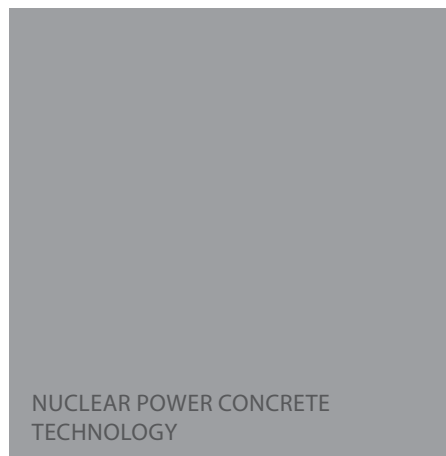
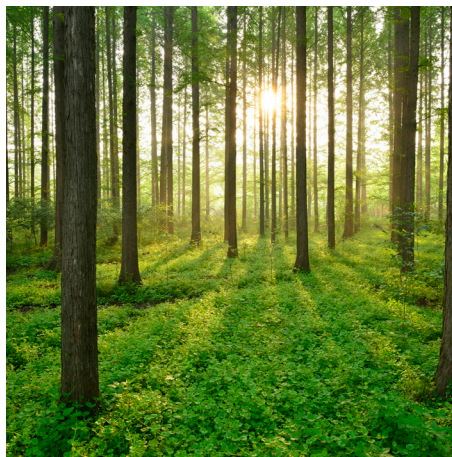


REMOTE INSPECTIONS OF CONCRETE STRUCTURES

REPORT 2024:1014



Remote inspections of concrete structures

Mapping of technologies, possibilities and limitations
and non-contact inspections of concrete structures

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Foreword

The Energiforsk Nuclear Power Concrete Program aims to increase the knowledge of aspects affecting safety, maintenance and development of concrete structures in the Nordic nuclear power plants. A part of this is to investigate possibilities to facilitate and simplify the work that is performed in the nuclear business.

The development of remote inspection technologies is reshaping the possibilities for inspection and data collection for many types of large concrete structures. The aim of this project is to better understand which existing and emerging technologies that can be used for concrete structures in the Nordic nuclear power plants.

The study was carried out by Cosmin Popescu, Andreas Wernersson, Ali Mirzazade and Björn Täljsten cooperating in an AFRY run project. The study was financed by the Energiforsk Nuclear Power Concrete Program, which in its turn is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, SSM and SKB.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

This report delves into how the implementation of remote inspection technologies is reshaping concrete structure inspection and maintenance. It includes state-of-the-art and state-of-the-practice technologies within remote inspection of concrete structures. It showcases new solutions that address conventional constraints, including accessibility issues, environmental risks, and the imperative to reduce operational downtime.

Key aspects of this report include:

The report commences with an overview of concrete structures, encompassing discussions on durability, deterioration processes, and current approaches to preliminary and detailed assessment. These assessment methods are categorized into two distinct levels: (1) non-contact assessment via visual inspection, and (2) close-contact inspection. Furthermore, it presents the assessment process on nuclear power station in Sweden as well as worldwide.

The report then extensively discusses promising defect identification and structural assessment capabilities offered by imaging sensors, including LiDAR, thermography, and advanced photogrammetric methods, which surpass traditional techniques. In the nuclear power industry, the detection of surface defects like cracking, delamination, and material degradation is the initial step of inspection. Consequently, this report delves into image-based remote inspection utilizing enablers, sensors, and Computer Vision techniques for defect detection. These methods were applied on large-scale concrete structures, which share characteristics with those found in nuclear power plants and discussed to show the potential of their applications on nuclear power plant concrete structures.

Looking ahead, the report emphasizes the trajectory of continuous improvement and innovation in remote inspection technologies. The integration of structural engineering knowledge, data acquisition vehicles and robotic systems, machine learning, and computer vision techniques can be able to ensure the structural integrity and longevity of critical infrastructures.

Keywords

Remote inspection, visual inspection, non-destructive testing (NDT), 3D imaging, thermography, acoustic inspection, imaging sensors, robots, drone scanning, computer vision.

Sammanfattning

Denna rapport behandlar hur teknologier för distansinspektioner just nu förändrar hur betongkonstruktioner inspekteras och underhålls.

Innehållet beskriver den senaste vetenskapen och praktiska erfarenheterna inom området betonginspektioner. I rapporten presenteras nya lösningar för bekanta utmaningar, såsom åtkomstproblematik, miljörelaterade risker, samt strävan efter att minimera tidsåtgång och begränsa driftstopp.

Huvudsakliga lärdomar:

I rapporten beskrivs betongkonstruktioner allmänt där aspekter som teknisk livslängd, degraderingsmekanismer och konventionella metoder för tillståndsbedömningar diskuteras. Tillståndsbedömningarna kan delas in i två olika nivåer: (1) beröringsfri bedömning via okulär besiktning, och (2) när besiktning. Vidare presenteras med ett par nationella och internationella exempel hur arbetet med betonginspektioner fram till idag bedrivs och har bedrivits vid olika kärnkraftverk.

Vidare avsnitt innehåller en omfattande genomgång av lovande identifikationsmetoder för betongavvikelse där bildteknik används. Genom metoder som nyttjar LiDAR, termografering eller avancerad fotogrammetri kan resultat uppnås som överträffar traditionella metoder. I kärnkraftsindustrin är detektering av avvikelser som betongsprickor, bområden och övrig degradering det första steget i inspektionen. Av denna anledning fokuserar rapporten på bildbaserade distansinspektionsmetoder genom användning av s.k. 'datorseende' (bildigenkänning, jämförelser m.m.). Dessa metoder tillämpades på storskaliga betongkonstruktioner, som delar egenskaper med de som finns i kärnkraftverk och diskuterades för att visa potentialen för deras tillämpningar på kärnkraftverks betongkonstruktioner.

En framåtblick visar att riktningen pekar mot fortsatt utveckling och innovation inom området distansinspektioner. Integration av kunskaper om byggkonstruktion, datainsamling genom robotteknik, maskininlärning och datoriserad bildhantering skapar en lovande situation där livslängd och integritet för kritisk infrastruktur kan ges de bästa av förutsättningar.

Keywords

Distansinspektion, visuell kontroll, oförstörande provning (OFP), 3D-scanning, termografering, akustisk inspektion, fotosensorer, robotar, drönarinspektion, datoriserad bildhantering.

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1 Introduction

Concrete structures, over time, face challenges related to aging and degradation due to factors like exposure to elevated temperatures, environmental conditions, and mechanical stresses. Maintaining the structural integrity of concrete elements is essential for ensuring safety standards, particularly in critical infrastructures such as nuclear power plants. Within these plants, typical concrete structures include the reactor containment, reactor building, and cooling waterways, all of which are susceptible to degradation from design or construction errors, accidental loads, and environmental effects. Periodic inspections are vital for identifying signs of distress in these structures, although the sheer size presents challenges to inspectors, similar to those faced in inspecting other large structures like bridges and dams. As such, there is a pressing need for new inspection techniques that enhance efficiency and reliability while reducing disruption and safety issues.

Remote visual inspection solutions have emerged as indispensable tools for scrutinizing complex components within these plants, leveraging emerging technologies such as sensors, robotics, computer vision, and reality capture techniques. This innovative approach enables inspectors to seamlessly merge digital information with the physical world, leading to numerous benefits such as faster task completion, reduced costs, heightened efficiency, and increased safety. Notably, in the context of the nuclear energy industry, remote inspection offers flexibility, repeatability, and safety.

1.1 BACKGROUND

The field of remote inspection in Nuclear Power Plants (NPP) has evolved as a response to the intricate challenges associated with maintaining, monitoring, and ensuring the safety of critical infrastructure. Nuclear power, playing a pivotal role in global energy production, necessitates stringent measures for periodic inspections to guarantee the structural integrity and operational efficiency of its facilities.

Traditional inspection methods often faced limitations, especially in the context of nuclear power plants. The complex and hazardous nature of these environments, coupled with the need for continuous operation, posed challenges to conventional inspection practices that required physical presence. As a result, there emerged a demand for remote inspection with innovative solutions that could overcome these challenges while upholding the highest standards of safety and reliability.

The advent of remote inspection technologies marked a transformative shift in the approach to assessing and maintaining concrete structures. Augmented and assisted reality, coupled with advancements in communication and sensor technologies, paved the way for inspectors to remotely access and scrutinize intricate components within concrete structures. This shift not only addressed safety concerns associated with on-site inspections but also introduced a range of advantages that significantly enhanced the overall efficiency of the inspection processes. Factors driving the adoption of remote inspection in NPP's concrete structures include the necessity for:

- **Continuous monitoring:** Nuclear power plants operate in dynamic environments, and continuous monitoring is essential to identify potential issues promptly. Remote inspection allows for real-time assessment without disrupting regular operations.
- **Safety and hazard mitigation:** Nuclear facilities pose inherent risks to human health, and minimizing personnel exposure to hazardous environments is a paramount concern. Remote inspection minimizes the need for physical presence in potentially dangerous areas.
- **Global collaborations and expertise access:** The global nature of the nuclear industry demands collaboration among experts from different regions. Remote inspection facilitates real-time communication and collaboration, enabling access to a diverse pool of experts without geographical constraints.
- **Cost/Time efficiency:** Reducing expenses and minimizing downtime during inspections contribute to cost efficiency. Remote inspection methods offer a streamlined and cost-effective approach to maintaining nuclear power plants.

In essence, the background of remote inspection in NPP's concrete structures is rooted in the pursuit of safer, more efficient, and technologically advanced methods for evaluating and sustaining critical components.

1.1.1 Aim and objectives

This report aims to identify effective remote inspection methods suitable for assessing concrete structures. Additionally, we seek to highlight emerging techniques currently in development, which show promise for customization to meet the specific needs of NPP concrete structures.

To achieve these objectives, we will first address the challenges posed by aging infrastructure, emphasizing the crucial role of concrete in nuclear facilities. We will then explore various inspection methods, focusing particularly on remote approaches. Following this, we will delve into both established and emerging technologies in hardware (such as enablers, and sensors) and software (including computer vision techniques). By examining these technologies, we aim to provide insights into their potential benefits for monitoring and evaluating the condition of concrete structures within NPPs. Our goal is to offer a clear understanding of the available options and opportunities for enhancing remote inspection capabilities in concrete structures in nuclear power plant environments.

1.1.2 Method and scientific approach

A problem-oriented strategy is the rapid introduction of new technologies for preliminary assessment by remote inspection of concrete facilities. This is the only way to ensure a comprehensible, technically, and economically optimized selection of inspection methods in practice. Therefore, this report entails acquiring essential background knowledge concerning the existing inspection techniques within concrete structures. This knowledge provides insights into the inspection

requirements, common damages, and the scale of these structures, which dictates the resolution requirements. For this, we would investigate publication databases from established organizations such as IAEA (International Atomic Energy Agency), and Swedish Radiation Safety Authority, as well as SCOPUS and ISI Web of Knowledge databases.

This report aims to explore existing preliminary and detailed concrete structure assessment techniques in two different levels of (1) non-contact assessment based on vision-based techniques, and (2) close contact inspection. Then, the focus goes through using vision-based non-contact defect identification solutions that are (i) suitable for field applications and (ii) capable of enhancing the inspection, monitoring, and assessment of existing civil infrastructures. Such solutions have the potential to improve the accuracy and efficiency of civil structure inspections by eliminating human error, mitigating safety risks, and enabling early detection of damage. Within this report, various available commercial methods for non-contact assessment of concrete structures will be presented.

1.2 CONCRETE STRUCTURES IN GENERAL

1.2.1 Materials

Concrete always consists of cement, water, sand, gravel, and stone. In addition, concrete may have different additives to give it specific properties in the fresh or hardening state. Cement can also contain constituents such as fly ash, silica fume, ground granulated blast-furnace slag. These materials can then replace a part of the cement in the concrete mix.

Concrete has many advantages, such as formability, high compressive strength, high stiffness, durable, in general long life, wear resistance, fire resistance, good noise properties, resistant to moisture and water and is also possible to reuse or recycle. Disadvantages is low tensile strength and rather large shrinkage and that manufacturing of cement with today's technology leads to large CO₂ emissions. To overcome the disadvantages of low strength, steel (other materials are used such as glass and carbon fiber bar/rods/tendons) reinforcement are used. The steel can also be prestressed. The process of prestressing consists in applying forces to the concrete structure by stressing tendons relative to the concrete member.

"Prestress" is used globally to name all the permanent effects of the prestressing process, which comprise internal forces in the sections and deformations of the structure. The prestress is applied by tendons made of high-strength steel (wires, strands, or bars). Tendons may be embedded in the concrete. They may be pre-tensioned and bonded or post-tensioned and bonded or unbonded. Tendons may also be external to the structure with points of contact occurring at deviators and anchorages.

1.2.2 Durable concrete structures

Reinforced concrete has historically been thought of as very forgiving when it comes to the amount of time the material takes in service. Although there is a good deal of truth to this, the environment certainly can shorten reinforced concrete's

life expectancy, resulting in costly repairs and disruption to everyday life. The performance of a structure is typically seen as how well it is operating related to its use. This can be further expressed as the performance of key principles like structural safety (load carrying capacity), serviceability, appearance (aesthetics) or mitigation of, for example falling concrete due to spalling. Performance is regarded by many as a quantifiable property and is always a function of time. When considering time in evaluating performance, degradation of the structural materials is regarded as the most important factor. This links the structure's performance directly with the durability of its materials.

Degradation is the reduction or decrease in performance over time and can be understood as the inverse of performance; therefore, measuring degradation allows one to assess performance related problems. Performance is then measured by a minimum acceptable level, while degradation is set by a maximum acceptable level. These levels are known as durability limit states and can be defined for future performance measurements. The limit state can be set to either an ultimate or serviceability limit, which defines the service life and ultimately the performance requirements of the structure.

When examining issues related to the deterioration of reinforced concrete, it's essential to focus on the primary materials involved: concrete and reinforcing steel. The durability of the structure is greatly influenced by the interaction between these two materials. If there are flaws in the original design or the selection of materials, along with factors that increase corrosion, such as heavy loads, degradation will likely occur over time. Additionally, the environment in which these materials are situated plays a significant role in determining how they will perform and degrade in the long term.

In contemporary construction practices, concrete structures are engineered with durability in mind. This involves considering factors such as exposure class, which indicates the severity of the environment and the risk of exposure to contaminants. Generally, the denser the concrete and the thicker the concrete cover, the better the structure can withstand environmental challenges.

Several factors must be taken into account during the design and casting of concrete. One crucial factor is the cover provided to the reinforcement. The design process involves classifying structures based on various criteria such as environmental conditions, structural class, and construction methods. The thickness of the cover over the reinforcement is determined based on the classification of the structure, ensuring its durability over time.

Preventing concrete from cracking entirely is nearly impossible due to environmental variations worldwide. However, it is feasible to control cracking to a certain extent, ensuring that it does not compromise the structural integrity, even in harsh conditions. The width and depth of cracks are critical factors affecting durability. Ideally, for a structure to remain durable, crack widths should be limited to 0.2 mm, or in extreme cases, to 0.1 mm.

The durability of concrete is significantly influenced by its strength class and water-cement ratio. Eurocode 2 provides a classification system for structures and based on their exposure class (as per SS-EN 206), recommends different strength

classes and concrete cover thicknesses depending on the exposure conditions. The water-cement/binder ratio directly impacts concrete strength, and in aggressive environments, this ratio should typically fall between 0.40-0.45. Therefore, selecting the appropriate strength class is essential in designing durable concrete structures. In aggressive environments, the permeability of concrete should ideally be less than 10^{-12} m/s when measured with fresh water, further emphasizing the importance of proper material selection and design considerations for long-term durability.

Ensuring durable concrete involves more than just its composition; it also encompasses proper design and workmanship. Concrete must be thoroughly mixed and compacted to prevent issues like segregation or voids. However, perhaps the most critical factor in achieving durability is proper curing of the concrete structure.

Curing involves the process of applying water to the structure shortly after pouring and during the hydration period, during which concrete gains its strength. Without adequate curing, concrete is unlikely to reach its full-strength potential. Controlling heat development in concrete, particularly in large structures, is crucial to prevent cracking, especially during cooling. In cold weather, heating may be necessary during concrete casting to prevent freezing in its fresh state.

Design considerations are also vital to ensure water can effectively drain off concrete structures. Additionally, for larger structures, joints may be necessary to accommodate shrinkage and temperature-related stresses. Overall, attention to these aspects during construction plays a significant role in enhancing the durability of concrete structures.

1.3 CONCRETE DETERIORATION PROCESSES

1.3.1 General

Concrete civil infrastructure and structures are prone to various deterioration processes and defects over time, which can compromise their performance and safety if left unchecked. These issues include cracking, bond loss, void formation, reduction of cover layer, corrosion, and delamination, among others. If not addressed, these defects can progressively degrade the structure, ultimately jeopardizing its integrity.

Continuous assessment of structure quality is essential to identify and mitigate potential problems, ensuring the longevity and structural integrity of the infrastructure. Figure 1-1 illustrates common causes of defects and deterioration in concrete structures, as outlined in ISO 16311-3 (2014). This framework helps to categorize and understand the underlying factors contributing to structural deterioration, guiding maintenance and repair efforts to prolong the service life of concrete infrastructure.

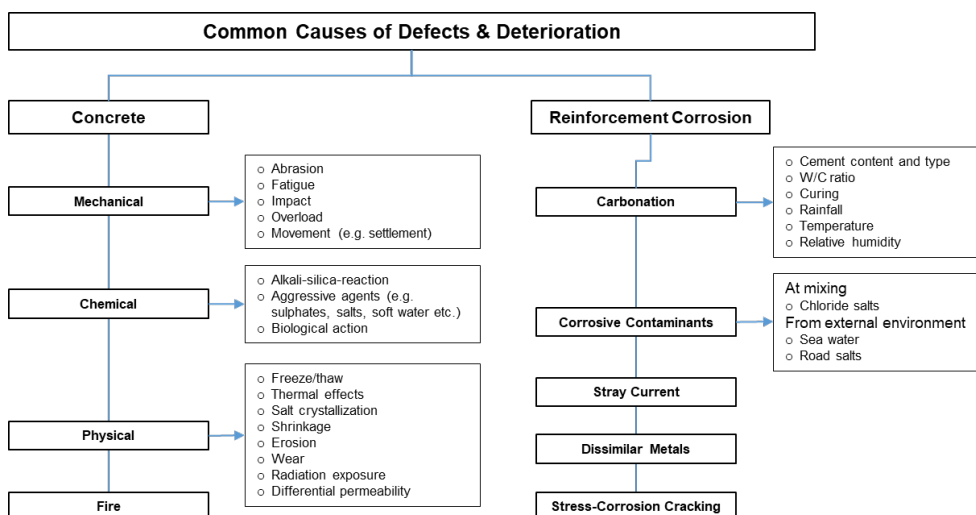


Figure 1-1 Common causes of defects and deterioration of concrete structures, based on (ISO 16311-3, 2014)

The deterioration of concrete structures involves distinct processes affecting both the concrete itself and the steel reinforcement within. Concrete degradation can arise from mechanical, chemical, physical, and fire-related factors, while steel reinforcement may deteriorate due to carbonation, corrosive contaminants, stray currents, dissimilar metals, and stress-corrosion cracking.

Cracking in concrete can stem from any of these causes, making it crucial to identify the underlying reason for each crack. Often, multiple processes interact to cause damage, complicating the assessment of structural integrity. Once cracks form, the rate of deterioration may accelerate, especially under conditions such as fatigue loading, freeze-thaw cycles, or exposure to corrosive contaminants. Understanding these complex interactions is essential for effective maintenance and repair strategies to mitigate further deterioration and ensure the long-term performance of concrete structures.

1.3.2 Cracks in concrete

In remote inspections of concrete structures, a comprehensive understanding of the causes and evolution of cracking is crucial. It's essential to discern the type of crack and its potential impact on the structure. Figure 1-2 provides a schematic representation of the various types of cracking that can manifest in concrete (Neville, 1995). Additionally, Table 1-1 elaborates on the different types of cracks, particularly concerning the timing of their occurrence (Neville, 1995). This information aids inspectors in identifying specific types of cracks, assessing their severity, and determining appropriate maintenance or repair interventions to ensure the structural integrity and longevity of the concrete infrastructure.

Table 1-1 Classification of intrinsic cracks in concrete, (Neville, 1995)

Type of cracking	Symbol in Figure 1-2	Subdivision	Most common location	Primary cause	Secondary causes	Time of appearance
Plastic settlement	<i>A</i>	Over reinforcement	Deep sections	Excess bleeding	Rapid early drying conditions	10 min – 3h
	<i>B</i>	Arching	Top of columns			
	<i>C</i>	Change of depth	Through and waffle slabs			
Plastic Shrinkage	<i>D</i>	Diagonal	Pavements and slabs	Rapid early drying	Low rate of bleeding	30 min 6h
	<i>E</i>	Random	Reinforced concrete slabs			
	<i>F</i>	Over reinforcement	Reinforced concrete slabs	Rapid early drying or steel near surface		
Early thermal contraction	<i>G</i>	External restraint	Thick walls	Excess heat generation	Rapid cooling	1 day to 2 or 3 weeks
	<i>H</i>	Internal restraint	Thick slabs	Excess temperature gradients		
Long-term drying shrinkage	<i>I</i>		Thin slabs and walls	Inefficient joints	Excess shrinkage inefficient curing	Several weeks or months
Crazing	<i>J</i>	Against formwork	Walls	Impermeable formwork	Rich mixes Poor curing	1 to 7 days, sometimes much later
	<i>K</i>	Floated concrete	Slabs	Over-troweling		
Corrosion of reinforcement	<i>L</i>	Carbonation Chloride	Columns, slabs, and beams	Inadequate cover	Poor quality concrete	More than 2 years
Alkali silica reaction	<i>M</i>		Damp locations	Reactive aggregate plus high-alkali cement		More than 5 years
Blister	<i>N</i>		Slabs	Trapped bleed water	Use of metal float	Upon touching
D-cracking	<i>P</i>		Free edges of slabs	Frost-damaged aggregate		More than 10 years

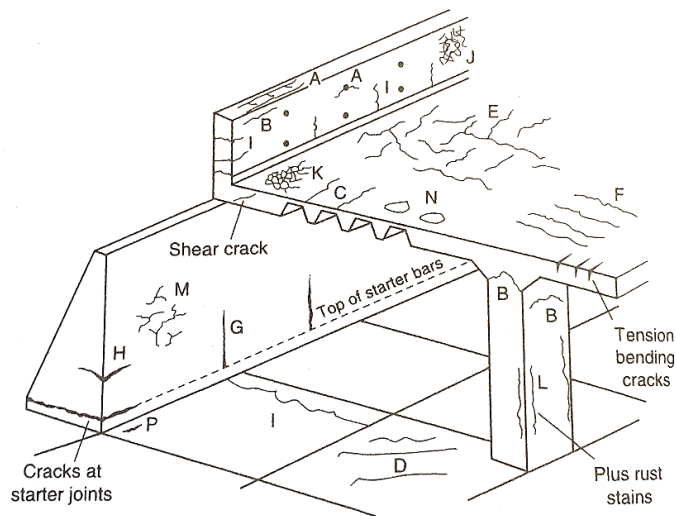


Figure 1-2 Schematic representation of cracks in concrete, (Neville, 1995)

It's important to differentiate between structural and non-structural cracks in concrete, as well as consider the timing of crack occurrence. The cracks can be categorized into three types: 1) Dead cracks, 2) Living cracks, and 3) Infected cracks.

