Application of Multispectral Sensing for Detection of Corrosion in Steel Infrastructure

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University

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Research Needs

Corrosion costs up to 4% of the global Gross Domestic Product each year (Koch 2017). Corrosion is an important phenomenon that many industries, such as manufacturing, automobile, military, transportation, and infrastructure, must address. Steel is widely used in the United States for constructing transportation-related infrastructure, storage, waterways, pipelines, railroads, and bridges. Protection from environmental corrosion is arguably the greatest challenge related to steel infrastructure. The direct cost of corrosion in the US increased from 5.5 billion US dollars in the 50s to 276 billion US dollars in 1999 (Revie 2011), excluding indirect costs such as maintenance and repair, over-design capacity, corrosion control/mitigation strategies such as coatings, and insurance, which could be essentially double the cost of steel corrosion. Furthermore, steel production is one of the most environmentally taxing industrial processes.

There are two approaches to preventing corrosion from making steel infrastructure obsolete: (1) limiting exposure to the environment (e.g., coatings) and (2) monitoring corrosion initiation and propagation through periodic inspections, which is the subject of this proposal. Visual inspections are the primary means of detecting corrosion in transportation infrastructure despite the development of many nondestructive evaluation methods (Bardal 2004). Visual inspections are tedious, dangerous, and sometimes inconsistent (Dorafshan et al. 2018). Therefore, a significant body of research and technical knowledge has been generated to address these challenges through automation. High readiness level artificial intelligence (AI) and uncrewed aerial system (UAS) applications for detecting corrosion in steel bridges have been successfully developed in the past decade, and many state DOTs and inspection companies are now using them for routine inspections and condition assessments (Feroz et al. 2021 &. Seo et al. 2018). Conventional and advanced AI models have been successfully employed to detect steel corrosion with high accuracy (Das et al. 2022); however, these methods are only effective for detecting corrosion in the human visual range.

Corrosion is an irreversible electrochemical reaction between free iron (Fe^{2+} and Fe^{3+}) and the oxygen and hydrogen that are abundant in our atmosphere. The onset of corrosion begins with the bonding of the free ions abundant in steel with water and oxygen (Equation 1). The corrosion product (rust) is a combination of ferric oxides in different chemical forms bonded with water, creating products such as hematite, geothite, and iron oxide hydroxide.

$$Fe + 3O_2 + 2H_2O = 2Fe_2O_3H_2O \qquad (1)$$

Transporting goods and people in North Dakota is primarily conducted via land due to the lack of navigable water, underscoring the importance of infrastructure such as bridges, pipelines, and railroads. Over a quarter of the bridges in North Dakota are made of steel, considering only the primary span material, which is prone to environmental corrosion (FHWA 2024). Pipeline corrosion was the cause of the state's biggest oil spill in 2013 (NBC News 2013). All railroad rails in the nation are made of steel and are prone to corrosion, especially when the ballast (aggregates supporting rails) is fouled, a common occurrence. Railroads are exposed to highly corrosive material spills, which cause derailments, such as the derailment that occurred in Minot in 2002 (KFYR TV 2023). Additionally, North Dakota has a prominent role in providing agricultural products and energy for the United States; therefore, investing in technologies to protect transportation infrastructure against corrosion is of national importance, especially considering the pivotal role of North Dakota infrastructure in energy and goods supply chain.

It is not possible to discern the nature of these chemical compounds using existing non-contact NDE sensing. As a result, misclassifications or high rate of missing a defect have been a big challenging. There is a need for a noncontact sensing technology, similar to visual imagery, to assess steel infrastructure against corrosion more robustly, benefiting the State of North Dakota and the region.

Research Objectives

Diffuse spectroscopy is the science of understanding light reflectance. This methodology has been used as a noncontact sensing method in many fields, such as medicine (Lu et al. 2022), environmental monitoring (Cloutis 1996), agriculture (Dale et al. 2013), and railroad ballast evaluation (Ichi & Dorafshan 2022). Hyperspectral imagery has recently become attractive to researchers who seek to extend its application beyond the aforementioned topics due to the ability to characterize materials from spectral information. Using this technology to detect corrosion in metals has been limited to understanding uniform corrosion in boilers (Degueldre et al. 1996 & 1998) and nuclear reactors (Castelli et al. 2009). The goal of this research is to study how diffuse reflectance can be used to investigate alternative noncontact sensing methods that complement visual imagery to detect and monitor corrosion in steel. Hyperspectral cameras can be mounted on UAS to capture both spatial and spectral features which makes this technology a great candidate for steel condition assessment.

<u>Objective 1</u> is to study how to augment steel corrosion detection by analyzing corrosion reflectance in a broader wavelength range than human vision (380 nm to 700 nm). The governing hypothesis of Objective 1 is that corrosion compounds can be identified in steel by analyzing incident light reflectance in the visual near-infrared range (400 nm to 1700 nm). Corrosion compounds in steel (rust) absorb light differently than sound steel, which manifests in brighter colors. The research question to be answered in Objective 1 is understanding what corrosion does to light reflectance beyond human vision.

