to capture material-related phenomena that remain invisible to purely geometric approaches.

A central objective of SurfConInspect is to move beyond proof-of-concept demonstrations and address the practical conditions of industrial deployment. This includes the acquisition of spectral data directly on operating coating lines, where wet surfaces, variable illumination, and high strip speeds represent the norm rather than the exception. In this context, particular attention is given to ensuring that spectral acquisition remains stable and interpretable despite environmental disturbances, aligning with the broader requirement of robustness identified for industrial inspection systems.

Equally important is the transition from raw spectral data to actionable information. The project does not treat hyperspectral imaging as an end in itself but focuses on the extraction of discriminative spectral features that can be reliably associated with specific surface conditions—such as contamination, oxidation, or the presence of liquid films. This involves identifying those wavelength regions that provide the highest sensitivity to relevant defects, thereby reducing data complexity while preserving classification performance under real-time constraints.

Another key dimension of the SurfConInspect approach is the integration of spectral and geometric information within a unified inspection framework. Rather than operating as separate subsystems, 3D and hyperspectral data streams can be considered jointly to improve defect characterization. Geometry provides a direct measure of morphological impact, while spectral data introduces sensitivity to composition and surface state. The combination enables a more robust interpretation of ambiguous cases, particularly in wet environments where optical effects can obscure or distort visual signals.

From an operational perspective, the project also emphasizes the role of inspection systems as decision-support tools for operators and quality dispatchers / engineers. The goal is not only to detect and classify defects, but to translate multi-dimensional data into clear, actionable insights that can support process control in real time. This includes improving situational awareness, enabling more targeted interventions, and reducing uncertainty in quality-related decisions.

By systematically addressing non-topographic defects through spectral analysis and integrating this capability with depth-aware inspection, SurfConInspect extends the inspection paradigm beyond geometry alone. The result is a more comprehensive and physically grounded understanding of surface condition, aligned with the complexity of real industrial environments and the requirements of high-performance steel production.

Conclusions

Surface quality control in flat-steel production lines cannot be reduced to geometric measurement alone. While depth-aware inspection has significantly improved the detection and quantification of topographic defects, the industrial reality of wet processing environments introduces a broader class of challenges driven by material variability. Chemical residues, oxidation states, and liquid films interact with the steel surface in ways that do not manifest through measurable geometry yet have a direct and often critical impact on downstream performance.

Hyperspectral imaging provides a principled and physically grounded approach to addressing these limitations. By leveraging wavelength-dependent reflectance behavior, it enables the detection and characterization of non-topographic defects through their material signatures rather than their visual appearance. The concept of spectral fingerprinting allows inspection systems to distinguish between surface conditions that are geometrically identical but chemically distinct, introducing a level of sensitivity that is not accessible through conventional 2D or 3D methods alone.

From an industrial standpoint, this translates into tangible improvements in inspection reliability and process control. Chemically relevant surface conditions—such as residual contamination or even heavy defects—can be detected with greater confidence, even under the presence of water, oil, or emulsions that would otherwise obscure or distort visual signals. At the same time, the reduced dependency on intensity-based interpretation increases robustness against environmental variability, a key requirement for high-speed production lines operating under non-ideal conditions.

The broader implication is a shift toward multi-dimensional inspection strategies. Geometry remains essential for quantifying defect morphology and assessing mechanical impact, as demonstrated in WP1, but it is no longer sufficient on its own. Material-sensitive information, accessed through spectral analysis, complements geometric data and enables a more complete understanding of surface condition.

Within this evolving framework, SurfConInspect plays a pivotal role by translating these concepts into industrial practice. The project does not treat hyperspectral imaging as an isolated analytical tool, but as an integral component of an online inspection ecosystem. It addresses the constraints of real production environments—high strip speeds, wet conditions, and the need for real-time decision support—while demonstrating how spectral and geometric data can be effectively combined within existing quality control workflows.

By integrating depth-aware and material-sensitive inspection within a unified approach, SurfConInspect advances the state of practice toward a more robust, data-driven paradigm for surface quality assessment in flat steel production. This evolution reflects a broader trend in industrial inspection: moving from appearance-based evaluation to physically informed analysis, capable of capturing both the shape and the substance of the material under inspection.

The Consortium

SurfConInspect unites a diverse group of partners:

- **Steel producers:** thyssenkrupp Rasselstein (RAS), Salzgitter Flachstahl (SZFG)
- **Research & Academia:** VDEh-Betriebsforschungsinstitut (BFI), Scuola Superiore Sant'Anna (SSSA), CETIC
- **Technology developers:** Clecim France (CLECIM)
- **Communication & dissemination experts:** yourscienceEDU (YSE)

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Together, we are shaping the future of **sustainable steel production**.