Dead cracks result from factors like overloading, movement, or shrinkage, but the causative factors have ceased.

Living cracks experience periodic opening and closing due to temperature variations or external loading.

Infected cracks are those where ongoing chemical or physical activities, such as reinforcement corrosion, alkali silica reaction, freeze-thaw cycles, or similar processes, contribute to their progression.

Table 1-2 provides a brief description of the causes behind these different types of cracks. Understanding the nature and origin of cracks is crucial for effective inspection and maintenance strategies, enabling timely interventions to mitigate further deterioration and ensure the structural integrity of concrete infrastructure.

Table 1-2 Causes to cracks divided into dead, living, and infected cracks, (Lindland, 2016)

Cause	Dead	Living	Infected
Plastic shrinkage	•		
Long term shrinkage	•		
Overloading (bending, tension, torsion, shear)	•	•	
Fatigue	•	•	
Reinforcement corrosion			•
Alkali Silica Reaction		•	•
Freeze-Thaw	•		(•)
Restraint	•		
Movement due to external temperature		•	
Heat development during hardening	•		

When assessing cracks, monitoring their evolution over time is crucial, not just identifying their type. Remote inspections, particularly distance inspections, are effective for tracking changes in crack size and width over time. It's important to consider the energy dynamics involved in crack development: extending an existing crack requires less energy than forming a new one. This phenomenon clarifies why, under applied loads, each subsequent crack tends to occur under higher stress than the preceding one. Understanding these principles aids in predicting crack propagation and assessing the structural implications of cracks in concrete infrastructure.

1.4 NUCLEAR POWER STATIONS

1.4.1 General

As of 2023, there are a total of 436 nuclear reactors operational worldwide. These reactors encompass various types, with the most prevalent being Pressurized Light-Water Moderated and Cooled Reactors (PWR) accounting for 305 units, followed by Boiling Light-Water Cooled and Moderated Reactors (BWR) with 62 units.

The majority of nuclear reactors, including all Swedish reactors, and approximately half of the reactors worldwide, were constructed prior to 1985. These reactors are now either in operation beyond 40 years or nearing this milestone, entering what is termed long-time operation mode. In Sweden specifically, there are currently 6 reactors in operation, while 6 reactors have been permanently shut down (refer to Table 1-3). Among the decommissioned reactors, progress in dismantling is most advanced for the Barsebäck reactors, while decommissioning efforts for the other closed reactors are still pending.

Table 1-3 List of Swedish full scale nuclear power plants.

Reactor name		Start	Status	End
Oskarshamn 1	O1	1972	Permanent shutdown	2017
Oskarshamn 2	O2	1974	Permanent shutdown	2015
Oskarshamn 3	O3	1985	In operation	>2040
Barsebäck 1	B1	1975	Decommission	1999
Barsebäck 2	B2	1977	Decommission	2005
Forsmark 1	F1	1980	Operation	>2040
Forsmark 2	F2	1981	Operation	>2040
Forsmark 3	F3	1985	Operation	>2040
Ringhals 1	R1	1976	Permanent shutdown	2020
Ringhals 2	R2	1975	Permanent shutdown	2019
Ringhals 3	R3	1981	Operation	>2040
Ringhals 4	R4	1983	Operation	>2040

As nuclear power plants age, ensuring the ongoing functionality of major components, structures, and buildings becomes paramount, as replacement of these elements is often impractical. Vigilant monitoring and maintenance are

therefore essential to ensure that all safety features continue to operate within their established acceptance criteria.

Concrete plays a critical role in nuclear power plants, constituting the majority of the mass within these facilities. Its passive yet vital functions include acting as a barrier, foundation, or tunnel for safety-related systems. With the increasing age of nuclear reactors worldwide, there is a growing emphasis on understanding the ageing of concrete and its implications for plant safety and performance.

1.4.2 Containment

The containment buildings in both Pressurized Light-Water Moderated and Cooled Reactors (PWR) and Boiling Light-Water Cooled and Moderated Reactors (BWR) are robust, cylinder-shaped concrete structures designed primarily to prevent the release of radioactive materials into the surrounding environment.

Located at the heart of the containment, the reactor pressure vessel is supported by the interior concrete structures, which bear the weight of various components such as pipes and major equipment. Additionally, these structures serve as a biological shield against radiation.

Constructed using slip form techniques, the cylindrical containment buildings feature an airtight steel liner. In Swedish reactors, this liner is typically fully embedded between a thick inner layer of concrete and an even thicker outer layer. The outer layer is prestressed with both horizontal and vertical tendons, enhancing the building's resilience beyond the design base accident threshold. Meanwhile, the inner concrete layer acts as a mechanical shield, protecting the steel liner from potential damage caused by incidents within the containment.

Boiling water reactor

In boiling water reactors, the containment structure is housed within another building known as the reactor building. This arrangement exposes the exterior of the containment to moderate temperatures and dry conditions throughout the year.

The design of Swedish reactors varies among individual units. Decommissioned reactors such as O1, O2, B1, B2, and R1 feature conical upper sections in their containment structures. This design creates a relatively narrow space between the walls and the pressure vessel at the top of the structure. In contrast, newer designs like F1, F2, F3, and O3 have a more cylindrical shape without the narrow conical sections at the top.

Pressurized water reactor

In a pressurized water reactor (PWR), the containment structure typically takes the form of a massive concrete cylinder, standing at approximately 50 meters in height. It features a flat bottom and is securely anchored on bedrock. The upper section is dome-shaped and made of concrete. While much of the exterior surface is exposed to the atmosphere, some parts are situated below ground level or form walls in adjacent buildings. Internally, the concrete surfaces of the containment are

subjected to elevated temperatures ranging from 30 to 60°C in general areas, and locally reaching up to 93°C during operation.

A distinguishing feature of Swedish PWRs (R2, R3, and R4) is that their cylindrical walls are entirely covered by an inner concrete layer, concealing the steel liner throughout. Only in the dome-shaped ceiling is the steel liner visible.

1.4.3 Waterways

At a nuclear power plant, an intricate network of canals and underground tunnels facilitates the transfer of large quantities of cooling water and discharge water generated during various plant processes. Swedish nuclear power plants rely on cleaned seawater, largely devoid of biological content, as the primary heat sink for their operations.

Each Swedish plant consumes approximately 40 cubic meters of seawater per 1000 MW of electrical energy generated. Of the thermal energy produced by the nuclear process, one-third is converted into electrical energy, while the remaining two-thirds is discharged back into the sea as heated water, resulting in a temperature rise of approximately 8 degrees Celsius. Consequently, the environmental conditions in the outlet waterways of these plants resemble those found in other geographical areas rather than being specific to the plant's location.

Typically, each plant features a large intake tunnel for the turbine heat exchanger, followed by a discharge tunnel. In cases where sister plants are located in close proximity, a common discharge tunnel may be utilized. Shotcrete and formwork concrete are commonly employed in the construction of intake tunnels at Swedish plants, sometimes in combination. For discharge tunnels, shotcrete, formwork concrete, and natural rock tunnels are utilized.

Additionally, all plants are equipped with smaller redundant tunnels for auxiliary water intake and discharge, which play a crucial role in safety-related systems. These tunnels are lined with formwork concrete or natural rock. Drainage systems are incorporated into almost all tunnels at Swedish plants, enabling the removal of biological content, facilitating inspections, or allowing for mechanical maintenance of submerged components. However, drainage procedures require careful planning and implementation due to associated safety considerations for both personnel and plant operations.

1.4.4 Other safety related structures

Structural integrity

Concrete structures play a critical role in ensuring the structural integrity of nuclear power plants and their associated systems. These structures must meet stringent requirements, including tolerance for seismic activity and extreme weather events.

In particular, structural bolting and foundations must be designed to withstand all potential forces, such as those from heavy objects and vibrations, to ensure the stability of the plant. Additionally, concrete structures must be able to withstand or

mitigate the effects of potential pipe breaks, which could result in the release of large amounts of steam or water. Overall, the durability and resilience of concrete structures are essential for the safe and reliable operation of nuclear power plants, safeguarding both personnel and the environment from potential hazards.

Confinement and shielding of radioactive material

Not all buildings at a nuclear power plant contain radioactive materials, but those that do often have stringent requirements for leakage tightness, known as the confinement function. This function aims to prevent the spread of radioactive materials into the environment. Thick concrete walls serve as effective radiation shielding and are commonly used as radiological barriers in the nuclear industry, alongside materials like lead and water. Lead is considered more effective than concrete for shielding against radiation, while water is generally less effective. However, concrete remains a key material due to its availability, affordability, and effectiveness in providing radiation protection.

1.4.5 Other non-safety related structures if malfunctioning could have negative impact on safety related systems

Concrete structures, often large and heavy, can pose risks to safety-related equipment even if the structures themselves are not directly related to safety. Malfunctions or failures of these structures could potentially cause harm to safety-related equipment. Examples of such structures include piles, roofs, and chimney stacks. Therefore, ensuring the integrity and stability of concrete structures throughout a nuclear power plant is crucial to overall safety and operational efficiency.

1.4.6 CODES, STANDARDS AND REGULATIONS

During construction, Swedish codes, standards, and regulations were adhered to for design purposes. For instance, 'Statliga betongbestämmelserna B5 – B7' was utilized for the general concrete design in most areas of the plants for normal operation. However, due to the nascent stage of the nuclear industry during the construction of most plants, there was a dearth of Swedish regulations specific to nuclear-related design features. In such cases, relevant American documents, such as the 'American Concrete Institute 349' for prestressed structures, were adopted instead. This ensured that the construction met rigorous safety and quality standards, albeit drawing from international sources where necessary.

2 Assessment of concrete structures

2.1 GENERAL

Concrete structures play a vital role in modern society, serving as the backbone of infrastructure and contributing significantly to social, industrial, and economic well-being. However, these structures are not immune to deterioration over time, facing threats such as corrosion, frost, abrasion, and chemical action.

Decisions regarding the maintenance, repair, strengthening, or replacement of concrete structures are essential throughout their lifespan. To ensure efficiency from societal, client, and cost perspectives, it's crucial to adhere to guiding principles. Figure 2-1 illustrates general principles for the maintenance, repair, and strengthening of concrete structures (ISO 16311-1, 2014).

Figure 2-1 comprises four key parts. Part 1 focuses on general principles related to the structure's performance, encompassing structural safety (load carrying capacity), serviceability, appearance (aesthetics), and the mitigation of hazards such as falling debris due to inadequate maintenance. Figure 2-2 provides a more detailed presentation of the structure's performance over time.

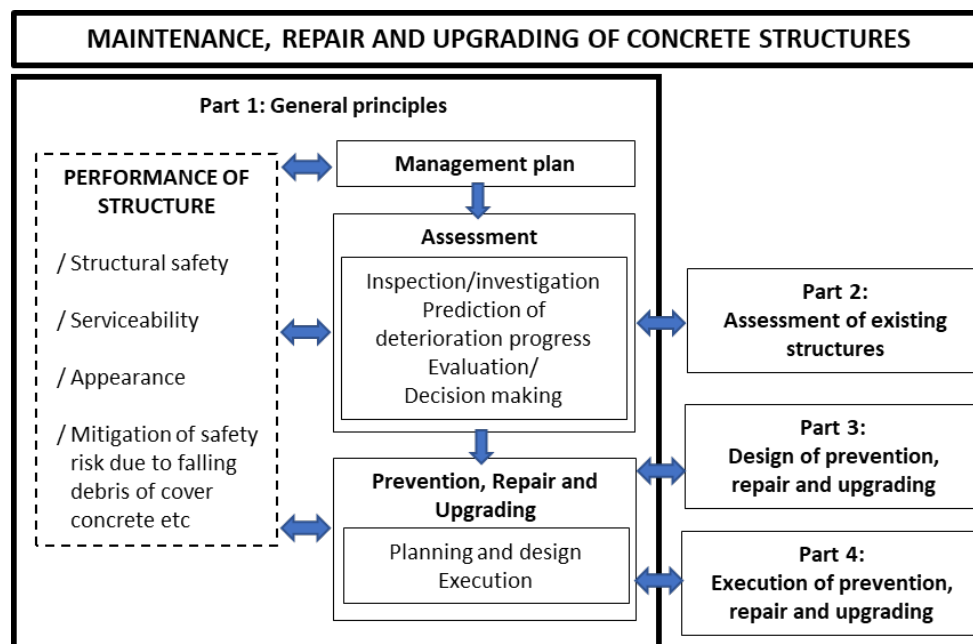


Figure 2-1 General principles for maintenance, repair and upgrading, based on (ISO 16311-1, 2014)

The structure typically has an initial performance level, with safety often dictating the minimum requirement for the structure. In Figure 2-2, it is assumed that an assessment reveals a faster degradation curve than anticipated during the design stage. Consequently, different repair strategies may be considered based on factors such as accessibility, time, or budget constraints.

In scenario A, a minor repair is conducted, either as a short-term fix or at intervals over time, extending the structure's life to its originally planned lifespan. Scenario B involves a major repair, restoring the performance to its original level and

prolonging the structure's lifespan. Finally, scenario C entails enhancing both the performance level and the expected lifespan of the structure.

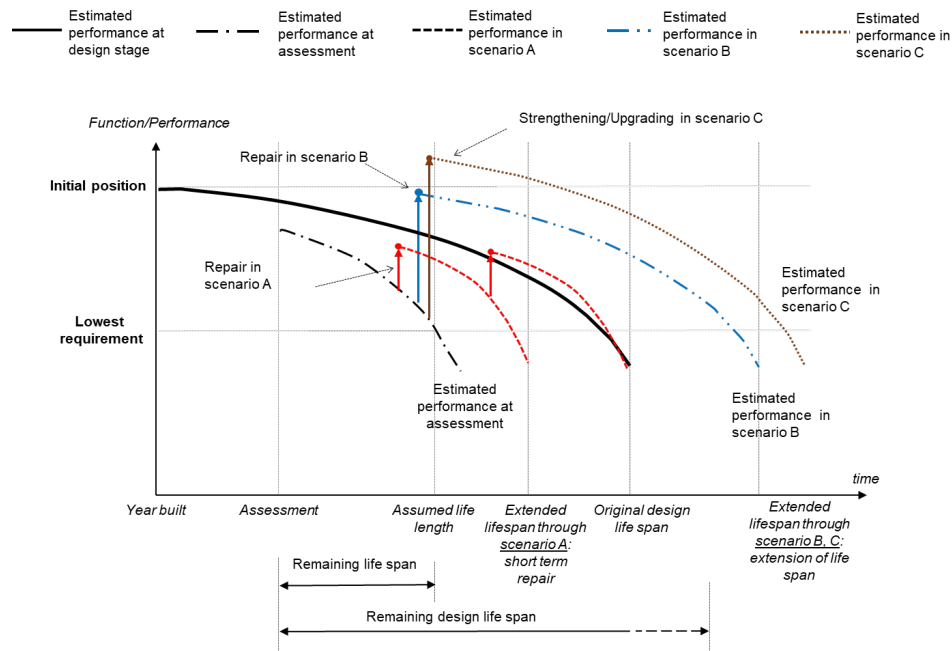


Figure 2-2 Performance of structure, based on (ISO 16311-1, 2014)

Part 2 of Figure 2-1 focuses on the assessment of existing structures, as depicted in Figure 2-3 (ISO 16311-2, 2014). The assessment process involves identifying and defining areas of distress in a concrete structure and verifying its structural performance based on the evaluated condition.

The objectives of the assessment are established in collaboration with the client and should consider factors such as risk, safety, continued function, performance, capacity, and individual client requirements. Scenarios, such as corrosion, mechanical damage, or chemical actions, are identified beforehand and verified or excluded during the assessment. Continuous monitoring of these scenarios is essential to address critical situations for the structure's integrity and performance, unforeseen issues that arise during the assessment, and the client's specific performance requirements.

The preliminary assessment aims to provide information on the structure's condition, identify the causes and consequences of degradation, establish a foundation for overall condition assessment, anticipate future safety and performance issues, and propose immediate measures if necessary.

The detailed assessment builds upon the preliminary assessment by conducting a more comprehensive study, including non-destructive testing, material testing, extensive structural analysis, and verification of load effects and carrying capacity. The results are reported, and decisions regarding future measures are made based on the findings.

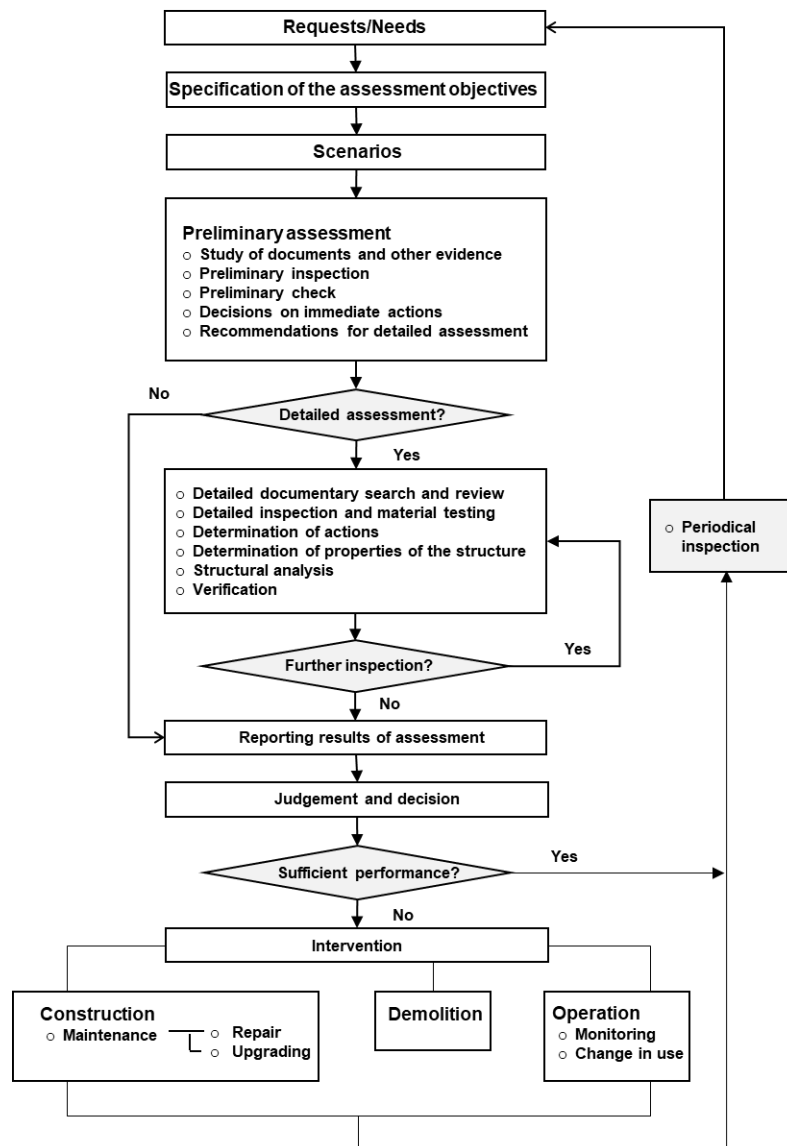


Figure 2-3 General flowchart for assessment of existing structures, based on (ISO 16311-2, 2014, ISO 13822)

In general, assessment methods can be categorized into inspection and monitoring, as illustrated in Figure 2-4. Inspection encompasses visual examination, non-destructive testing (NDT) utilizing suitable systems and methods for the specific concrete structure, and sometimes semi-destructive or even destructive testing, depending on the depth of investigation required.

Action monitoring involves observing a structure's response over time and space to known loads or studying the loads themselves. In contrast, performance monitoring evaluates whether a structural component meets performance requirements under known or any loads (Honfi et al., 2018). Stress monitoring, often utilized directly in structural assessments without intermediate interpretation using a structural model, is part of Structural Health Monitoring (SHM) systems. These systems aim to monitor a structure's in-situ behavior accurately and efficiently over time, assess its performance under various service

loads, detect damage or deterioration, and determine the structure's health or condition.

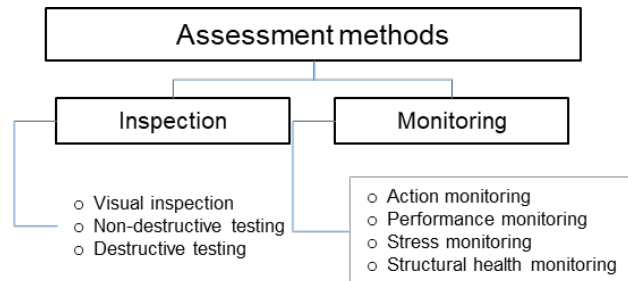


Figure 2-4 General classification of assessment methods, based on (Honfi et al., 2018)

Judgment and decision-making should be informed by all available information gathered from existing documentation, inspections, tests, and structural analysis. The condition of the structure is evaluated and classified based on its condition level and the corresponding consequence level. It is essential to determine the probability of consequences, and the conclusion drawn from this evaluation provides an estimate of the associated risk resulting from damage or degradation, as depicted in Figure 2-5. To assess the performance of the structure and potential consequences, five performance levels and five consequence levels are recommended (ISO 16311-2, 2014). The various performance levels are detailed in Table 2-1.