<u>Objective 2</u> is to develop a model to associate corrosion with one or a series of light reflectance representatives (features). The hypothesis regarding Objective 2 is that steel corrosion will be detectable at different wavelengths as corrosion progresses. The research question to be answered in Objective 2 is determining what features in reflectance data can be leveraged to identify corrosion and complement visual inspections.

Research Methods

Existing equipment and resources will be used to meet the objectives proposed in this project. The methods are both. The research includes updating the technical knowledge through continuous literature review, performing a series of experimental procedures, e.g., sample preparation, and computational operation, e.g., modeling and analysis. The results will be validated via variety of methods, direct comparison with existing state of knowledge or technology.

Relevance to Strategic Goals

This proposal’s goal aligns with the US DOT’s strategic goals for safety and environmental sustainability. The investigation will result in a better understanding of steel corrosion, which could be further developed to assess different types of corrosion with different severities. Additionally, this proposal’s objectives will ensure that corrosion is identified in a timely manner since a significant amount of corrosion cannot be detected visually. The augmented defect identification model developed in this proposal could result in longer service life if relevant maintenance and repair tasks were implemented, leading to the increased service life of steel infrastructure; therefore, less steel would be required to repair and replace severely corroded steel transportation infrastructure if the technology is properly developed and implemented.

By providing better preservation, the result of this project is a contribution to less manned inspection for safer infrastructure, improved connectivity in transportation for resilient supply-chain, and introduction of autonomous systems to the future transportation system to system.

Educational Benefits

The outcome of the investigation will be used in existing courses at the Department of Civil Engineering at UND. The PI is the instructor of Applications of AI in Civil Engineering (CE 590). One of this course's modules is dedicated to infrastructure condition assessment, where the datasets and models generated in this project will be instrumental. The outcomes can be used as a case study in ChE 435/535 Materials and Corrosion to benefit engineering students.

Outputs through Technology Transfer

The findings from this proposal will be transferred to other researchers via presentations at local (UND Grad Achievement Day), regional (ND Transpiration Conference), and national (Transpiration Research Board) conferences. Additionally, the results will be transferred to professionals and practitioners via Professional development hours (PDHs) via the North Dakota ASCE and North Dakota SPE. Further technology development for commercialization will be assessed through discussion with the UND Center of Innovation.

Expected Outcomes and Impacts

The following outcomes are expected to be produced upon completion of this project:

- Technical knowledge about the reflectance properties of corroded steel
- Visual and spectral datasets for corroded and non-corroded steel
- Descriptive model to establish relationships between corrosion and reflectance
- Presentation and publications in scientific conferences and journals

Work Plan

Objective 1 Task 1: Generation of nonuniform corrosion in steel
Structural steel samples will be acquired. The samples will be weighed, and the surfaces will be cleaned. Corrosion will be accelerated through exposure to different corrosive environments, such as changing the pH and temperature in the corrosion chamber.

Objective 1 Task 2: Data collection
Different exposure times will be used to investigate corrosion at early stages and determine the onset of corrosion before visible rust is formed. Additionally, samples will be exposed to longer periods of accelerated corrosion to understand how and at what rate corrosion formation changes reflectance. Diffuse spectroscopy using hyperspectral imaging will be collected for individual samples. Corrosion onset may not be visually detectable; therefore, an alternative ground truth is required. X-ray diffraction (XRD) will be used to detect corrosion product formation at early stages. XRD will also be used for longer-term exposure to determine when corrosion decelerated.

Objective 1 Task 3: Feasibility data analysis
An average spectrum for each sample will be developed, representing the average stage of corrosion. Spectra is a time series with reflectance on the Y-axis plotted against different wavelengths (X-axis). Changes in reflectance spectra will be assessed by comparing the samples as the corrosive environment, pH, and exposure time are varied. Another outcome of this task will be to identify at which wavelengths light reflectance exhibited the most changes with respect to other variables.

Objective 2 Task 1: Determination of corrosion reflectance features
Models will be developed to establish relationships between reflectance features and corrosion. Early-stage corrosion relationships will be established with the amount of corrosion products, such as hematite, identified using XRD versus a suite of features from the reflectance spectra. The change in these features, along with changes in exposure time, moisture content, and medium pH, will be investigated separately. These features will be used to construct a two-dimensional representation of non-uniform corrosion at different stages.

Objective 2 Task 2: Comparison between visual and hyperspectral imagery
The human vision system detects colors by combining red, green, and blue wavelengths: 630 nm, 532 nm, and 465 nm, respectively; therefore, visual image representation can be obtained by combining diffuse spectroscopy reflectance data in these wavelengths. Visual images will be constructed for each sample and compared with corrosion feature maps developed in previous objective.

Table 1. Tasks to be performed and their forecasted completion with respect to the project start date

Task/Milestone	**Title**	**From start date**
O1T1	Generation of nonuniform corrosion in steel	3 months
O1T2	Data collection	6 months
O1T3	Feasibility data analysis	9 months
O2T1	Determination of corrosion reflectance features	14 months
O2T2	Comparison between visual and hyperspectral imagery	18 months
Report	Report submitted to the prime organization	18 months (+1 month of no-cost extension)

Project Cost

Total Project Costs: $197,514
CTIPS Funds Requested: $ 98,757
Matching Funds: $ 98,757
Source of Matching Funds: University of North Dakota

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