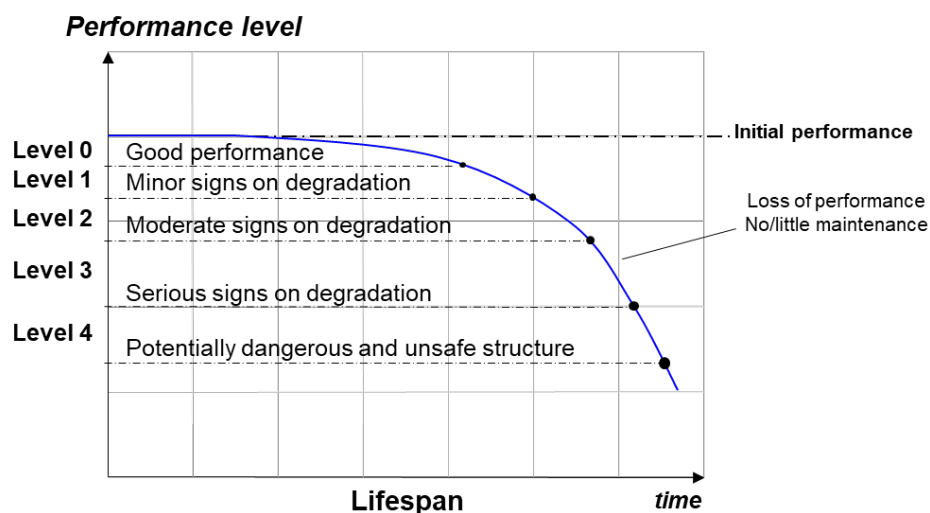


Figure 2-5 Principal illustration of the condition levels, depending on time, based on (ISO 16311-2, 2014)

To uniformly classify the consequences of the observed condition for a structure or structural component, the concept of consequence levels is introduced. These levels express the seriousness of the consequences of an object relative to a defined reference level. The following types of consequences may be evaluated:

- **Safety:** This includes considerations such as fire safety, traffic safety, load-carrying capacity, risk to individuals, and the potential for falling parts.
- **Cost:** This encompasses factors such as investments required for repairs or upgrades, labor costs, accessibility issues, ongoing maintenance costs, etc.
- **Aesthetics:** This involves aspects related to the appearance of the structure, including color, surface texture, presence of cracks, discoloration, etc.

- **Health and Environment:** This category covers considerations such as noise levels, vibrations, pollution, dust generation, and their potential impact on human health and the surrounding environment.

Table 2-1 Performance levels related to Figure 2-5, based on (ISO 16311-2, 2014)

Performance level	Explanation
Level 0 - No signs of degradation	No visual signs on degradation. But, a larger part of the initiation phase, e.g. depending on carbonation or chloride intrusion, have already begun.
Level 1 - Minor signs of degradation	Minor visual signs on degradation. This level only gives the condition at the time for inspection and says nothing about the rate of degradation
Level 2 – Moderate sign of degradation	Moderate visual signs on degradation. This level provides only the condition at the time for inspection and says nothing about the rate of degradation.
Level 3 – Serious signs of degradation	Visible signs on serious degradation. Falling parts can be dangerous, but the loss of service or safety for the structure is minimal
Level 4 – Potential dangerous and unsafe	Clear signs on degradation, the consequences significantly reduce the safety. Immediate action needs to be taken

It is suggested that the following consequence levels are introduced, see Table 2-2.

Table 2-2 Consequence levels, based on (ISO 16311-2, 2014)

Consequence level	Explanation
Level 0 - No consequences	Performed evaluation shows that there are no consequences.
Level 1 – Small consequences	The evaluation shows that the consequences are small
Level 2 – Medium consequences	The evaluation of the situation shows that the consequences are moderate
Level 3 – Large consequences	The evaluation of the situation shows that large consequences are found
Level 4 – Hazardous consequences	The evaluation shows that the structure is unsafe and that the consequences are potentially dangerous.

If the performance or consequences of a structure are deemed unacceptable, interventions such as maintenance, repair, or upgrading may be necessary. In some cases, monitoring to track and manage the degradation process or actual loads may be recommended. In extreme scenarios, the structure may need to be demolished and replaced. The appropriate intervention depends on the underlying cause of the defect or deterioration process.

For prestressed concrete structures, defects are not always visible, especially for tendons enclosed in ducts filled with cement grout. Therefore, a comprehensive desk study and planning are crucial. It is often impractical and uneconomical to expose all hidden components for inspection, and various factors must be weighed before initiating any investigation. Important considerations include:

- Is the component critical to the safety of the structure?
- What are the consequences of the component's failure?

- Can the component be safely exposed?
- Will exposing the component cause damage to the structure or the component itself?
- Will exposing the component lead to long-term durability issues?
- Is it economically feasible to expose the component?
- What impact would the investigation have on the operation of the structure?

Additionally, the owner of the structure may have specific constraints that need to be considered during assessment. Investigations into hidden defects can be conducted either as special investigations or incorporated into the regular inspection regime. Special investigations should be prioritized where the risk of failure of a hidden component with significant consequences is high before the next scheduled inspection. If it's not feasible to inspect all hidden components within the required cycle, those posing the greatest risk should be given priority.

Determining the suitability of different remedies and methods for a particular condition requires a thorough evaluation of the component or structure. This evaluation should consider maintenance, repair, and upgrading design principles, including:

- a) Ensuring that interventions do not harm the structure or its members.
- b) Adopting proven techniques and products with a documented track record of success in similar projects.
- c) Aligning prevention, maintenance, repair, and upgrading strategies with budgets and planning constraints.

Finally, the execution of interventions should adhere to established routines and codes and standards for the chosen methods, as outlined in ISO-16311-4 (2014).

2.2 INSPECTIONS

2.2.1 Preliminary assessment

Design and inspection documents, such as original designs, drawings, project specifications, structural calculations, as-built documentation, previous assessments, and interventions, are crucial sources of information for evaluating the condition of existing structures. However, for many structures, locating and verifying such information can be challenging. Both structural requirements (such as service loads, dead loads, overloads, wind, snow, etc.) and environmental conditions (including chlorides, gases, temperature, etc.) should be documented, along with any changes that may have occurred over time. Any deviations in the use of the structure from its original design assumptions should also be documented, if possible (ISO-16311-2, 2014).

A preliminary assessment primarily involves visual inspection of the structure, potentially supplemented by field measurements and laboratory testing (such as carbonation depth of concrete cover, chloride content, etc.). The objectives of a preliminary assessment may include the following (ISO-16311-2, 2014):

- Providing a general evaluation of the condition of a structural part, a structure, or multiple structures.
- Determining whether previously identified areas of visual deterioration have worsened.
- Documenting the initial progression of deterioration.
- Identifying the consequences associated with the presence of defects.
- Developing plans for a detailed assessment, if necessary.
- Evaluating the need for preventive actions.

Since a preliminary assessment primarily relies on visual inspection, extensive equipment such as scaffolding or lifts is typically unnecessary. Inspections can be conducted from the ground, boats, or accessible locations on the structure, such as roofs or balconies, using tools like binoculars or cameras with zoom lenses.

A standard framework outlining the inspection items and the expected information in the preliminary assessment is presented in Table 2-3.

Table 2-3 Items of inspection for preliminary assessment, (ISO-16311-2, 2014).

Performance	Items of assessment	
	Document review	Visual inspection
Safety and serviceability	<u>Characters at completion and records</u> • dimensions, shapes • reinforcement • materials strength (concrete, steel) • quality control records <u>Actions</u> • design loads • working (service) loads	• Deterioration and deformation • cracking • deflection, settlement, inclination • spalling
Durability	<u>Characters at completion and records</u> • cover thickness • concrete strength • materials and mix proportions of concrete • years after completion <u>Actions</u> • temperature, humidity, distance from coastline and the like • wetting condition such as rainfall	<u>Deterioration and deformation</u> • cracking • spalling • rust stain • color change • substance extruded

Information obtained from the construction and operation phases of a structure is invaluable for understanding its design, operational characteristics, identifying critical or exposed structural components, facilitating registration and testing, and minimizing the scope of further assessments. Although documentation from these

phases is often incomplete, efforts should be made to gather as much relevant data as possible. Even limited information can prove to be highly beneficial in practice.

If the preliminary assessment uncovers situations that warrant further scrutiny, especially those related to safety or potential hazards, the assessment report should include recommendations for conducting a detailed assessment. This detailed assessment would delve deeper into the identified issues to provide a more comprehensive understanding of the structure's condition and any necessary actions to address concerns.

2.2.2 Detailed assessment

A detailed assessment involves a comprehensive examination of the structure, including thorough visual inspections and extensive measurements conducted both on-site and in laboratory settings using samples obtained from the structure, (ISO-16311-2, 2014). The objectives of a detailed assessment may include:

- Surveying the extent of damage observed.
- Identifying the root cause(s) of the observed defects.
- Assessing the potential for worsening damage if left untreated.
- Evaluating suitable repair and maintenance methods and principles.
- Providing essential information for designing repair work, including recommendations for repairs.
- Offering insights for planning ongoing maintenance activities.

The detailed investigation typically entails close examination of concrete surfaces to register visual defects, symptoms, and the extent of damage. Access to the structure may require the use of scaffolding, lifts, ladders, boats, rafts, or other specialized equipment. Additionally, inspections may extend to submerged areas or previously inaccessible sections of the structure, if necessary.

A detailed assessment is guided by a structured approach, aligning the items of investigation with the expected information outcomes, as outlined in Table 2-4. This ensures that all relevant aspects of the structure are thoroughly evaluated, providing a comprehensive understanding of its condition, and informing subsequent decision-making processes regarding maintenance and repairs.

Table 2-4 Items of investigation for detailed assessment. (ISO-16311-2, 2014).

Performance	Items of assessment		
	Document review	Visual inspection	Test and measurement
Safety and serviceability	<u>Characters at completion and records</u> • structural calculation methods • correctness of structural calculation • other information unchecked in preliminary inspection <u>Actions</u> • records on topography • subsoil conditions • ground water level • other information unchecked in preliminary inspection	<u>Deterioration and deformation</u> • cracking (pattern, width, depth) • spalling (area, depth)	<u>Characters at present</u> • dimensions, shapes • reinforcement • concrete strength and modulus of elasticity • stiffness of structure (loading test) <u>Deterioration, degradation and deformations</u> • deflection, settlement, and inclination <u>Actions</u> • working load
Durability	<u>Characters at completion and records</u> • quality control records • inspection records • maintenance records • other information unchecked in preliminary inspection <u>Actions</u> • records on topography • subsoil conditions • winds • seawater splash • other information unchecked in preliminary inspection	<u>Deterioration and deformation</u> • cracking (pattern, width, depth) • spalling (area, depth) • rust stain (area) • color change (area) • substance extruded (thickness, hardness)	<u>Characters at present</u> • cover thickness • concrete strength • materials and mix proportion of concrete <u>Deterioration, degradation and deformations</u> • carbonation depth • Cl⁻ content <u>Actions</u> • temperature, humidity • CO₂ concentration • transported Cl⁻ • precipitation

It is crucial to emphasize that the scope of the investigation should be proportionate to the size, significance, and risk associated with the structure, as well as its estimated remaining service life.

2.3 ASSESSMENT OF NUCLEAR POWER STATIONS

Nuclear power stations worldwide conduct a wide range of assessments, with increasing emphasis on ageing management as plants grow older. While different sites employ varying methods for ageing management, the underlying principles are often similar and are typically based on interpretations of approaches outlined in documents such as the IAEA Specific Safety Guide 48 (Figure 2-6). This guide serves as a foundational reference for developing strategies to address ageing-

related concerns and ensure continued safe and efficient operation of nuclear power plants.

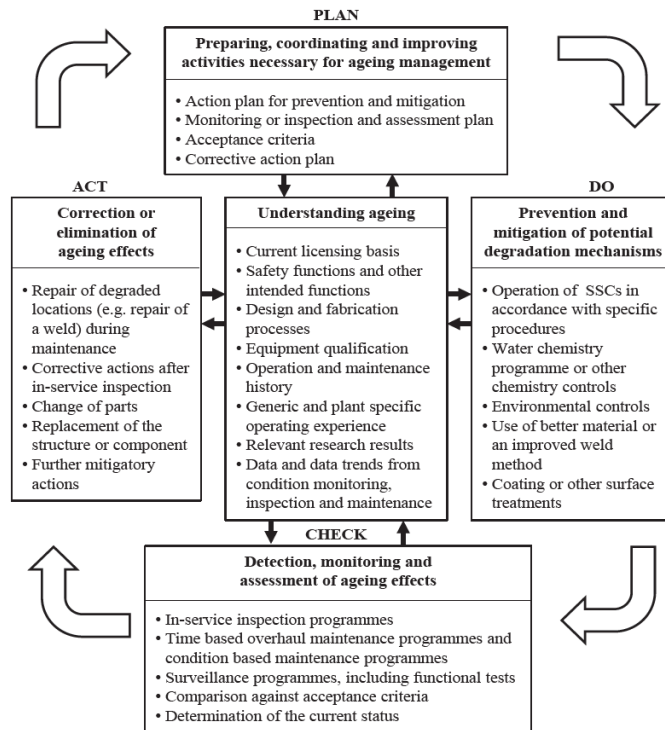


Figure 2-6 Systematic approach to ageing management in nuclear power plants (IAEA Specific Safety Guide 48 - Google Search, n.d.).

In the area of buildings and structures at nuclear power plants, an Ageing Management Program (AMP) typically consolidates information regarding design specifications, materials used, degradation mechanisms, historical data, and plans for future maintenance and upgrades. Additionally, the AMP outlines a periodic inspection schedule and establishes acceptance criteria to ensure that the structures remain safe and reliable over time. This comprehensive program is essential for effectively managing the ageing process of critical infrastructure within nuclear facilities.

2.3.1 Inspection requirements and particularities of nuclear power plants

The Swedish regulations regarding ageing management of structures and buildings are found in 3§ 3rd chapter of SSMFS 2008:1:

“Underhåll, fortlöpande tillsyn och kontroll

3 § Byggnadsdelar, system, komponenter och anordningar av betydelse för säkerheten vid en anläggning ska fortlöpande kontrolleras och underhållas på ett sådant sätt att de uppfyller de säkerhetskrav som ställs. För detta ska det finnas program för underhåll, fortlöpande tillsyn och kontroll samt hantering av åldersrelaterade försämringar och skador. Programmen ska genomföras med metoder som är validerade för sina ändamål. Mät- och provningsutrustning ska hållas kalibrerad i enlighet med fastställda instruktioner. Programmen ska vara dokumenterade samt ses över och uppdateras mot bakgrund av vunna erfarenheter och utvecklingen inom vetenskap och teknik.”

The paragraph states that structures, systems, and components with relevance to safety of the power plant must regularly be monitored and maintained in such a way that the safety requirements are fulfilled. To achieve this there shall be a program for maintenance and testing as well as known corrective actions for age-related degradation and other defects. Programs shall be carried out by methods validated for their purpose. Testing equipment shall be calibrated in accordance with established instructions. The programs must be documented and reviewed with relevant experiences and new knowledge from scientific and technological developments.

In practice monitoring of concrete structures is usually carried out using the conventional method of visual inspections by plant staff. If a defect of potential significance is found further investigation is initiated using primarily non-destructive methods such as hammer sounding tests and detailed measuring. To learn more about the condition of concrete destructive testing is also used regularly, both in case of learning more about discovered defects as well as a proactive act on a structure of interest. (Available at www.stralsakerhetsmyndigheten.se, Report Number: 2018:10 ISSN: 2000-0456)

The frequency for the periodical inspections is not stated in the Swedish regulations, but industry praxis states that the interval should be based on the structure's importance to safety together with its current condition or historical record. A maximum interval of 5 years is considered satisfactory according to IGALL experience (Tanaka, 2014).

2.4 BEST PRACTICE FROM SWEDEN

Interviews with experienced plant workers were carried out to learn what methods are used to access remote concrete structures so that an inspection of a satisfactory level can be carried out.

2.4.1 Forsmark

Marcus Edin Forsmark Kraft Aktiebolag (FKA)

Containment

Most exterior concrete surfaces of the containment are quite easily available from the surrounding rooms in the reactor building. For the interior parts, especially Forsmark 2 has a design that makes visual inspections at close range hard in the uppermost parts of the building. The use of 'enablers' such as unmanned aerial vehicles to get a more detailed inspection has been discussed but not tried.

Reactor building

The concrete in all rooms is in practice accessible for ordinary inspections using conventional methods. Due to high radiation from radioactive filters in a few rooms the use of robots or shafts equipped with cameras could be a method for reduction of radiation exposure to personnel.

Waterways

It is possible to drain all inlet and outlet tunnels at the three Forsmark reactors. To maximize the safety margins all inlets to F3 are not usually drained. Since the system is in standby for operation even during outages there is a risk for sudden increase of water velocity which makes the use of ROV (remotely operated [underwater] vehicle) or professional divers an unsuitable approach.

F1 and F2 feature a shared discharge tunnel and since the scheduled plan for annual outages does not usually overlap there's therefore always at least a waterflow of 40 m³/s. On unplanned events both reactors have been stopped at the same time historically and the opportunity has then been used for ROV inspections. The tunnel is a rock tunnel and therefore out of the scope for this report in the concrete program although the experience of using ROV is worth mentioning.

Rooftops

Ladders are mounted to the buildings allowing access for inspectors to reach all rooftops for inspections of concrete, roofing felts, roof drainage and other components. There have been discussions about using drones for roof inspections, but since there is no need for scaffolding at FKA site, the staff sees no economical or informational winnings of using robots instead of manual work from a person.

Stack

All three Forsmark reactors are equipped with tall concrete stacks. Historically the exteriors have been inspected manually by climbing their attached ladders. Their interiors have never been monitored. The stacks are subject to ageing analyses and the use of for example drones have been discussed.

Turbine building

The turbine building of BWR's, such as Forsmark, are a radiological area. The turbine is of course of crucial importance for energy generation but is also an area with many safeties related components.

Major structures are available for inspection, but for example concrete anchors are sometimes located at high levels and therefore hard to get good views of. The use of drones has been discussed for this purpose but not yet tested.

2.4.2 Ringhals

Interview with Krister Skoglund Maintenance Engineer at Ringhals Aktiebolag (RAB).

General

Since the result from the Swedish referendum regarding nuclear power meant that a stop date for all nuclear power plants were expected early in the 21st century not much focus on Ringhals were historically put on the aspects of age-related degradation of concrete in the long term. When the discussions changed to

prolonged commissioning of the plants, large projects were initiated for repairing and preventing concrete degradation at the site.

Containment

Exterior parts

PWR containments are huge structures with major parts not accessible at normal conditions. The top of the containment, the 'dome', features a 'railway' where a lifting device that is a RAB property can be mounted. The lifting device gives access to the whole exterior concrete surfaces above ground or surrounding building's roof levels. The mounting of such a device is an expensive and time-consuming activity and is not done only for inspections of concrete. The use of the lift is mainly for periodic testing of tendons which nowadays is carried out every 10 years for each individual plant in commissioning mode (R3 and R4). At those occasions a careful visual inspection is usually performed, the opportunity has also been used for doing non-destructive as well as destructive tests.

The outside of the containment needs to be inspected more regularly than 10 years so instead a cheaper (still not cheap) way has been to rent a mobile crane and through a lift basket inspecting the concrete at close range. Spotting scopes on tripods and spot-checks on the containment wall from the stairway to the dome has also been tried but these methods are not on par with a close-range inspection.

The use of drones has historically been prohibited by a general flying embargo at Ringhals site. The adaptations to a more digital age have made this change quite recently and it is now possible to get allowance for necessary drone usage at site. But this has yet to be tried outside for the purpose of monitoring concrete.

Other exterior parts of the containment are located in both a better and at a somewhat worse place. The parts that make up walls of surrounding buildings are located in a dry and stable environment, few to none defects of concrete have been found in these sites, but the large surfaces located in high elevation sometimes makes it difficult to reach the structure to perform for example sounding tests with hammer.

The lowest of the exterior parts of the containment are found in the excavated bedrock part of the plant. Here the moisture and presence of chlorides makes it an important area for concrete monitoring. Poor light and big distances make the visual inspections a bit difficult and new methods could perhaps help make it more detailed.

Interior parts

The interior part of the containment is only accessible for inspections during the annual outages. The concrete on the inner wall is not of the same level of interest regarding safety or degradation as the exterior one since it is the exterior wall that contains the tendons and is exposed to a harsher environment.

The interior ceiling is the only one in R3 and R4 where the leakage tight steel liner is visible. That part is of great interest regarding safety but out of the scope for this report. One area of interest that is within the scope of the report is where the embedded steel liner comes out from the inner wall. This part of the plant is in the inspections program and has regularly been inspected using scaffolding together

with a long stick with a camera at the end. Since 2019 drones have instead been used for these inspections and the new technology saves a lot of time even though the resolution with the current camera is not on par with the former method.

The concrete that sits closest to the reactor pressure vessel is hidden behind a liner and has not been inspected since built. It is a very massive structure, and the outer parts of this structure are accessible for inspections using conventional methods.

The bottom floor of the containment is accessible even though some particular rooms have high radiation. The bottom itself contains the embedded steel liner which at the now decommissioned R2 have caused big issues historically. The design of the bottom at R3 and R4 has a better design and can be satisfactory inspected using conventional methods.

Waterways

The by Swedish conditions relatively chloride rich seawater at the Ringhals site on the Swedish Westcoast creates a rather harsh environment for the reinforcement in the concrete as well as for other steel structures along the waterways.

Intake tunnels

The major intake tunnels are drained and cleaned for biological content each outage. During this period of a few days the whole tunnel is accessible for inspections. The ceiling of these tunnels is situated quite high above ground (approximately 6 – 7 meters) and is therefore hard to reach. Tall shafts have been tried to check for imperfections in the adhesion of shotcrete. There have also been discussions about a “midlife” check at closer range on the whole ceiling using a small mobile crane. To transport such a crane down to the tunnels has proved to be hard and alternative solutions are discussed.

The smaller intake tunnels are typically drained every two years and are then checked carefully using visual and sounding methods. The smaller tunnels are easier to access a bigger proportion of the surfaces and the methods used today are considered adequate.

Discharge

The tunnels leading from the plant are not drained regularly. It is only the part of the tunnels located directly after the turbine heat exchanger of R3 and R4 that have been drained and conventionally inspected recently.

For the other discharge tunnels (9 in total) there is a requirement for regular inspections. This is generally possible for all tunnels except the main discharge tunnel since it is served by water from both R3 and R4. The outage schedule is designed so that only one of the two plants is supposed to have an outage at each time. To perform these inspections different types of ROVs have been used with satisfying results. The ROV's have been equipped with a sonar (2D radar) and an ordinary camera. The inspections are rather costly but since professional divers are not allowed to go deep into tunnels this is the only known way of performing the inspections without draining the systems.

An interesting general experience is that concrete at different sites along the discharge at Ringhals significantly show a higher degree of degradation than the intake. More turbulence, higher oxygen content, higher temperatures, additionally added chlorines have been discussed as potential causes.

Chimney stack

The tall concrete stack of R1 is the highest elevated point of all structures at Ringhals site (113m above sea level). The plant is now in decommissioning mode and the monitoring of concrete is not on the same level as it was during operation.

However historically the stack has been in focus for detailed inspections and some minor repairs of local defects during the years 2006 – 2010. The first inspections were carried out at the base of the stack as well as at different points along the attached ladder to its top. For the more detailed inspections both professional climbers and mobile cranes were used.

A new condition assessment was performed during 2015 using professional climbers which stated that the stack was in good condition. Because of the condition, and the fact that only a short time remained of commissioning, later inspections have used cost-effectively remote inspections using a digital camera attached to a spotting scope and tripod. Pictures could thereafter be compared, and the potential rate of degradation evaluated.

2.4.3 Oskarshamn

Interview with Ulrik Brandin Oskarshamns Kraftgrupp (OKG).

Containment

All relevant parts for inspections at O3 have been inspected using conventional methods. No remote parts of interest are identified. The biological concrete shield surrounding the reactor pressure vessel is steel lined and not accessible.

Reactor building

All concrete areas of interest for inspection are available for visual inspections. At areas with high radiation the use of 360-degree cameras has been tested with good results.

Waterways

The O3 reactor is the only plant in operation at the site and it has its own waterways which therefore are fully available for inspections during outages.

2.5 BEST PRACTICE FROM NORTH AMERICA

A big share of the world's nuclear power plants is found in the North American continent. Like the situation in Western Europe many of the American plants were also commissioned during the second half of the 20th century. This means that they are also likely to experience symptoms of concrete degradation soon or already. During conferences regarding structural component issues in nuclear much focus

is on topics like containment leakage tightness, integrity of spent fuel pools, tendon monitoring and integrity during seismic events.

EPRI experience indicates that most of the monitoring carried out at American plants are using very basic conventional methods such as visual inspections by naked eye. While at least some sites are mentioning using non-destructive testing with acoustic methods such as hammering test and chain dragging.

2.5.1 Crystal River Unit 3

An EPRI innovative project was carried out at hydro and nuclear power plants at the Crystal River, US in the years of 2012 - 20213. The project tried to find out a technical solution of how to access and perform concrete monitoring on huge vertical structures such as cooling towers, hydroelectric dams, and nuclear containment buildings.

After careful consideration, an airborne vehicle of helicopter type and a concrete crawler using vacuum were selected as the two most promising methods for inspections. Subsequent testing revealed that the concrete crawler yielded the best results in terms of accessibility and carrying capacity. Further research was conducted to develop a positioning system and identify suitable tools to equip the crawler with (EPRI Journal Staff and Contributors, 2013).

3 Existing methods for concrete structures inspection

3.1 GENERAL

Detecting signs of distress through regular inspections is important for ensuring the integrity of critical infrastructure like nuclear facilities. However, the immense size of these structures presents a significant challenge for inspectors. This challenge is not unique to nuclear power plants but is also faced by other large concrete structures such as bridges, dams, or cooling towers. Inspecting such vast areas manually would be extremely time-consuming and potentially unsafe. Therefore, one solution would be development of new inspection techniques that minimize disruption, enhance efficiency, and improve the reliability of the collected data.

This chapter explores and discusses various techniques used to find surface defects on reinforced concrete structures. Concrete assessment process usually starts with defect detection, using methods that can be classified as close-contact and remote inspection. Thus, this report briefly explores close-contact methods, specifically NDT, and then focuses on remote inspection, which is the main topic of this report. The cutting-edge technology solutions for remote inspections will be explored, which can be practical for accessing difficult-to-reach areas in big-scale concrete structures. Case studies will also be included to demonstrate the performance, accuracy, and resolution of these techniques.

3.2 CLOSE-CONTACT INSPECTION

3.2.1 Non-destructive testing (NDT)

Reinforced and prestressed concrete structures often incorporate essential components within the concrete, making direct inspection challenging. Elements like reinforcement bars or internal post-tensioning elements are not easily visible to the naked eye. Detecting potential issues thus relies on external indicators, which may prompt intrusive investigations at significant expense and disruption.

Unlike visible signs of deterioration in reinforcement, such as rust stains or spalling, anomalies associated with prestressing tendons may not be visually apparent. Internal inspections present inherent difficulties and risks of damage, underscoring the critical need for suitable Non-Destructive Testing (NDT) methods.

Non-destructive testing (NDT) plays a vital role in ensuring the structural integrity of nuclear power plant containments, especially those with thick concrete structures and liners cast in concrete, like Nordic designs (Kristensen, 2016). During the last decades, there has been a notable surge in the application of non-destructive testing (NDT) (Dwivedi et al., 2018). NDT techniques enable the detection of various structural aspects, including:

- Position of reinforcement, and cable ducts and tendons
- Geometry of a structure
- Voids and honeycombing
- Voids in cable ducts
- Thickness of concrete structures
- Concrete cover
- Concrete delamination in decks, walls, or overlays
- Crack widths and depths of cracks
- Concrete compressive strength and modulus of elasticity
- Corrosion and corrosion rate in reinforcement

While few NDT methods function without direct contact, many require direct contact with the concrete surface. To maximize the effectiveness of NDT inspections, a combination of different techniques is recommended. NDT inspections can complement both preliminary and detailed inspections and should be an integral part of the overall assessment process. Numerous methods and equipment are available for NDT inspections, broadly classified into four categories:

- Mechanical methods
- Electromagnetic methods
- Electrochemical methods
- Optical methods

The suggested classification, along with some useful methods, their applicability, advantages, and limitations, is summarized in Table 3-1.

Table 3-1 Possible areas for NDT inspection

Classification	Method	Applicability	Advantages	Limitations
Mechanical	Rebound hammer	Concrete strength	Simple to use	Limited to surface assessment
	Ultrasound	Crack depth, thickness, honeycombs, voids, detection of reinforcement, concrete quality, modulus of elasticity	Provides detailed internal information	Requires skilled operator; limited penetration depth
	Impact-Echo	Voids, honeycombs	Non-destructive; suitable for large areas	Limited to relatively shallow depths; surface preparation required
Electromagnetic	Radar	Placement of reinforcement, delamination, detection of ducts	Penetrates concrete; provides depth information	Limited resolution and accuracy in complex structures
	Thermography	Delamination, water infiltration, heat loss	Rapid assessment of large areas; detects subsurface anomalies	Affected by surface conditions and environmental factors
	Cover meter	Concrete cover, sometimes reinforcement diameter	Direct measurement of cover thickness	Limited to cover depth measurement; requires access to rebar
Electrochemical	Potential measurements	Corrosion potential	Identifies areas at risk of corrosion	Limited to surface assessment; requires reference electrode placement
Optical	Photometric measurement	Geometric measurements, deformations, strains, cracks and crack development	Provides detailed geometric data; non-contact measurement	Limited to visible surfaces; affected by lighting conditions
	3D laser scanning	Geometric measurement, create 3D images	High precision and accuracy; captures detailed surface information; useful for as-built documentation	Expensive equipment; requires skilled operator; limited to surface assessment and line of sight

The EU-project CONMOD (2002-2005) extensively investigated various NDT methods for NPP concrete structure inspection, with subsequent reviews tracking method advancements since 2005. For further details, refer to (Kristensen, 2016) for a follow-up on the CONMOD project, specifically focusing on non-destructive testing methods applied to concrete structures in nuclear applications. Objectives included evaluating selected NDT techniques' capability and performance in thick, structure-like containment and obtaining information on typical structure characteristics.

The project report (Kristensen, 2016) covers numerous field NDT methods, including Ground Penetrating Radar (GPR), High Energy Computed Radiography (HECR), Impact Echo (IE), Multichannel Analysis of Surface Waves (MASW), Spectral Analysis of Surface Waves (SASW), Drilled Cores (CORES), Ultrasonic Pulse Echo (UPE), UK 1401 for ultrasonic measurements, PUNDIT for near-surface ultrasonic measurements, and Relative Humidity (RH) measurements in boreholes on-site. However, as the report primarily focuses on image-based remote inspection, applications of GPR and HECR, which yield results transferable as optical data, are discussed along with their obtained results.

Application of Ground Penetration Radar (GPR)

The CONMOD project utilized ground-penetrating radar (GPR) with 800 and 1000 MHz antennas from Malå GeoScience for near-surface surveying in concrete structures. GPR emits high-frequency electromagnetic pulses into concrete, detecting variations in material conductivity. It's most effective on dry, compacted concrete with small aggregates. GPR detects reflections from embedded metals, making it suitable for locating reinforcement and cable ducts, Figure 3-1.

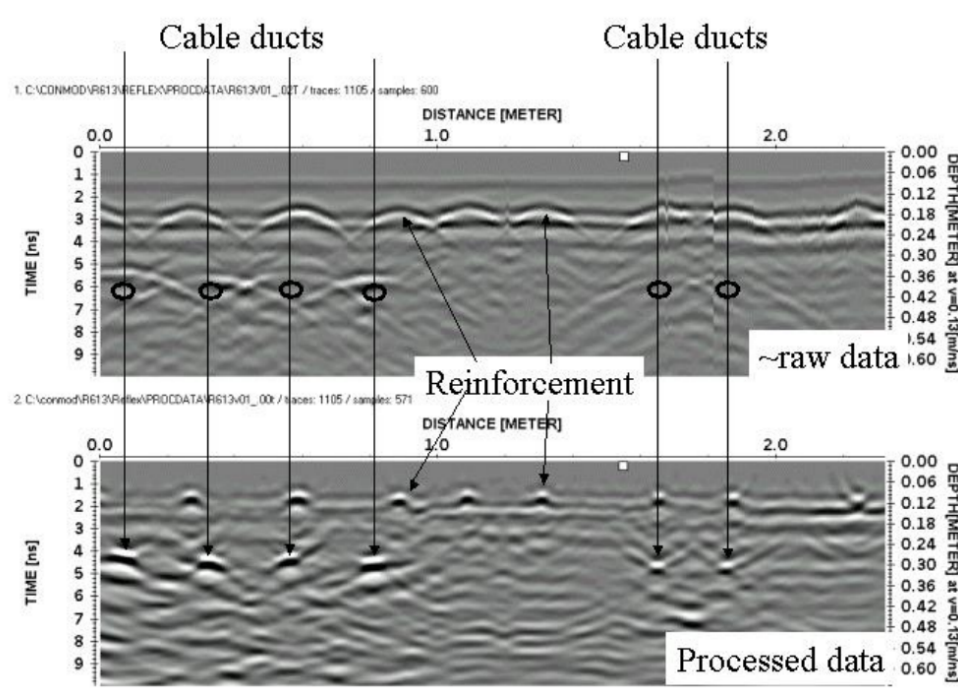


Figure 3-1 Radar scan from the CONMOD report showing reflections from both reinforcement and cable ducts. At the top the raw data are shown, and below processed data (Kristensen, 2016).

During CONMOD, GPR successfully detected reinforcement and cable ducts, measuring spacing and depth and identifying reinforcement laps. It discerned individual bars with 50 mm spacing and detected up to three layers of rebars/cable ducts at depths of 250-350 mm. GPR also identified voids and steel plates embedded in concrete, offering promising results for detecting structural elements. However, interference from reinforcement affects results. Despite limitations, GPR presents good potential for non-destructive testing, particularly for nuclear applications.

Application of High Energy Computed Radiography (HECR)

High Energy Computed Radiography (HECR) was employed in the CONMOD project using a 7.5 MeV Betatron X-ray accelerator from JME Ltd, along with digital image plates and a computed radiography system from Agfa Strukturix. The Betatron, a portable electron accelerator, emitted pulsed radiation with a peak energy of 5 Rads/hour at 1 meter in air, allowing investigation of concrete up to 1500 mm thick. It produced high-resolution digitized images using image plates placed on the opposite side, which were scanned by a laser beam and processed for analysis. HECR offered superior dynamic range compared to film and allowed for various image processing techniques.

During CONMOD, the Betatron detected reinforcement, cable ducts, and voids in grout. Trials on mock-ups demonstrated the detection of voids in cable ducts and small voids in concrete. Tests also assessed the capability to detect holes in embedded steel liners, yielding mixed results depending on structure thickness. Optimal results were obtained when image plates were positioned closest to the object under investigation.

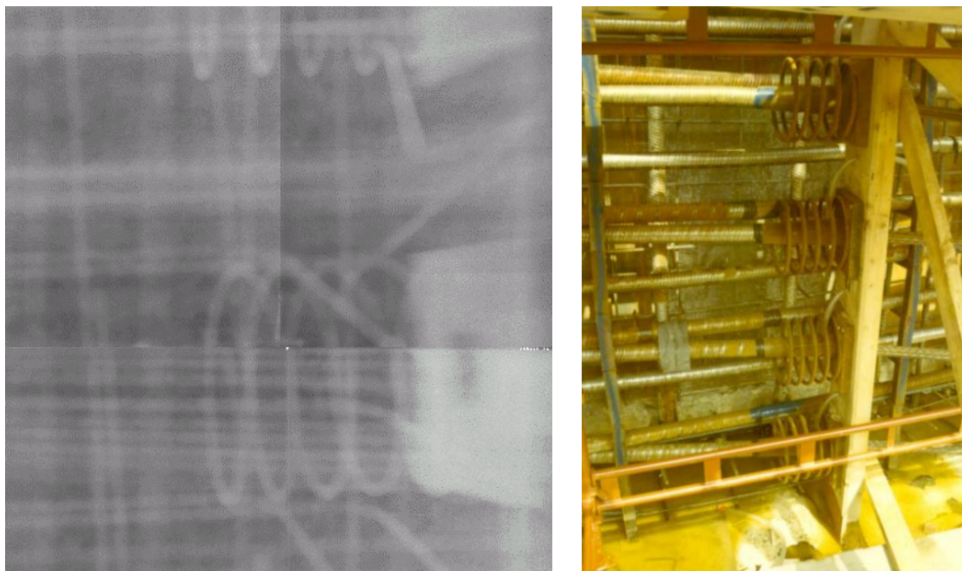


Figure 3-2 Example of X-ray picture from the CONMOD report. The X-ray picture is of the pilaster where the tensioned cables are anchored. The wall is 1300 mm thick, and still it is possible to distinguish single threads in the cables. To the right, a picture from the construction phase is shown, for comparison with the X-ray picture, (Kristensen, 2016).

In a separate investigation at Barsebäck 2, HECR was used to inspect the containment wall for voids potentially causing leakage from the condensation

pool. While no immediate defects were found, HECR proved valuable for structural examination.

There is also another study by (Surin et al., 2021) to compare different NDT techniques. He claimed that Ultrasound, as mechanical technique, and Radiographic, as electromagnetic technique, are the most common two methods used in investigation steam generators. The advantage of radiography is that it provides a permanent visual record of the pattern of the degradation. The main disadvantage is that it is relatively insensitive to tight cracks (Surin et al., 2021). On the other hand, ultrasonic testing is used to find internal defects within weld or in metals being tested, though it has primary drawbacks limitation to materials above 6 mm thick and it is very dependent on skill of the operator (Hughes, 2009).

(Garnier et al., 2017) examined non-destructive testing (NDT) techniques for evaluating concrete properties and cracks in containment walls, crucial for anticipating accidents in nuclear plants. This project divided into two parts, the project first develops and selects relevant NDT methods in the lab, then applies them to real containment structures. Tests involve ultrasonic techniques like acoustic emission, energy diffusion, and surface wave analysis, providing comprehensive mapping of parameters. Results demonstrate the efficacy of these techniques in evaluating crack generation, propagation, and characteristics, with digital image correlation enhancing data coherence. The study underscores the importance of NDT in assessing concrete integrity for nuclear plant safety.

In other hand, advancements in technology have paved the way for non-contact assessment methods, allowing assessment of concrete structure without direct physical interaction. These methods can contribute to minimizing potential structural disruptions and enhancing overall inspection effectiveness. The main existing vision-based assessment techniques that are promising for preliminary inspection are discussed through the next section.

3.3 REMOTE INSPECTION

Innovative sensor technologies, including 3D imaging sensors (both active and passive), thermography, acoustic inspection, and synthetic aperture radar imaging, play a crucial role in remote inspection methodologies for concrete structures. These sensors enable inspectors to capture data about the condition of concrete surfaces, identifying defects such as cracks, delamination, and material degradation. Additionally, advanced vehicles equipped with these sensors, including aerial drones, terrestrial robots, and underwater vehicles, provide unprecedented access to remote or hard-to-reach areas of concrete structures. Furthermore, advancements in processing tools, such as computer vision techniques, can be employed to analyze the vast amount of data collected by these sensors and vehicles. These tools enable remote defect detection, pattern recognition, and structural assessment, reducing the time and effort required for data interpretation.

Compilation of methods used in other fields but with similar characteristics (bridges, dams, wind turbines, chimneys) would be used as starting point since

there is a high likelihood for transfer of technology. In this section, the focus will be on investigation of three main areas:

- Sensors – hardware components attached to the enablers which are collecting data necessary for inspection. The sensors' selection should be able to provide the inspector with the same information as if he/she was physically there. Such sensors refer to still RGB cameras, video, thermal cameras, infrared sensors, laser scanners, etc.
- Enablers – hardware component that gives us access to distant as well as hard-to-reach areas. Such enablers include manned or unmanned aerial vehicles (also known as drones), climbing robots, etc.
- Processing tools – algorithms for data processing used for damage detection and storage of information. Typical techniques include photogrammetry, digital-image correlation, Computer Vision, etc. New trends are emerging within the area of machine learning for automatic damage detection.

The abovementioned parts would form a technology mapping for remote inspection in different areas, however, with particular focus on large structures like what we usually observe in nuclear power plant concrete structures.

Following this overview, case studies will illustrate the practical application and effectiveness of these technologies in real-world inspection scenarios, demonstrating their impact on enhancing the safety, reliability, and longevity of concrete structures.

3.4 3D IMAGING SENSORS

Emerging technologies are now becoming more and more common in the civil engineering field. One such example is the use of optical methods – arguably a more advanced visual inspection – where the imaging characteristics of an object are recorded using high precision, high sensitivity cameras. According to (Fathi & Brilakis, 2011), optical-based sensors are classified as active or passive sensors. Active sensors obtain information by emitting energy and recording the reflected signals. Passive sensors make use of ambient light to capture the surrounding environment, and with the use of post-processing techniques, range data are obtained. Existing techniques of 3D imaging can be as Table 3-2.

Table 3-2 Active vs. Passive sensors in capturing environmental depth information.

3D IMAGING TECHNIQUES	
ACTIVE	PASSIVE
Structured light LiDAR Technology Spectral imaging	Stereo-vision Fixed-view approach Multiple-view approach

3.4.1 Active 3D imaging – active sensors

Structured light

Structured light is an active 3D imaging technique as it employs structured light without depending on external light source. As it is illustrated by Figure 3-3, the cameras project a modulated pattern to the surface of a scene and calculate the disparity between the original projected pattern and the observed pattern deformed by the surface of the scene. The light source can be chosen between visible light, laser or infrared. Structured light 3D scanning devices use projected light and a camera system to shoot light onto the surface of an object. The cameras are mostly used indoor because of sunlight interference with projected light pattern. With the increase of AR/VR (augmented reality/virtual reality) there has been a growing demand in this type of technology due to their ability captures depth information with high accuracy in short to medium range. Notable commercial products (Figure 3-4) are: GOM GmbH ATOS Core, Afinia EinScan-Pro, Matterport Pro2, Intel® RealSense™ Depth Camera D455. The working distance is about 4-5 m although the Intel D455 solution can collect data from up to 20 m.

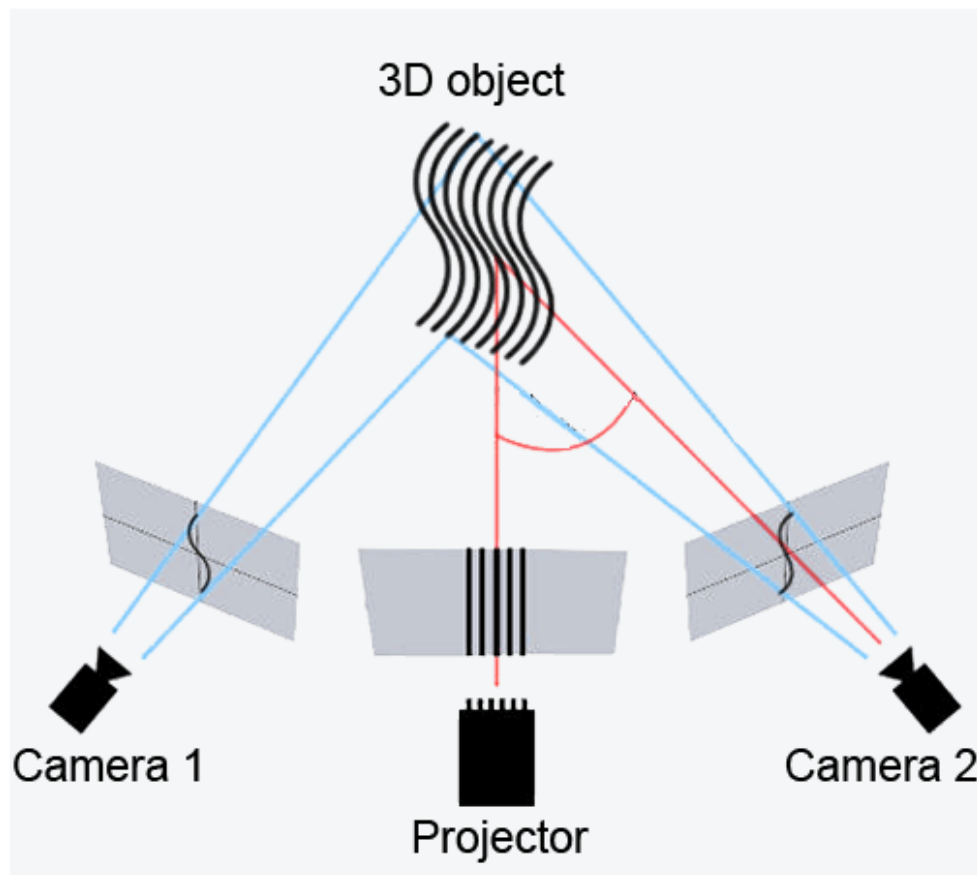


Figure 3-3 Schematic presentation of structured light technique.



Figure 3-4 Noteworthy commercial 3D scanning solutions leading the market.

Several technical reports have explored the application of a specific technique. For instance, (Popescu, Täljsten, et al., 2019) utilized the Matterport Pro2 camera to assess its effectiveness in creating three-dimensional (3D) models of existing concrete bridges. The Matterport scanning solution employs RGB-D cameras along with an infrared camera and projector to enhance images with depth information. Structured infrared light patterns are projected onto the scene, and the reflected light is captured by the infrared camera to calculate depths.

The Matterport Pro2 3D Camera used in the study (depicted in Figure 3-4 (c)) features three infrared sensors for capturing depth data alongside visual data (RGB) with a 360-degree horizontal and 300-degree vertical coverage. Images are captured at a resolution of 8092x4552 pixels, with the camera wirelessly connected to a tablet for scanning purposes. Each scan takes approximately 40 seconds, including transfer and alignment time, and has a range of about 4.5m indoors. Outdoor scanning requires more positions to mitigate alignment issues, and it's recommended to conduct scans during civil twilight or on cloudy days to avoid interference from sunlight. Upon completion, the scans are uploaded to Matterport's cloud service for 3D data registration, resulting in a point cloud (as shown in Figure 3-5). Additionally, the scan positions around the bridge can be visualized for further analysis.

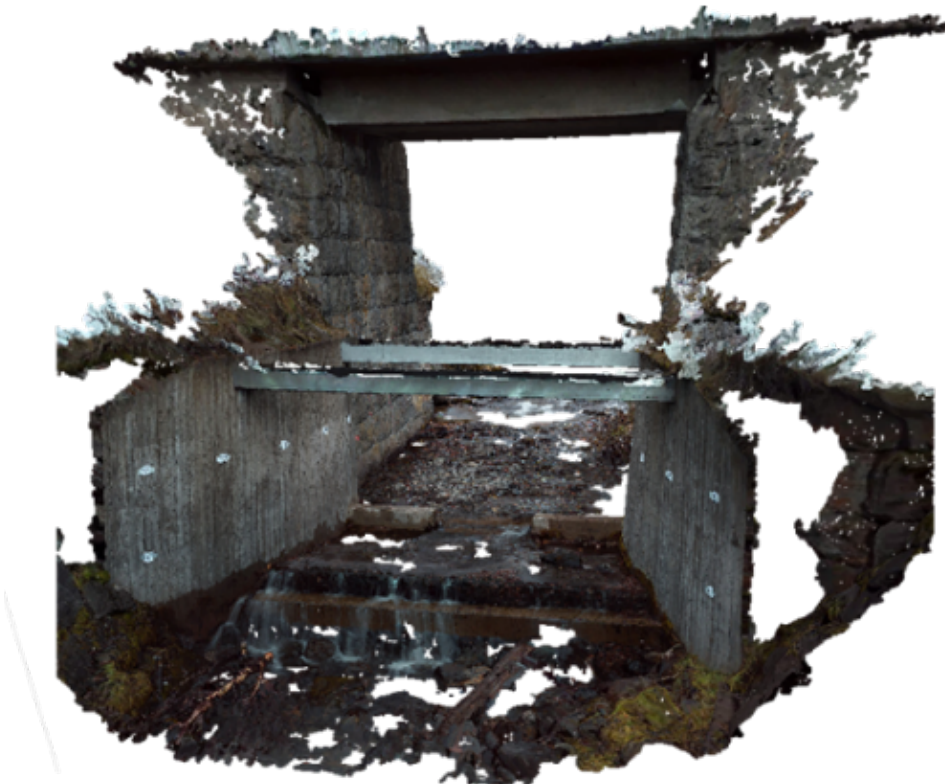


Figure 3-5 Infrared scanning using Matterport Pro2 camera for Juvajokk Bridge (Popescu, Täljsten, et al., 2019)

In a separate investigation (Sayyar-Roudsari et al., 2020), an alternative approach to visual inspection was proposed, employing Intel RealSense D435 depth cameras to identify external defects in reinforced concrete (RC) members. These cameras were affixed to a robot, facilitating examinations of hard-to-reach areas such as crawl spaces or other confined spaces where human access is restricted. Utilizing MATLAB toolbox, the matrix data was processed using image processing techniques, with Mesh Plot utilized for image capture. Additionally, Intel RealSense D435 depth cameras (depicted in Figure 3-4 (d)) were mounted on a drone, as illustrated in Figure 3-6. This setup enables inspection of areas that are typically challenging to access, either as standalone units or when affixed to robots.



Figure 3-6 Intel RealSense D435 depth cameras installed on a drone.

LiDAR Technology

Light Detection and Ranging (LiDAR) use laser beams to create detailed three-dimensional representations of concrete structures. This technology facilitates accurate geometric measurements and aids in creating comprehensive 3D images of the inspected area. LiDAR is highly practical in limit access areas with a wide range of climate condition, and provides a non-contact, high accurate and productive method to acquire cloud points describing the surface of the structure. Compared with traditional surveying techniques, LiDAR shows high potential for deformation monitoring, thanks to its fast data acquisition, high data density, and 3D object representation. It also can save the time required for data acquisition, almost 1 million points per second, using in various related civil engineering applications, such as nuclear power plants. There is no specific manner for data acquisition by LiDAR especially engineering structures, but based on experience, a general workflow of data acquisition is included four following issues which is represented in Figure 3-7.

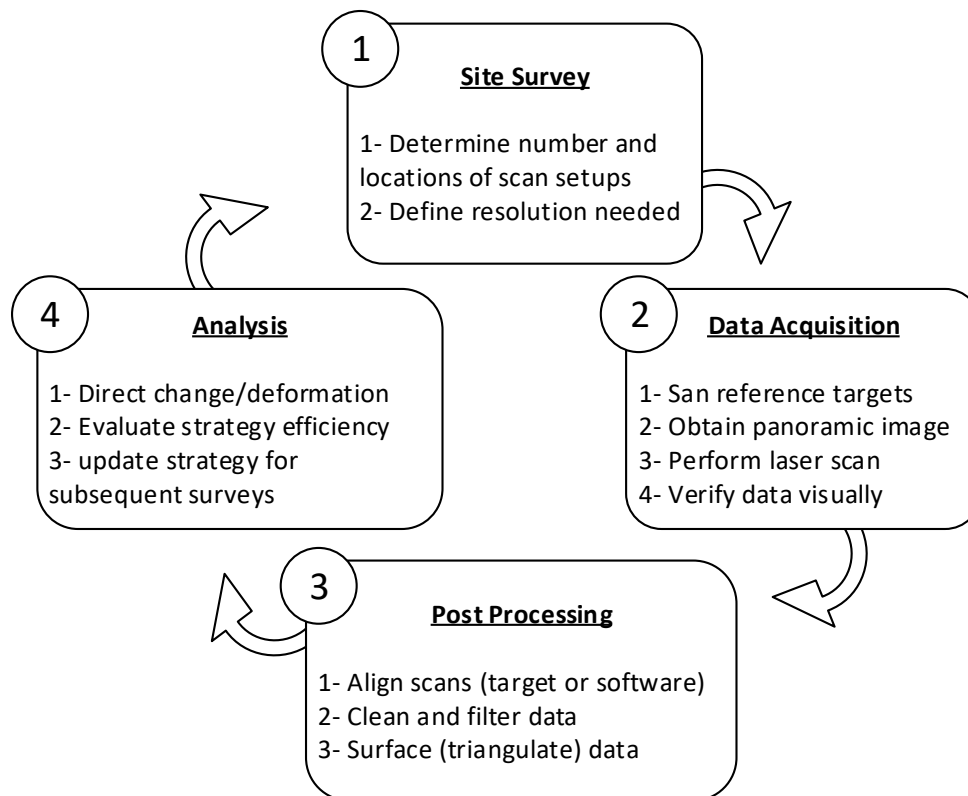


Figure 3-7 Workflow for laser scanning.

There are three different laser scanning technologies for data acquisition, including:

1. **Triangular Laser Scanners:** These scanners utilize the principle of triangulation to calculate range, providing accurate measurements. They are particularly effective for capturing surface details and small features in millimetre level due to their high resolution. They are mainly handheld and similar to structured light sensors. The difference is the density of points clouds and accuracy of the scans. Commercial scanners are for example FARO Freestyle3D X, Creaform HandyScan BLACK, etc.
2. **Time-of-flight (TOF) based scanners:** TOF scanners determine coordinated points by measuring the time taken for laser pulses to travel to the surface and return. They offer a longer range of data collection, making them preferable for scanning large structures (Riveiro & Solla, 2016). In optimal conditions, TOF scanners can achieve accuracies in the range of millimeters to centimeters. They can detect various surface details, including textures, edges, and discontinuities. Concrete cracks as small as a few millimeters in width can be detected with TOF scanners, although the detection accuracy may vary depending on factors such as surface conditions and scanner specifications.
3. **Phase-based laser scanners:** These scanners evaluate distance by comparing phase shifts in laser waves, offering high precision and accuracy. They are suitable for capturing fine details and complex surfaces. Phase-based scanners can detect surface features with sub-millimeter

accuracy and are capable of detecting concrete cracks as narrow as a fraction of a millimeter.

Before conducting a survey, it is crucial to choose a suitable laser scanner based on the condition of the structure and the inspection objectives. Factors such as scanner technology, range, speed, resolution, and accuracy should be carefully considered to ensure optimal results. Additionally, the approximate accuracy of each Lidar method should be taken into account, with TOF and phase-based scanners generally offering higher accuracy compared to triangular scanners. For large structures, TOF scanners are preferred because of their longer range of data collection (Voegtler et al., 2008).

Each LiDAR scanning method offers unique advantages and capabilities depending on the specific requirements of the application and the environmental conditions involved. Notable commercial 3D laser scan systems can be seen in Figure 3-8 and Figure 3-9.



Figure 3-8 Examples of time-of-flight laser scanners.

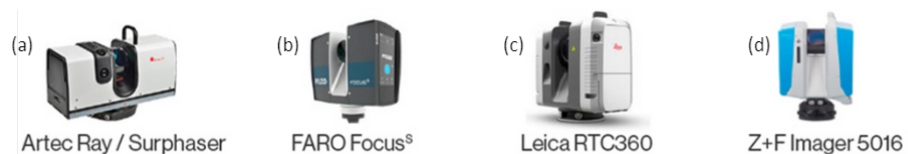


Figure 3-9 Examples of phase-based laser scanners.

After data acquisition, data registration (post-processing) is the subsequent step, especially in big scale projects when point clouds are collected from many different control points, where the scanners are set up. In this step cloud points need to be merged for completing the 3D model. Also, controlling deformation, deterioration or any kind of movement needs to compare all the datasets, collected in many time intervals, under one common coordinate system. For these two approaches, it is necessary to assume unique reference point describing all the data sets in a common coordinate system.

LiDAR scanning methods can be categorized into three main types based on their deployment platforms:

1. **Aerial LiDAR:** Aerial LiDAR involves mounting LiDAR sensors on aircraft, drones, or helicopters to capture data from above. This method is commonly used for large-scale mapping and surveying of terrain, vegetation, infrastructure, and other features over extensive areas. Aerial LiDAR is particularly advantageous for its ability to cover vast areas quickly and efficiently, making it ideal for applications such as land use planning, forestry management, and environmental monitoring.

Hinterhofer et al. (2018) deployed LiDAR on a UAV to gather incident-related information in nuclear disaster locations. They used specialized

equipment like the RIEGL VUX-1UAV laser scanner and a gamma radiation probe, integrated with a RiCOPTER-M UAV. By processing data through field tests in real-time, they achieved precise localization of radiation sources and offer a flexible and potentially life-saving tool for first responders in time-critical scenarios.

2. **Terrestrial LiDAR:** Terrestrial LiDAR, also known as ground-based LiDAR or TLS, utilizes stationary or mobile LiDAR scanners positioned on the ground to capture data from various perspectives. This method is well-suited for detailed 3D scanning of objects, structures, buildings, and landscapes with high precision and resolution.
3. **Underwater LiDAR:** Underwater LiDAR involves deploying LiDAR sensors in aquatic environments, such as rivers, lakes, reservoirs, oceans, and underwater archaeological sites. This method enables the mapping and visualization of underwater structures with remarkable detail and accuracy.

Dong et al. (2019) developed underwater LiDAR scanning system to inspect the reactor cavity pools, the component pools and spent-fuel storage pools. It offers the enhancement in operational safety in the field application.

Spectral imaging

Spectral imaging is an active method that provides data of reflectance information over a certain wavelength range in the electromagnetic spectrum that cannot be seen by the human eye (Ptacek et al., 2021). Depending on the number of frequency bands and its width, spectral imaging can be divided in multi- or hyperspectral imaging method (see Figure 3-10). The main difference between multispectral and hyperspectral is the number of bands and how narrow the bands are. Multispectral imaging considers 3 to 10 wide bands between infrared and visible electromagnetic spectrum. Hyperspectral imaging utilizes narrower bands (10 to 20 nm), and higher number of bands are considered (order of hundreds or thousands). The typical core or common components of any spectral system are a light source, detector, wavelength dispersion device, and a computer supported with image acquisition software.

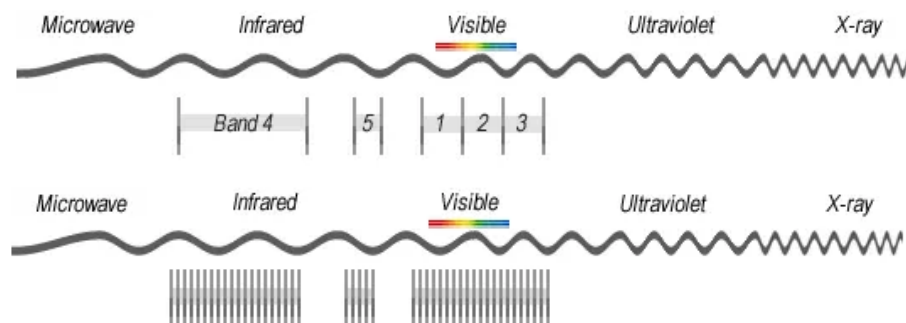


Figure 3-10 Principle of multi- and hyperspectral imaging (GIS Geography 2021)

Valença et al. (2013) have tested multi-spectral image analysis of concrete surfaces, in order to classify surface images of exposed concrete buildings where biological colonization, exposed aggregates, repairing mortars and cracks were previously detected on a visual inspection (Figure 3-11). The method automatically produces Concrete Damages Maps with an overall accuracy of 94%.

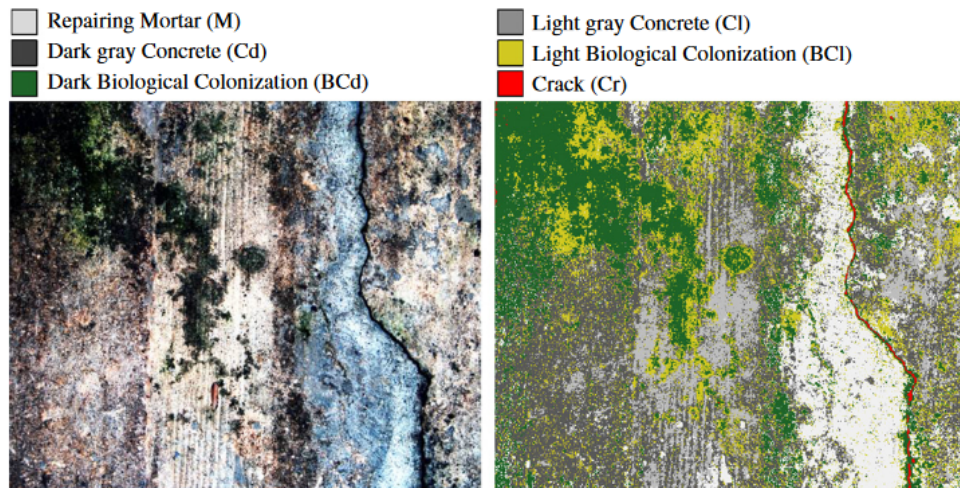


Figure 3-11 Concrete surface analysed with multi-spectral image analysis: RGB image vs concrete damage map (Valença et al., 2013).

Hyperspectral Imaging can be paired with LIDAR in order to obtain a 3D model to highlight the spectral properties of the concrete surface inspected. Headwall company (*Headwall Photonics - Hyperspectral Imaging Systems & Components*, n.d.) published an application note highlighting opportunities in infrastructure inspection and corrosion detection using hyperspectral data and imagery either from the air using a custom-made drone or on the ground for remote detection of material degradation. Their sensors come with different spectral sensitivity ranging from 250 nm to 2500 nm, Figure 3-12.



Figure 3-12 Headwall's hyperspectral sensor integrated with lidar-enabled drones.

3.4.2 Passive 3D imaging

Stereo vision

The technique simulates human visual depth perception. The cameras have two lenses spaced at 60 mm apart (similar to humans' eyes) which enables them to capture slightly different images. These images are then post-processed in order to generate the depth map. The cameras require no external light other than ambient

light. Suitable for outdoor applications in good light conditions. The stereo cameras work in short range, about 2 m, which makes it feasible only when is mounted on a drone. A commercial example is the ZED 2K Stereo Camera from Stereolabs is shown in Figure 3-13.



Figure 3-13 ZED 2K Stereo Camera from Stereolabs (ZED 2 - AI Stereo Camera | Stereolabs, n.d.).

Fixed-view approach

The approach uses single or multiple cameras optical non-destructive and contactless measurement technique used to acquire information on the state of the structure without interrupting its normal service. This information relates to geometry, displacement and deformation data using three main components: an image acquisition tool (digital camera), image processing tools and enablers (lighting, robots, etc.). A series of images are recorded using digital cameras, and coordinates of points (targets), patterns, and features in the images are subsequently identified using image processing techniques (Baqersad et al., 2017). A single camera is used when in-plane (2D) measurements are needed while two synchronised cameras gather data when both in- and out-of-plane (3D) measurements are likely to be important. Depending on the type of optical targets the photogrammetry can be categorized into point-tracking (PT), digital image correlation (DIC) and target-less approaches (Baqersad et al., 2017). A series of optical targets, e.g. retro-reflecting circular points, are mounted at discrete points on the object under investigation. Their displacements are determined by tracking their movement in different time stages and comparing it with the reference stage (Baqersad et al., 2017). In contrast to PT, where displacement is recorded at only a handful of points, the DIC technique is a full-field measurement technique. To enable DIC measurements, the monitored surface needs to be prepared beforehand. These preparations require a high contrast speckle pattern, ideally stochastic, on the structure (usually black and white). The measurements start by imaging the specimen's surface in initial undeformed and later deformed stages to obtain deformation (strain) data. Subsequently, a software divides the image into multiple facets for analysis in the reference stage (undeformed state), which are tracked in all subsequent images (deformed). In the target-less approaches, no

optical targets or speckle patterns are created in order to find the deformation (Baquersad et al., 2017); a less accurate method, however, with its own advantages when there is no possibility to create a pattern or to add optical targets. Several techniques in computer vision are used for damage detection in this case. According to (Baquersad et al., 2017) the most used ones are the edge detection and pattern matching algorithms.

Several DIC systems are now commercially available. One such example (see Figure 3-14) is the ARAMIS system (GOM mbH) which has the ability to acquire full-field as well as point-based measurements, both in 2D and 3D. Its field of view ranges from few millimetres to several meters in size (GOM mbH).

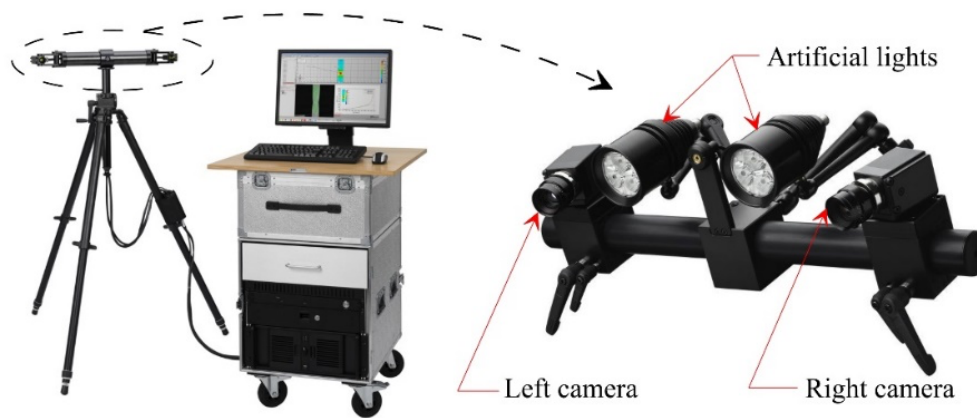


Figure 3-14. 3D-DIC system and ARAMIS system (GOM mbH)

In practice, the method is more suitable for long-term changes occurring in the field-of-view of the camera(s). For large structures where long-range measurement is expected, telephoto lenses are required together with retro-reflective targets. The retro-reflective targets help in monitoring changes in harsh environments where light and dust are of concern. Real-world applications need a displacement-free location for the camera. The technique has been successfully implemented in applications for displacement monitoring on bridges (Popescu, Täljsten, et al., 2019) or crack development over time in dams (Popescu, Sas, et al., 2019). DIC has been tested at R.E. Ginna nuclear power plant in the US. DIC was utilized on selected containment concrete surfaces (Hohmann et al., 2013). The objective of the testing was to quantitatively measure the behaviour of the concrete while being pressurized. The information, such as increased magnitudes of local strains or increased crack opening displacements, was recorded and compared with future results for change detection.

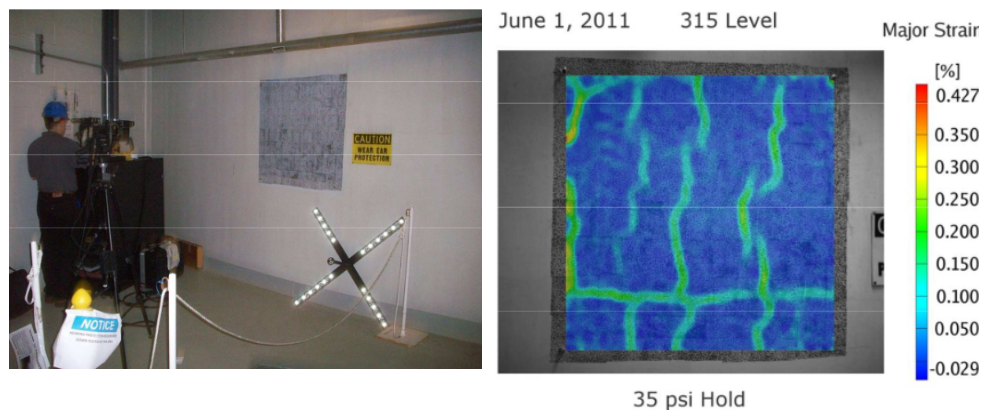


Figure 3-15 DIC application during a containment pressure test: Left) DIC cameras and inspection location; and Right) principal strain at 0.24 MPa showing strain concentrations – a sign of hairline cracks on the concrete surface (Hohmann et al., 2013).

Multiple-view approach

Passive multiple view 3D imaging is also called photogrammetry. In photogrammetry, a series of images are recorded using digital cameras, and coordinates of points (targets), patterns, and features in the images are subsequently identified using image processing techniques (Baqersad et al., 2017). When the image acquisition is done, by single or more cameras, triangulation is used to calculate distance of a point from two or more images taken from different viewpoints. The process of estimating the 3D structure of a scene from a set of 2D images is known as structure from motion (SfM). The approach relies on pixel correspondence between images and, in contrast to older photogrammetry algorithms, no pre-calibration of the camera is necessary. To make the process easier, the surfaces of the imaging object must have distinct features, either natural (sharp edges, discoloration, bolts, rails etc.) or artificial (targets). A minimum of 60% overlap between images is necessary, in both the longitudinal and transversal directions. The equipment consists of either a digital single-lens reflex camera (DSLR) camera (for ground-based photogrammetry) or a digital camera mounted on a drone (airborne photogrammetry).

According to the rules of best practice in cultural heritage imaging, the following camera settings are recommended: (1) the aperture should remain fixed during the capture sequence (preferably not smaller than $f/11$ on a 35mm camera to avoid diffraction effects); (2) the lowest possible ISO setting should be used; (3) image stabilization and auto-rotate camera functions should be disabled and (4) in variable light conditions, the camera should be set to aperture priority mode (with the f -stop ranging from 5.6 to 11) which locks the aperture and evens out exposure by varying the shutter speed. These recommendations should be followed as closely as possible; however, given the particularities of each structure, some deviations might occur.

The basic steps of photogrammetry involve (1) detecting features within each image, (2) matching these features across multiple images, and (3) reconstructing their relative 3D position in the observed scene. Figure 3-16 illustrates the typical processes used in each step. For a more detailed explanation of the theoretical

background to image-based 3D reconstruction algorithms, interested readers are referred to Remondino et al. (2014).

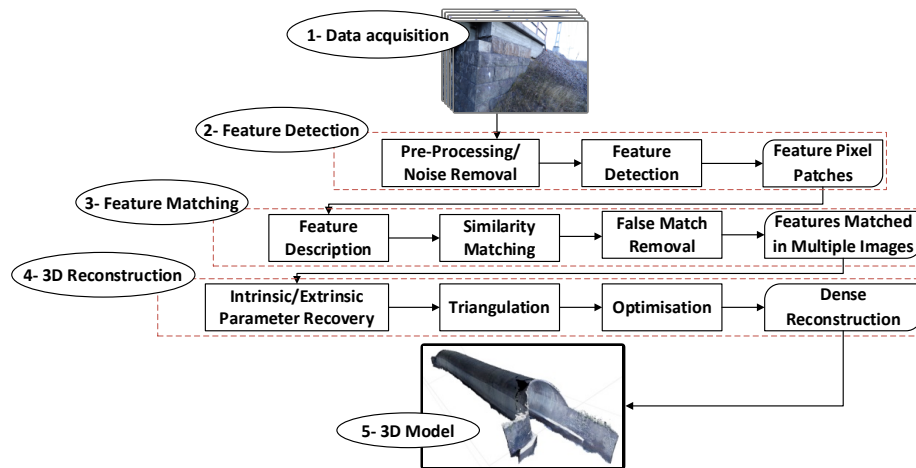


Figure 3-16 Photogrammetric reconstruction process.

There are two primary types of photogrammetry:

Aerial Photogrammetry: In aerial photogrammetry, a camera mounted on an aerial platform such as a drone captures images of the target area from above. The accuracy of aerial photogrammetry can vary depending on factors such as the quality of the camera, the flight altitude, and the ground control points used for georeferencing. In optimal conditions, the accuracy of aerial photogrammetry can range from a few centimeters to several millimeters.

Terrestrial Photogrammetry: Terrestrial photogrammetry involves capturing images from ground-level perspectives using handheld or tripod-mounted cameras. This method is suitable for close-range inspection of structures and objects. The accuracy of terrestrial photogrammetry is influenced by factors such as camera resolution, image overlap, and the quality of ground control points. In ideal conditions, terrestrial photogrammetry can achieve accuracies similar to aerial photogrammetry, ranging from millimeters to centimeters.

Photogrammetry has proven to be effective in identifying concrete cracks of different widths. Utilizing high-resolution imagery and sophisticated processing methods, photogrammetry can discern fine details, including cracks as narrow as a few millimeters. The level of detail captured is influenced by various factors, such as lighting conditions, camera resolution, image quality, and the algorithms used in processing. Notably, Ground Sampling Distance (GSD) and Field of View (FOV) are critical considerations in scale of defect detection in photogrammetric techniques, which will be elaborated further in Section 3.8.2 Application of drone scanning, Computer Vision approach.

Photogrammetry offers several advantages in remote inspection as below:

- **Non-contact method:** Photogrammetry allows for remote inspection without direct physical contact with the structure, minimizing safety risks to inspectors.

- **High accuracy:** Modern photogrammetric software can produce highly accurate 3D models and measurements, providing detailed information about the structure's condition.
- **Cost-Effectiveness:** Compared to traditional methods such as manual measurements or laser scanning, photogrammetry can be more cost-effective, requiring only a camera and software.
- **Rapid data collection:** With advancements in drone technology, photogrammetry enables rapid data acquisition over large areas, reducing inspection time and cost.
- **Accessibility:** Photogrammetry can reach inaccessible or hazardous areas of concrete structures, providing comprehensive coverage for inspection purposes.

However, photogrammetry has some limitations that should be considered:

- **Environmental conditions:** Photogrammetry is sensitive to environmental factors such as lighting conditions, weather, and shadows, which can affect the quality of the captured images and the accuracy of the results.
- **Skill and expertise:** Generating accurate 3D models from photographs requires expertise in photography, image processing, and photogrammetric software, which may pose a challenge for non-experts.
- **Data processing time:** Processing large datasets generated from photogrammetry can be time-consuming and computationally intensive, delaying the delivery of inspection results.
- **Accuracy degradation:** The accuracy of photogrammetric measurements can degrade with distance from the camera, limiting its effectiveness for inspecting large or distant structures.
- **Limited depth perception:** Photogrammetry may struggle to accurately capture the depth of complex concrete structures, leading to potential inaccuracies in the resulting models.

Approaching the application of this technique in nuclear power plant inspection, (Sato et al., 2018) presents a novel method for three-dimensional (3D) image reconstruction of radioactive substances utilizing a compact Compton camera. Through integration with photogrammetry, the approach enables visual recognition of the precise position of radioactive materials in real space. This innovative technique offers a comprehensive solution for accurately mapping radioactive sources, facilitating improved localization and characterization in various environments.

3.4.3 Application of imaging sensors and comparative discussion

Collected image-based datasets can provide an informative description of the concrete structure in a brief data acquisition. The summary of the obtained accuracy by imaging sensors, and traditional methods during the last two decades is presented in Figure 3-17. Then, (Popescu, Täljsten, et al., 2019) utilized Close

Range Photogrammetry (CRP), Terrestrial LiDAR Scanning (TLS), and Infrared Scanning (IS) with structured light, and compare the techniques in terms of accuracy, cost-efficiency, automation, portability, data acquisition range and range distance (Figure 3-17).

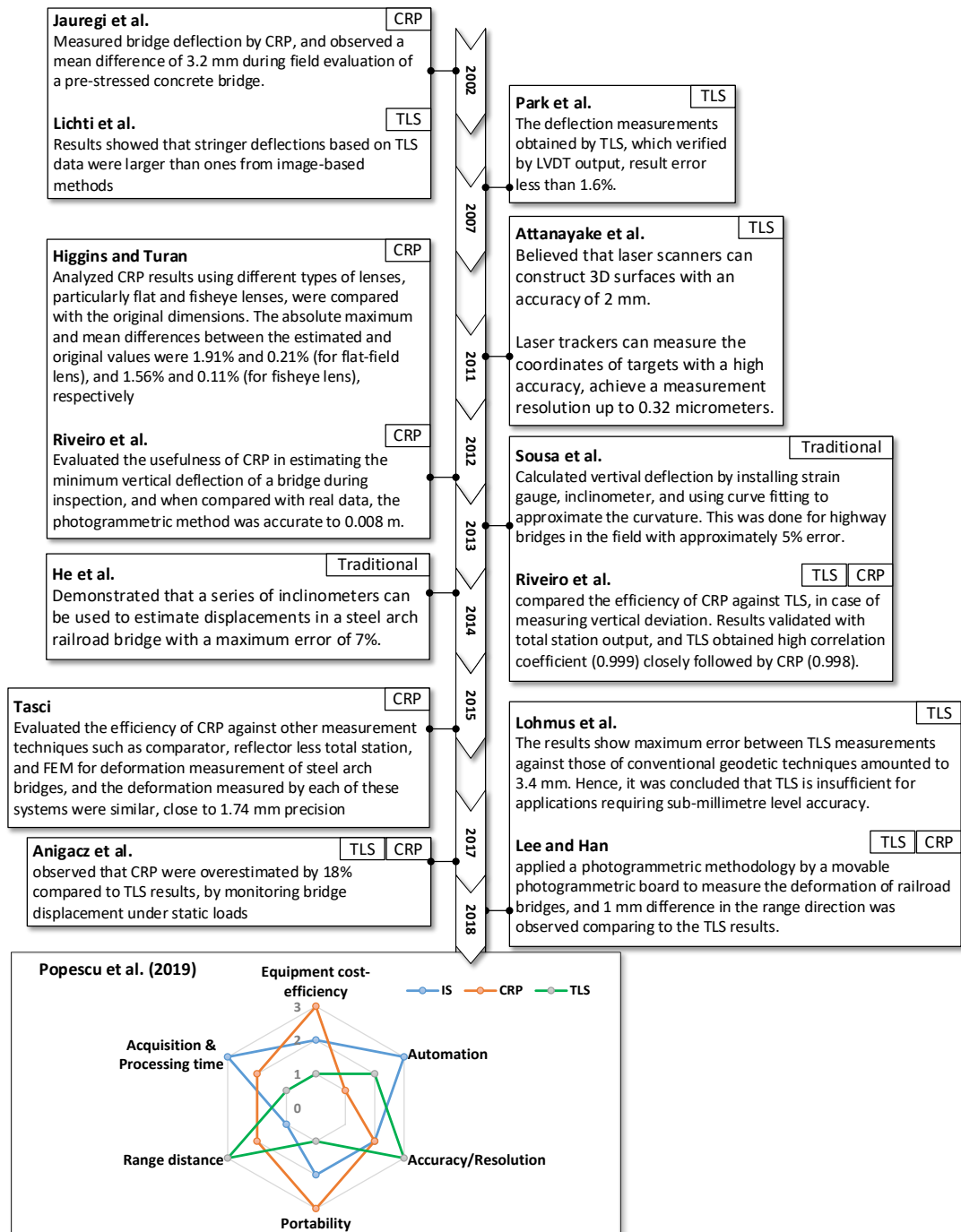


Figure 3-17 Review of the obtained accuracy by optical and traditional methods during last two decades.

The terrestrial laser scanning method, as demonstrated in previous research by (Popescu, Täljsten, et al., 2019), has shown good results in capturing with high accuracy the geometrical characteristics of a concrete bridge (Figure 3-18). The

equipment used in this study was a long-range, RIEGL VZ-400, 3D terrestrial laser scanner (Figure 3-8 (c)). This 3D scanner operates on the time-of-flight principle and can make measurements ranging from 1.5m to 600m with a nominal accuracy of 5mm at 100m range. It uses near infrared laser wavelengths with a laser beam divergence of 0.3 mrad, corresponding to an increase of 30mm of beam diameter per 100m distance. The instrument's maximum vertical and horizontal scan angle ranges are 100° and 360°, respectively. The raw TLS data, i.e. point clouds captured from multiple scans, were post-processed (registered and geo-referenced) using the Leica Cyclone software package, which automatically aligns the scans and exports the point cloud in various formats for further processing.

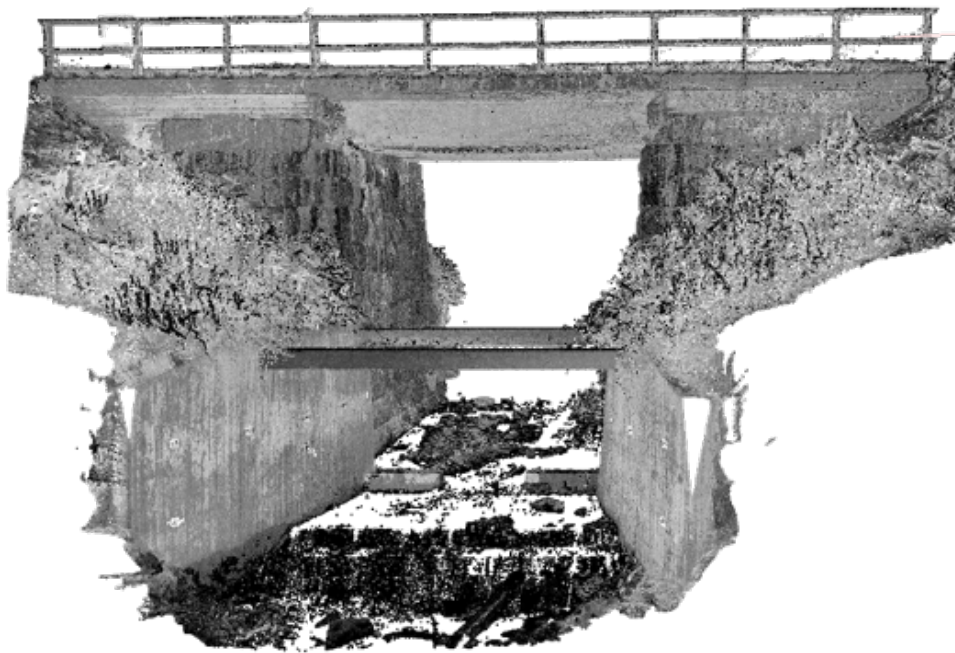


Figure 3-18 3D model of Juovajokk bridge obtained by terrestrial-laser scanning (Popescu, Täljsten, et al., 2019).

Practical application of the defined technique by laser scanning has been compared with the photogrammetry technique in terms of accuracy. The field deployment is the reconstruction of Juvajokk Bridge by (Popescu, Täljsten, et al., 2019), Figure 3-19. The equipment for photogrammetry consisted of a digital single-lens reflex camera (DSLR) camera, a Canon EOS 5D. This is equipped with a full-frame (35.8 × 23.9 mm) complementary metal–oxide–semiconductor (CMOS) optical sensor giving 12.8 megapixels (4368 × 2912 pixels) resolution. The camera was equipped with a Canon EF 35mm wide-angle prime (fixed zoom) lens. On a full-frame camera body, this lens gives a large field of view angle (54° horizontal viewing angle), thus covering a broad area, meaning that fewer images are needed to capture the entire structure. Although the size of the bridge is relatively small (6 m span length) certain areas were difficult to scan using regular cameras. As presented before in Figure 3-17, photogrammetry as a multiple-view approach technique, shows good performance in terms of accuracy, cost-efficiency, and portability, compared with Laser scanning and infrared scanning (Popescu, Täljsten, et al., 2019).



Figure 3-19. Left) Ground-based photogrammetry camera for Juvajokk Bridge; Right) Artificial targets used in the alignment process and for scaling: (a) coded targets and (b) calibration scale bars.

(Mirzazade et al., 2023) studied the accuracy of generated 3D model of Juvajokk Bridge by both multiple-view approach and laser scanning comparing with the existing as-built drawings, as the ground truth. Both methods provided good accuracy, less than 1% error, as can be seen from Table 3-3.



Figure 3-20 Measurements of bridge structural elements in both CRP (left), and laser scanning (right) method.

Table 3-3 TLS and CRP accuracy comparison corresponding to as built dimensions.implementation

Component	As-built dimension (mm)	TLS		CRP	
		(mm)	Error (%)	(mm)	Error (%)
Span	5500	5432	-1.2%	5456	-0.80%
Width	3800	3805	0.13 %	3810	0.26%

In another study, (Broome, 2016) has shown that there is no significant differences between accuracy of close range photogrammetry (CRP) and LiDAR, and as measured differences were only between 0-7 mm. In addition, a cost benefit analysis showed that CRP is overall a lot more cost effective due to the equipment being relatively inexpensive compared to TLS system. However, LiDAR has scored better on accuracy and required skillful operator (Broome, 2016). In addition, generated point-cloud for infrastructure inspection must have sufficient accuracy and resolution to represent the types of small-scale visual details that inspectors look for during an inspection, and details that are often less than a millimeter in size. Studies by (Valença et al., 2013) have shown that cracks with 1.25 mm width can be detected using a TLS scanner if the scanning parameters were set properly. However, in real built structures, it is difficult to monitor cracks in submillimeter scales, due to dirt and moisture stains covering cracks. Thus, data acquisition

needed to start after a short site pre-checking to performing dust removal of interior spaces, cleaning dirt on surfaces, removing shady vegetation, and ensuring access to designated spaces.

3.5 THERMOGRAPHY

Infrared Thermography, also known as Thermal Imaging, is a non-contact technique used for detecting and visualizing the temperature distribution of surfaces and objects. It operates based on the principle that all objects emit infrared radiation as a function of their temperature. By measuring this radiation, infrared thermography produces thermal images, also called thermograms, which depict temperature variations across the scanned area.

This technique relies on specialized cameras called thermal imagers or infrared cameras, equipped with sensors capable of detecting infrared radiation. These cameras detect the intensity of infrared radiation emitted by surfaces within their field of view. The detected radiation is converted into temperature data using algorithms, which are then represented as color-coded images where different colors correspond to different temperatures. Warmer areas appear as lighter colors (e.g., white or red), while cooler areas appear as darker colors (e.g., black or blue).

Infrared thermography is capable of detecting temperature differences as low as a fraction of a degree Celsius, depending on factors such as the camera's thermal sensitivity and the environmental conditions. For example, many thermal imagers on the market today offer a millikelvins measurement of $>50\text{mK}$, with higher quality models ranging down to $>40\text{mk}$ and top of the range units getting as low as $>35\text{mk}$, enables detecting the finest temperature differences reliably. This level of sensitivity enables the detection of subtle thermal anomalies indicative of various defects or irregularities in concrete structures, such as crack, delamination, moisture intrusion, and thermal bridging. In optimal conditions, high-quality infrared cameras can achieve a spatial resolution ranging from a few pixels to sub-millimeter levels, depending on the camera specifications, allowing them to detect small temperature differences in small-scale defects with high precision.

To be able to take measurements a heat source must exist. The natural source, the sun, fulfils the requirements in most of the cases. However, in difficult to reach areas, artificial heat must be produced by other methods such as laser for surface heating, lamps, etc. Infrared thermography can be divided in two approaches: the passive approach and the active approach, see Figure 3-21 (a).

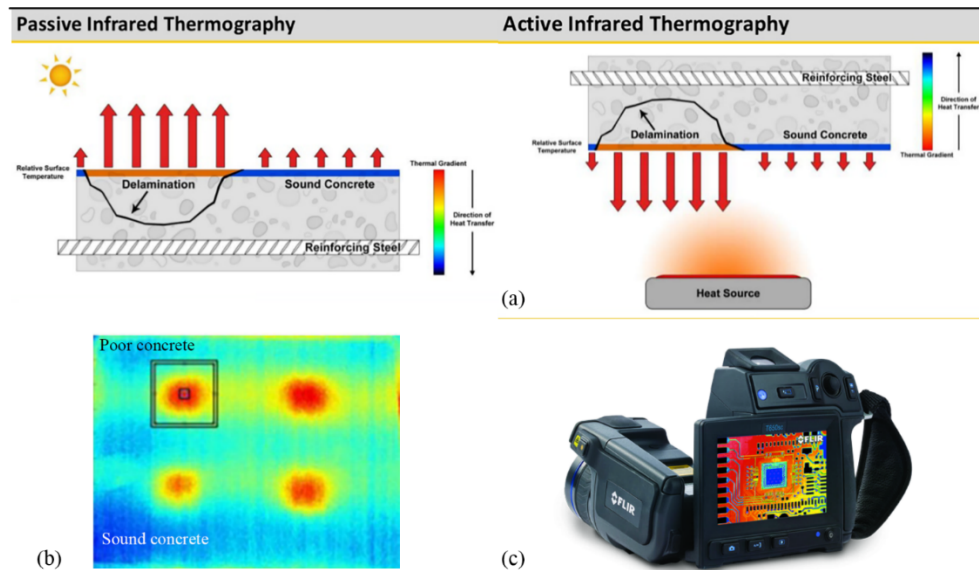


Figure 3-21 Infrared thermography: (a) the principle of passive and active thermography (Ahlborn 2015); (b) typical results indicating concrete quality, and (c) a commercially available camera T630sc (Support for FLIR T630sc - Discontinued | Teledyne FLIR, n.d.)

External stimulations are not needed for passive approach while active thermography needs thermal excitation. A comprehensive review on active thermography has been published by (Milovanović & Banjad Pečur, 2016). The method creates surface temperature patterns by detecting thermodynamic properties of the object under investigation. A sound concrete would reveal uniform temperature over the whole surface monitored due to its high thermal conductivity. A poor-quality concrete has low thermal conductivity, and this will be highlighted by differences in the temperature patterns, see Figure 3-21 (b). This means that delaminated areas, heat up faster (and cool down rapidly, respectively) than a good-quality concrete. It is a very useful method for inspection of large surface areas (in the range of kilometers if proper lenses are available, (Rehman et al., 2016)). However, the depth of the anomalies cannot be detected. In such cases where the depth is important, it is advisable to use the method in combination with ground penetrating radar (Rehman et al., 2016). Infrared thermographic equipment is commercially available, see FLIR T630sc camera shown in Figure 3-21 (c). The thermal cameras can be deployed on drones for easy access. One example is WIRIS® Pro S1 thermal camera equipped with an LWIR (Long Wave Infrared Cameras) microbolometric sensor with 640×512 px resolution (in the 7.5 – 13.5 μm range), and its 'Super Resolution Mode' functionality delivers a final thermogram in 1266×1010 px resolution (Figure 3-22).

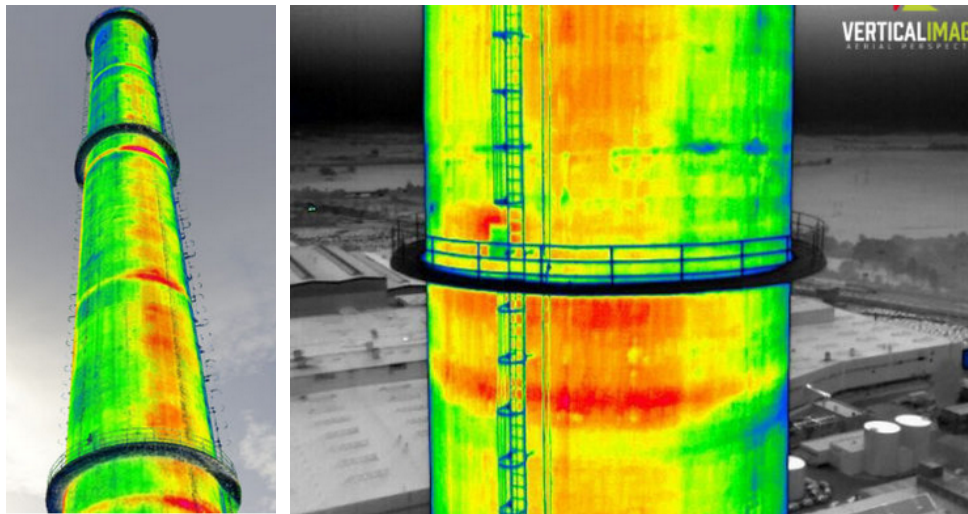


Figure 3-22 3D chimney model captured by workshell WIRIS thermal cameras for drones (*Drone-Based 3D Thermal Modeling | Drone Thermal Camera, 2019*)

This technique is used to locate near surface defects in concrete. Common applications include delamination in bridge decks, delamination in members strengthened by fibre-reinforced polymers, defective cladding on buildings and energy loss in buildings (IAEA 2002). (Renshaw et al., 2015) reported a study evaluating the feasibility of thermographic inspection of pipes, tanks, and containment liners from nuclear power plants. The authors showed that thermographic inspection can provide fast inspection of large areas.

The use of infrared thermography, in which infrared photographs are taken during the cooling of a heated structure, has been utilized to detect delamination in concrete structures (in particular, concrete bridge decks) (Tomita & Chew, 2022) (Omar et al., 2018). The detection of delamination by infrared thermography is based on differences in surface temperatures between sound and unsound concrete. As concrete heats and cools, a substantial thermal gradient develops within the concrete due to its poor thermal conductivity. As a result, variations in surface temperatures due to the presence of delamination will be observed. The time and power required to heat concrete to establish the necessary thermal gradients prevent the use of artificial heat sources. The infrared thermography equipment consists of an infrared scanner, a control unit, a battery pack, and a display screen. To provide a hard copy of test results, the images are usually recorded on photographic plates or videotape. The equipment is readily available on a rental basis. Figure 3-23 shows some of the most popular brands in the market.



Flir thermal imaging cameras



Fluke Thermal Imaging Cameras



Testo Thermal Imaging Cameras



RS Pro Thermal Imaging Cameras

Figure 3-23 Samples of commercial solutions for thermal imaging.

(Kim et al., 2012) applied IR thermography to detect wall-thinned defects in nuclear power plants during normal operation. Using a pipe model and specimen made of the actual NPP material, simulations revealed that closer proximity and higher intensity of the cooling fan facilitated easier defect detection. Experimental results confirmed partial identification of defects.

Based on the existing experiences in the literature review, Infrared thermography offers several advantages, including:

- **Non-contact measurement:** Infrared thermography allows temperature measurement without physical contact, minimizing the risk of damage or contamination to the target object.
- **Rapid inspection:** Thermal imaging enables rapid and comprehensive inspection of large areas or multiple components simultaneously, reducing inspection time and labor costs.
- **Early detection of anomalies:** Infrared thermography detects thermal anomalies invisible to the naked eye, allowing for early identification of potential issues before they escalate into failures or accidents.
- **Non-destructive testing:** Infrared thermography is a non-destructive testing technique, preserving the integrity of the inspected objects or structures.

Despite its numerous advantages, infrared thermography has some limitations that should be considered:

- **Surface emissivity:** Infrared thermography relies on surface emissivity, which may vary depending on the material composition and surface conditions. Certain materials with low emissivity may produce inaccurate temperature measurements.
- **Environmental factors:** Environmental conditions such as ambient temperature, humidity, and air movement can affect thermal imaging results, leading to inaccuracies or false positives.
- **Resolution and sensitivity:** The resolution and sensitivity of infrared cameras may limit their ability to detect small temperature differences or anomalies, particularly in complex or cluttered environments.
- **Cost and training:** High-quality infrared cameras can be expensive, and their effective use requires specialized training and expertise in thermography techniques and interpretation of thermal images.

3.6 ACOUSTIC INSPECTION

The method, a non-contact inspection technique, uses air-borne sound waves to excite the concrete surface. The sound waves are generated by a high-powered sound source. The vibration velocity on the concrete surface is optically detected by a scanning laser Doppler vibrometer. Figure 3-24 shows the working principle of the method. If any damage exists under the concrete surface, the upper part on the defect behaves similar to a vibrating plate with its own distinctive resonance frequency of flexural vibration (SUGIMOTO et al., 2014). By conducting a frequency analysis, abnormal vibration signals can be identified, indicating areas of damage.

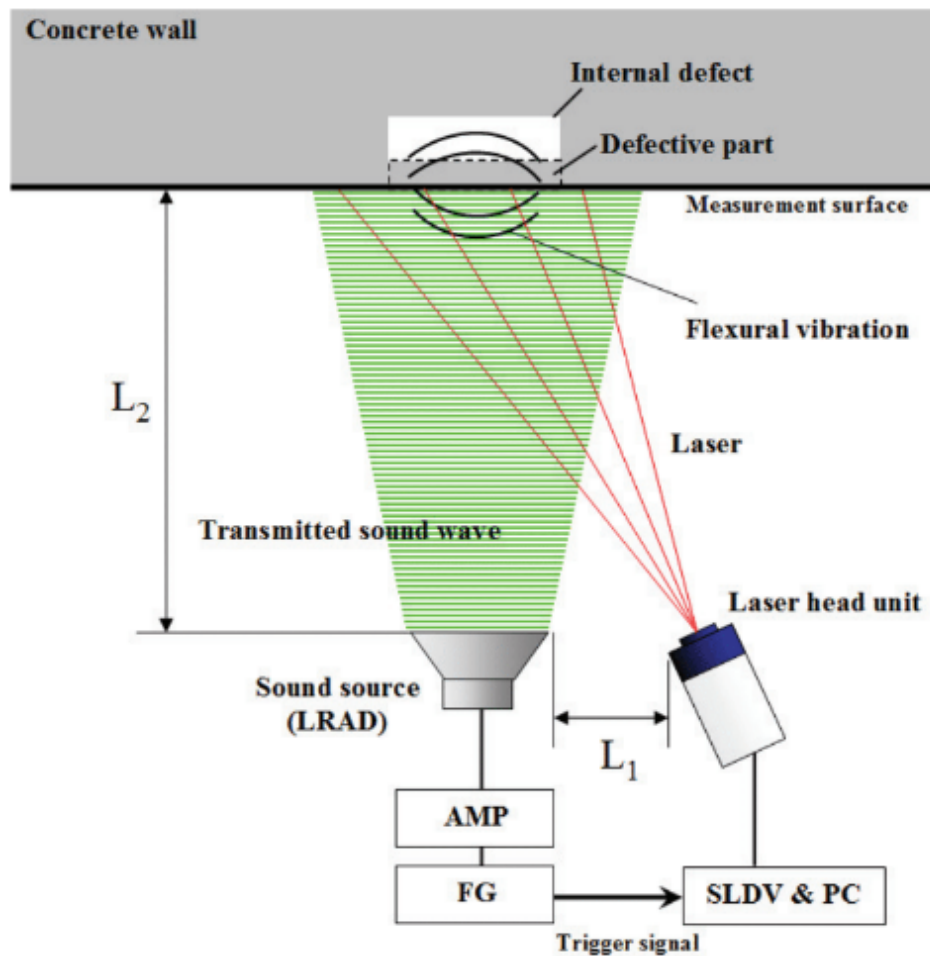


Figure 3-24 Working principle of the non-contact acoustic inspection method (SUGIMOTO et al., 2014)

(SUGIMOTO et al., 2014) performed an in-situ demonstration of the method and compared the results against tradition hammering method. The test was performed on a box-culvert concrete bridge that had a side wall damaged by salt water. Experimental results obtained by using the hammer method were compared with those using the non-contact acoustic investigation method are shown in Figure 3-25. The distance from the sound source to the investigated concrete surface was about 4 m.

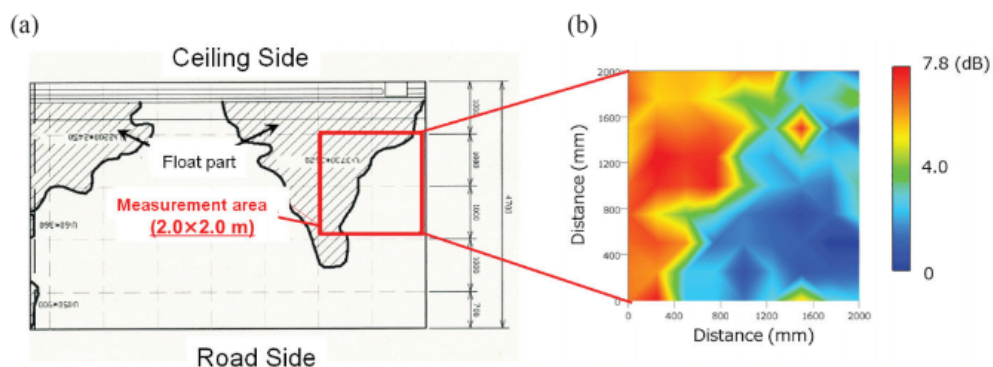


Figure 3-25 Experimental results: (a) hammering test; and (b) acoustic investigation method (SUGIMOTO et al., 2014)

In another filed study (Sugimoto et al., 2017), performed an inspection test on damaged concrete bridge in an attempt to increase the distance from the sound source to the investigated concrete surface. A long-range acoustic device was used as the excitation sound source and a scanning laser Doppler vibrometer was used as a measurement, both of which were located at a distance of about 34 m from the surface of target under the bridge. The sound source was generated using a strong ultrasonic sound source, and the outcomes are depicted in Figure 3-26.

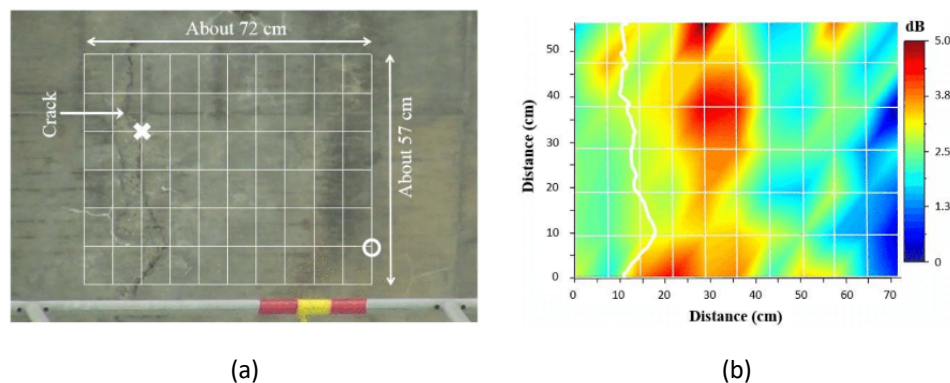


Figure 3-26 Experimental results from a damaged concrete bridge deck measured from a distance of about 34 m: (a) measurement area indicating the visible damages; and (b) Distribution of vibration energy ratio (300-4000Hz) (Sugimoto et al., 2017)

(T.-Y. Yu & Haupt, 2010) used a distant acoustic-laser a high powered standoff parametric acoustic array and laser Doppler vibrometer, for the detection of debonding and delamination in multi-layer composite systems (e.g. glass-fiber reinforced polymers - concrete). The research demonstrated that accurate measurements could be obtained even at distances exceeding 30 meters. The study also highlighted potential areas for future research, including assessing the performance of the acoustic-laser setup in noisy environments and investigating its feasibility for detecting smaller defects.

3.7 SYNTHETIC APERTURE RADAR IMAGING

The radar method is a viable technique used to assess the condition of concrete structures. Information about the surface as well as subsurface condition of concrete is obtained by a radar sensor able to emit electromagnetic waves penetrating dielectric materials (such as concrete). When coupled with electromagnetic scattering theory and dielectric properties of concrete, anomalies are detected and quantified (Owusu Twumasi et al., 2020). There are several non-destructive radar methods, however, the synthetic aperture radar (SAR) is able to produce images with good resolution from distance. For example, the ground-penetrating radar can perform remote sensing within close range (less than 0.5m) (Bungey, 2004), while SAR imaging technique can extend the range up to 15 m as demonstrated by (T. Yu et al., 2017). SAR imaging has been applied for the detection of steel rebars and concrete delamination (Rhim & Büyüköztürk, 2000), and steel rebar corrosion (Ghasr et al., 2015). Field application have been reported

by (T. Yu et al., 2017) where a composite wall, a retaining wall, and a bridge abutment have been studied by SAR imaging, Figure 3-27.

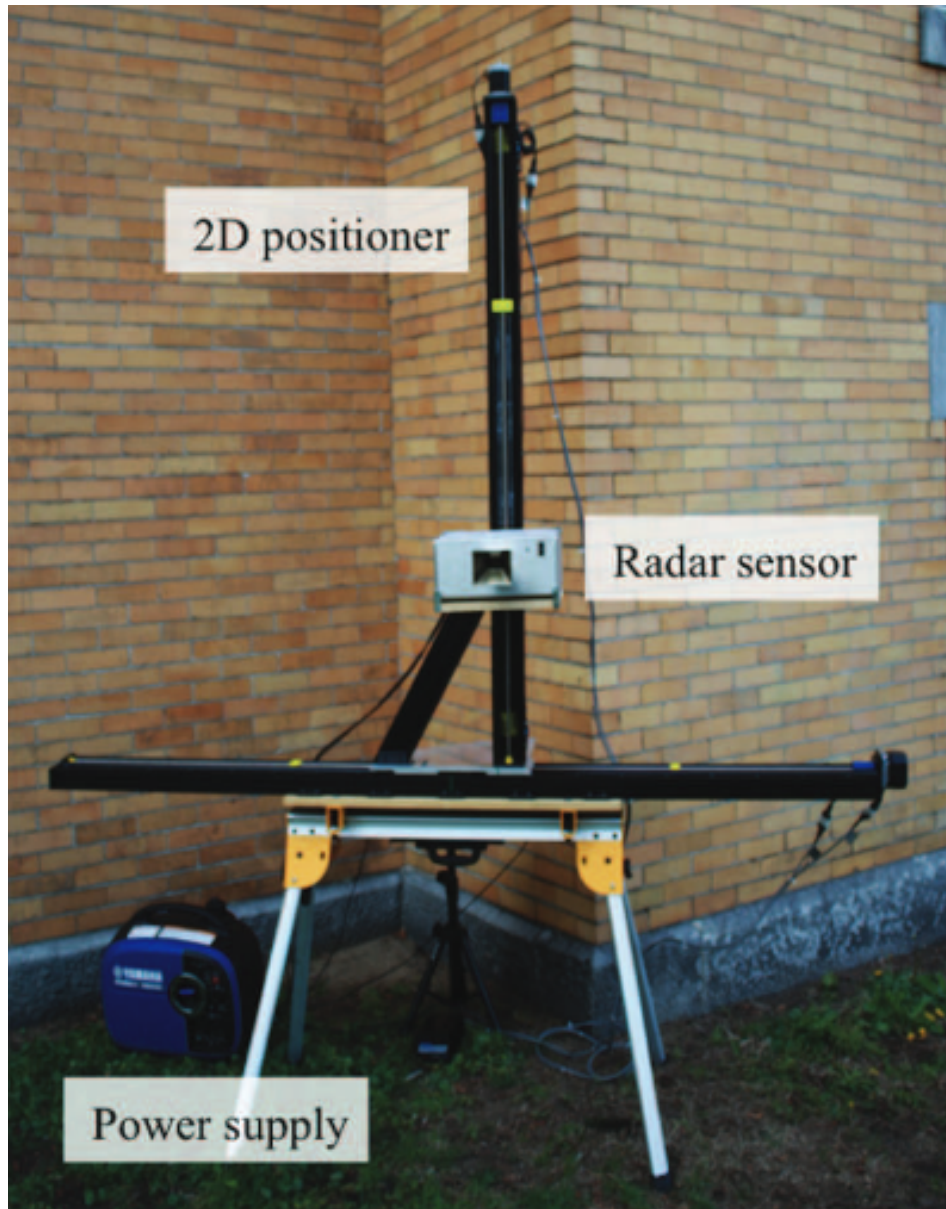


Figure 3-27 Portable radar system (T. Yu et al., 2017)

3.8 ADVANCED TECHNOLOGIES FOR DATA ACQUISITION AND PROCESSING

The corrosion detection techniques relying on imaging presented in this section are inherently not quantitative and still require human comparison and rating. However, recent efforts have aimed at overcoming these drawbacks by applying machine learning algorithms and artificial intelligence. The implementation of advanced technologies is going to become integral to the efficient inspection of concrete structures. This section explores the applications of robotics and computer

vision, each playing a pivotal role in enhancing various aspects of concrete structure assessment.

3.8.1 Application of robotics for data acquisition enablers

Examples of commercial robots designed for hard to access areas can be categorized into several general groups based on their functionalities and capabilities. These robots have the potential to be used as enabler for data acquisition in NPP concrete structures. Here are some common categories:

Inspection Robots

Ground-based Inspection Robots: These robots, Figure 3-28, are designed to navigate on the ground and perform visual inspections of various environment and components within concrete structures that can potentially be utilized in environments, such as pipes, pressure vessels, and reactor components.



Figure 3-28 Samples of commercial ground-based inspection robots.

Aerial Inspection Drones: Drones, Figure 3-29, equipped with cameras and sensors for aerial inspections of structures that may be challenging to access using ground-based robots.

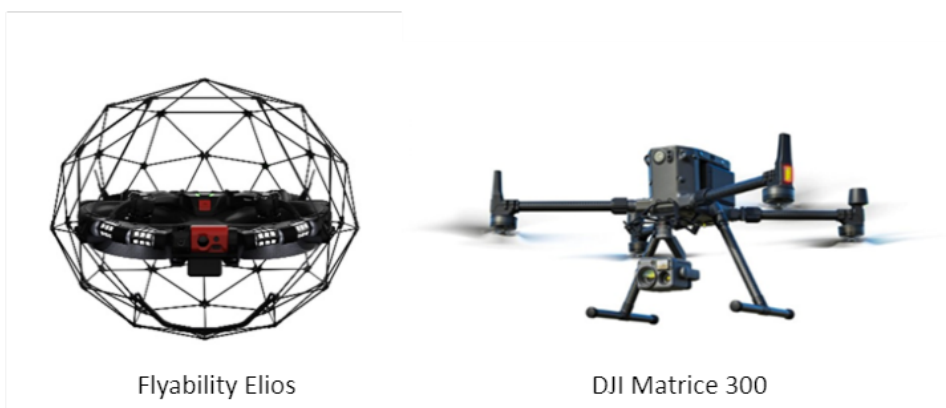


Figure 3-29 Samples of commercial aerial inspection drones.

Radiation Detection and Measurement Robots

Robots equipped with specialized radiation detectors for measuring radiation levels and mapping radioactive contamination areas within the nuclear facility. Figure 3-30 demonstrates some of the concerns facing robots in remote inspection tasks.

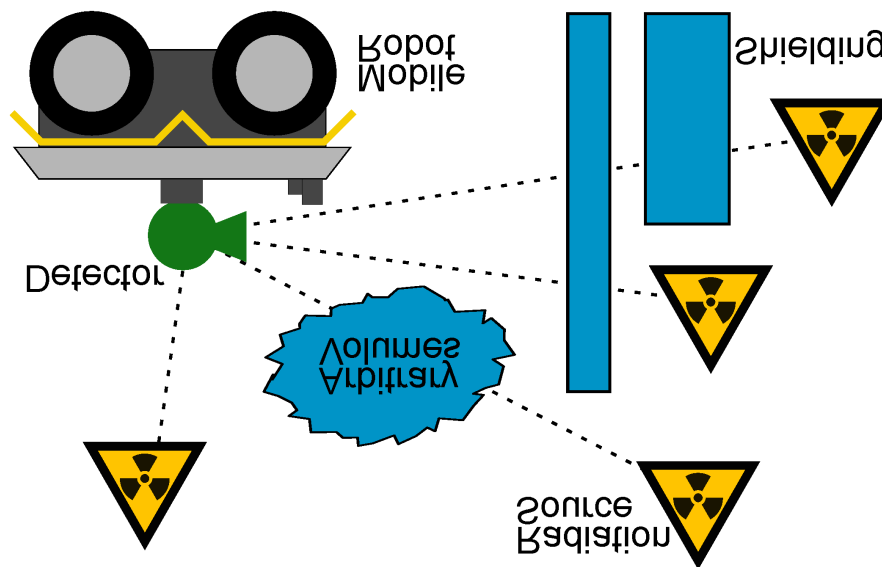


Figure 3-30 Example of issues facing robotic inspection tasks, with multiple radiation sources, detector sensitivity profiles and unknown environments (Wright et al., 2021).

Manipulator Robots

Robots with robotic arms or manipulators capable of handling tools and performing maintenance or repair tasks within the plant.

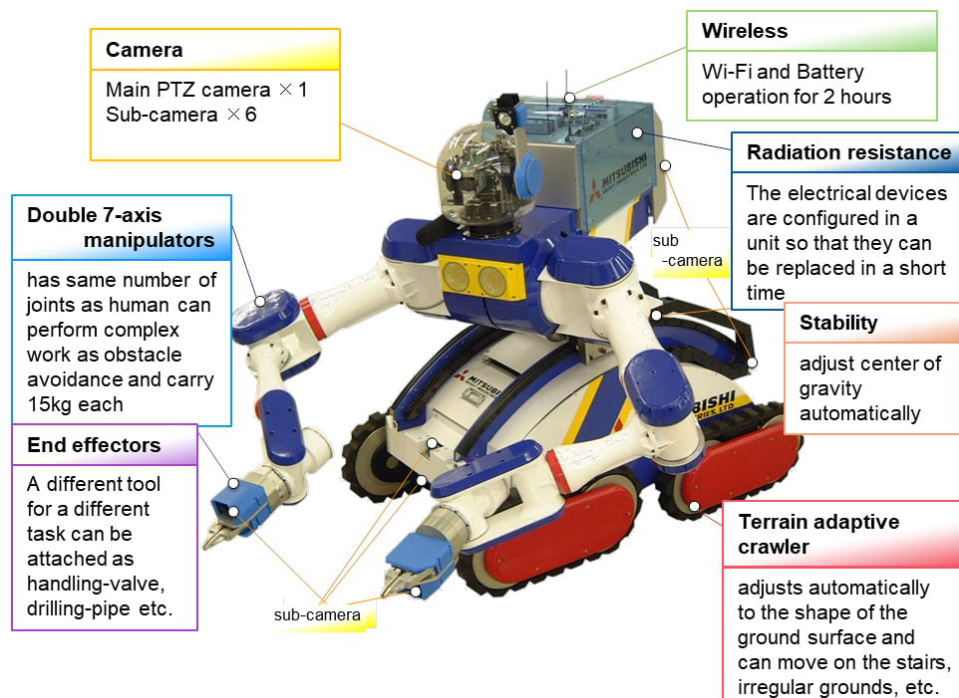


Figure 3-31 The MEISter, dual arm mobile robot designed by MITSUBISHI (Mitsubishi Heavy Industries, Ltd. Global Website | Dual Arm Mobile Robot (MEISter), n.d.)

Crawler Robots

Robots, Figure 3-32, designed to crawl on vertical or horizontal surfaces, including walls and ceilings, for inspections and assessments.



The Remotely Operated Robotic Crawler Solution for Confined Space Inspections in Nuclear Power Plants, designed by Eddyfi Technologies' robotic (<https://www.eddyfi.com/>)



Automated wall-climbing robot, designed by Hausbots (<https://hausbots.com/>)

Figure 3-32 Samples of commercial crawler Robots.

3.8.2 Application of drone scanning, Computer Vision approach

Image-based methods for defect detection and measurement based on the analysis of optical data such as images, videos, and 3D models using image processing and computer vision techniques have become popular in infrastructure's structural health monitoring (SHM). Image processing technology (IPT) has historically been the method of choice for detecting and evaluating defects. However, IPT relies on carefully designed feature extraction algorithms that impose limitations when seeking to autonomously extract high-level features from images because they are only effective for images with specific characteristics and their performance can be compromised by common types of noise including illumination, shadows, and surface imperfections.

These limitations can potentially be overcome using groundbreaking computer vision methods based on Convolutional Neural Networks (CNNs). The training of a CNN instills inherent feature extraction capabilities for detection, classification, and segmentation on multiple axes, significantly improving remote inspection by optical data. Computer vision techniques using CNNs are thus more robust and "intelligent" than conventional IPT approaches, enabling defect detection, classification, and localization in a way that resembles human visual reasoning.

The role of application of Artificial Intelligence (AI) in nuclear power plants is studied by (Lu et al., 2020), showing that computer vision, empowered by advanced image processing and pattern recognition, is able to play a pivotal role in the monitoring and analysis of nuclear power plants, offering transformative capabilities for safety enhancement and operational efficiency.

The primary goal of remote inspection is to detect damages as early as possible, allowing maintenance work to be carried out while minimising disruption. The strategy outlined here involves generating a digital model of a structure and then conducting a semi-automated damage detection process which can provide a comprehensive picture of the overall condition of the structure (Mirzazade et al., 2023). The strategy can be broken down into five steps as follows:

Step 1: Preparation of the site. Before an inspection, the site must be properly prepared. The client should tour the structure and its surrounding terrain to ensure easy access to designated spaces and take steps such as clearing vegetation which shades the site and removing dust from interior spaces. It is also important to provide good lighting in dark environments and place multiple control points on the structure for calibration and scaling of the 3D model.

Step 2: Image data collection. In this step, images of the structure are captured from various perspectives, following a predefined flight path. To ensure that the 3D model is accurate it is important that the flight path starts and ends from the same point. When planning the inspection, consideration must be given to the scale of the expected damages and the appropriate distance from relevant surfaces for the drone sensor in use. To obtain the most precise possible 3D model it is crucial that the images captured overlap. This step will be discussed further in the section “Drone scanning, data collection, and flight path”.

Step 3: Pre-processing and damage detection. This step starts with preprocessing and quality enhancement of the captured images, including background removal, brightness analysis, and blurring correction, to maximize the accuracy of the 3D model. However, the primary task at this stage is to apply deep learning classification and semantic segmentation algorithms to detect damages into the images collected. Two Convolutional Neural Networks (CNNs) are used for autonomous damage detection and pixel-wise segmentation, which is used to quantify the extent of any cracks detected.

Step 4: 3D model generation. The next step is to import the processed images into a photogrammetry algorithm to generate a 3D model and map the detected defects onto it. This step is described in section 3.4.2 part “Multiple-view approach”.

Step 5: Interactive platform: Although a detailed discussion is beyond the scope of this chapter, we suggest that the final stage of this strategy should involve the creation of a collaborative platform for sharing and inspecting 3D models of the structure. This would be hugely beneficial to the development of this new technology and its application in this field. Such a platform would ideally be useable on any device, enabling engineers and inspectors to access existing information, guidance, and equipment. It could incorporate numerous tools to assist with, for example, camera navigation, visual markup, and measurement, and more generally facilitate effective communication and collaboration between engineers, inspectors and other stakeholders involved in infrastructure maintenance.

These five steps constitute a comprehensive and innovative strategy for the successful remote inspection of the condition of specific structures, using drone scanning and a hybrid approach of photogrammetry and machine learning. Figure

3-33 summarizes these steps, each of which will be discussed in further detail in the rest of this section.



Figure 3-33 5-step strategy for remote inspection of concrete structures, using UAVs and computer vision.

Drone scanning, data collection, and flight path

Following preparation of the site as the first step, the starting point for 3D model reconstruction through image-based methods is image data collection. Images must be captured from various points of view, following a predefined flight path. To determine the best flight path for scanning a concrete structure, the following points should be taken into consideration:

- **Camera orientation:** the camera should be oriented to obtain optimal coverage of the structure while avoiding obstructions and ensure sufficient overlap between images.
- **Overlap and side-lap:** Both overlap (front-to-back overlap between consecutive images) and side-lap (side-to-side overlap between adjacent images taken in different lines) need to be extensive enough to ensure sufficient data for accurate 3D reconstruction. A general rule of thumb is to have a minimum of 60% overlap and 30% side-lap.
- **Working distance:** This has a major impact on the quality of the 3D model generated. Both the Ground Sampling Distance (GSD) and Field of View (FOV) should be calculated based on the specifics of the sensor being used for image acquisition. The GSD refers to the dimension of each pixel on the target surface, with smaller values corresponding to higher resolutions. Meanwhile, the FOV refers to the area on the target surface captured in each image, and larger FOV values mean that fewer images need to be captured. Therefore, the process involves first defining the expected scale of the defect to be detected, so that the GSD can be set to obtain the appropriate resolution, and then determining the optimum FOV and working distance, depending on the interior orientation of the available sensor, and minimum scale of the damage to be detected.

- **Waypoints:** The drone flight path should be planned using waypoints around the structure which will ensure that light conditions and GPS coverage are adequate, all areas of interest are captured, and the drone is kept within its operational limits.
- **Flight safety:** Safety guidelines relating to drone operations should be followed, and the flight path must avoid restricted airspace, other aircraft, and other potential hazards.

Equipment

When it comes to drone scanning, having the right hardware is critical to obtaining high-quality data. In this section we outline the essential equipment for remote inspection following the strategy outlined above. Key components include the drone, camera, navigation system, and any additional hardware that may enhance the data collection process, such as lighting equipment or a control station. By understanding the role and importance of each of these components, it is possible to ensure that the resulting 3D models are accurate and usable for various applications including remote inspection, virtual reality simulations, and visualisations. In this section we are going to explore needed hardware and software equipment for collecting and processing the data, detecting damages using the computer vision technique, and 3D model reconstruction.

Hardware

The following equipment is needed for data collection and processing to generate a 3D model of a concrete structure.

Drone: The drone should have stability and navigation features which enable a smooth and controlled flight. A mechanical gimbal should be installed to ensure that the camera remains stable during flight. The use of a GPS receiver and RTK system can greatly enhance the accuracy of drone positioning, generating a higher quality 3D model. A suitable device for storing large amounts of image data is also needed.

Typically, multi-rotor drones such as quadcopters or hexacopters are used for scanning big-scale structures, and they have the following features:

- Stable flight and hovering capability, for accurate image acquisition.
- Good payload capacity, for carrying a high-quality camera and other equipment.
- The ability to fly at low altitudes, for close-up images.
- GPS stability, to maintain accurate flight paths.
- Long battery life, for extended flight time.

Camera/other sensors needed: It is worth investing in a high-resolution camera which can capture images in appropriate detail. High-resolution digital cameras with a large number of pixels are essential for photogrammetry, as they provide the level of detail needed for damage detection and producing accurate 3D models.

The camera should offer manual control over ISO, shutter speed, and aperture, as these parameters can affect the quality of the images captured in various conditions.

The type of camera installed on the drone is a key consideration for designing the flight path as it determines the distance from the surface of the structure at which images can best be captured. The working distance, based on GSD and FOV, depends on the specific camera's sensor; as an example, Table 3-4, Figure 3-34 and Figure 3-35 show how these can be calculated as functions of the working distance of two different types of sensors.

Table 3-4 Interior orientation of the sensor used.

Lens	24 mm	20 mm
Aperture	f/2.8-f/22	f/ 2.8 - f/ 22
Diffraction-Limited Aperture	f/9.3	
Closest Focusing Distance	0.66' / 0.20m	0.25 m (0.82 ft)
Horizontal Viewing Angle	74°	84°
Diagonal Viewing Angle	84°	94°
Vertical Viewing Angle	53°	62°
Filter Diameter	58 mm	72 mm
Focal Length	24 mm	20 mm
Pixel Dimensions	6240 x 4160	
Pixel Size	5.75µm	
Sensor Size	35.9 x 24.0mm	
Shutter Speed	30-1/4000 sec in 1/3 stop increments	
Frame Rate	29.97 fps	

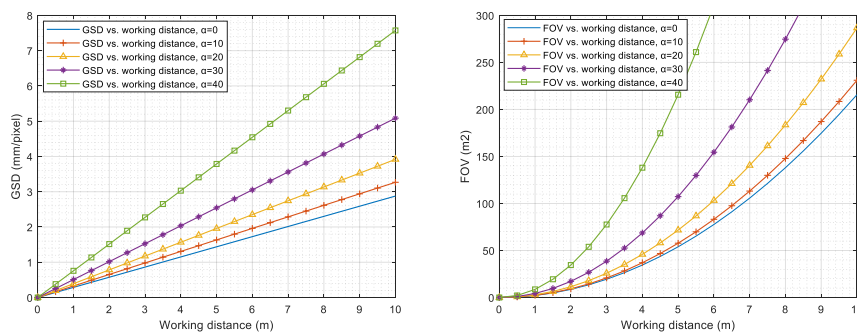


Figure 3-34 GSD and FOV as functions of working distance with a 20 mm lens.

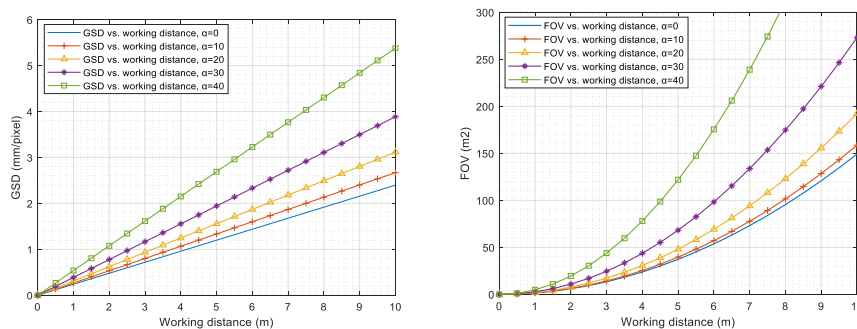


Figure 3-35 GSD and FOV as functions of working distance with a 24 mm lens.

After calculating the GSD and FOV, an appropriate Working Distance (WD) and tilt angle (α) can be selected to meet the objectives of the image collection. The graphs presented in Figure 3-34 and Figure 3-35 show that, at any given working distance, a 24 mm lens gives a lower GSD (i.e., a higher resolution, capturing more detail) than a 20 mm lens. However, its FOV is lower than that of a 20 mm lens, meaning that more images must be captured and processed to cover all surfaces of the structure. Consequently, scanning with a 24 mm lens requires more processing time and resources to generate a good 3D model. Use of a zoom lens (a mechanical assembly of lens elements whose focal length can be varied to maintain a consistent GSD at different working distances) can help to strike an optimal balance between processing time and resolution.

In addition to zoom lenses, other sensors may be necessary for drone scanning, depending on the specific requirements of the project. For example, LiDAR sensors can be used to generate a high-resolution point cloud of the structure, and thermal imaging cameras or multispectral cameras can be used to capture other data that may be useful for detection or documentation purposes.

The choice of sensors will have a significant impact on the accuracy, efficiency, and cost of a scanning project, and therefore requires careful selection according to the particular needs of the particular project in hand. It is also essential to ensure that the sensors are properly integrated and calibrated with the drone and camera, to ensure accurate data acquisition and 3D model generation.

GPS/GNSS: GPS and GNSS play a critical role in 3D reconstruction through photogrammetry. These systems are used to determine the location and orientation of the drone as it captures images of the structure. This information is then used to align the images precisely and create a 3D model. It is important to use a high-quality GPS/GNSS system that provides real-time positioning information with great accuracy and stability. A RTK (Real-Time Kinematic) GPS/GNSS system, which can provide centimetre-level accuracy, is able to do this.

It is also important to consider the type of antenna used. For outdoor photogrammetry applications, it is recommended to use a GNSS antenna with a high-precision receiver and low multipath error, and a high-gain patch antenna for GNSS signal reception. Using a RTK GPS/GNSS system and a high-precision antenna, the resulting 3D model should be both high quality and accurate.

Ground Control Points (GCPs): GCPs are physical markers placed on the ground in the vicinity of the object being scanned. These serve as reference points for photogrammetry software, providing accurate positional information for the images captured by the drone. GCPs are crucial for achieving accurate results in 3D model generation through photogrammetry. There are several important points to consider when deploying GCPs for drone scanning:

- **Placement:** GCPs should be placed in visible locations that are easily identifiable in the images captured by the drone. Ideally, they should be evenly spaced around the structure being scanned to provide comprehensive coverage.

- **Number:** The number of GCPs needed will depend on the size and complexity of the structure being scanned. A larger number of GCPs will provide more accurate results, but this increases the time and effort required to collect the data.
- **Accuracy:** This is critical to achieving accurate results, and the positional accuracy of the GCPs should be consistent with the accuracy required in the resulting 3D model. Common methods for measuring GCP accuracy involve using total station surveying or a RTK GNSS system.
- **Reflectivity:** The markers used for GCPs should be highly reflective to ensure they are easily identifiable in the images captured by the drone.

Assuming the above considerations are addressed, GCPs can be deployed very effectively to support accuracy and reliability in scanning and 3D modelling of the structure.

Software (Computer Vision algorithm for defect detection)

Computer vision allows for the classification, localisation, and segmentation of objects, mimicking the process of visual recognition in human vision. It offers improved efficiency and robustness for real-world defect detection. Computer vision techniques, unlike IPT, do not require manual threshold values or rules. Developing an intelligent machine involves selecting a suitable network structure, an evaluation function appropriate to the modelled output, and a reasonable optimization algorithm. The main advantage of computer vision is its ability to automatically extract features once the machine learning model has been trained.

Support Vector Machine (SVM) is a supervised machine learning method that has been used to detect cracks and corrosion during structural health monitoring activities, but it still requires the application of post-processing techniques, and only a single type of damage can be detected.

To overcome these limitations, deep-learning algorithms can be applied by using Convolutional Neural Networks (CNNs) to analyse inspection images. This approach allows for multiple classifications and the addition of new damage types without the need for post-processing. The advantage of using deep learning is that it is a data-driven method that does not require manually designed rules. Building a model simply involves selecting a suitable network structure, a loss function to evaluate the model output, and a reasonable optimization algorithm. Damage-sensitive features are automatically calculated while the CNN is being trained. This is a key advantage of this approach.

Recent advancements in damage detection using CNN have led to remarkable progress in classifying and locating individual damages from images. Object detection algorithms including Region-Based Convolutional Neural Networks (R-CNN) (Girshick et al., 2015), Fast R-CNN (Girshick, 2015), Faster R-CNN (Ren et al., 2015), Mask R-CNN (He et al., 2017), and You Only Look Once (YOLO) (Jocher et al., 2020) have evolved from simple image classification to multiple object (defect) detection, localisation, and segmentation.

Figure 3-36 shows the most common Image Processing Technique (IPT) and Deep Learning (DL) methods for damage detection:

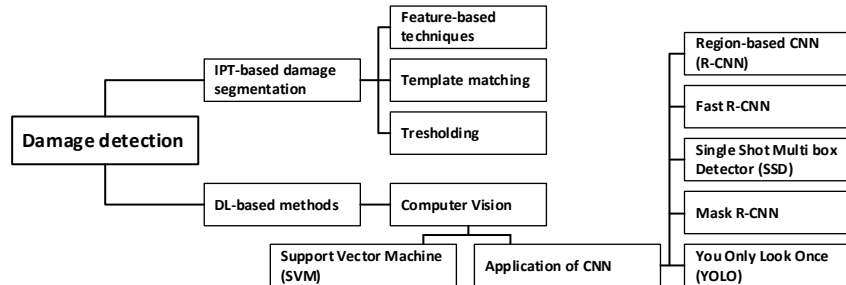


Figure 3-36 Common IPT and DL-based methods for damage detection.

Assessing concrete damages requires a 3D approach in order to generate precise quantification, localization, and documentation. Therefore, once damage has been detected on 2D images, the classified and segmented images are stitched together to reconstruct a 3D model of the structure. Detected damages are then mapped onto this 3D model of the scanned structure. The segmented damage can then be measured by determining the orientation of the camera's position for each photo relative to the detected defect. The workflow of this procedure, which is proposed by (Mirzazade, 2023) and illustrated in Figure 3-37, is summarised in five different steps: (1) data acquisition, (2) dataset preparation, (3) designing and training CNNs, (4) damage detection and localisation by splitting images into sub-images that are classified into "Crack" or "No Crack" areas using the CNN classifier, and (5) crack segmentation, mapping cracks onto a 3D model, and crack quantification.

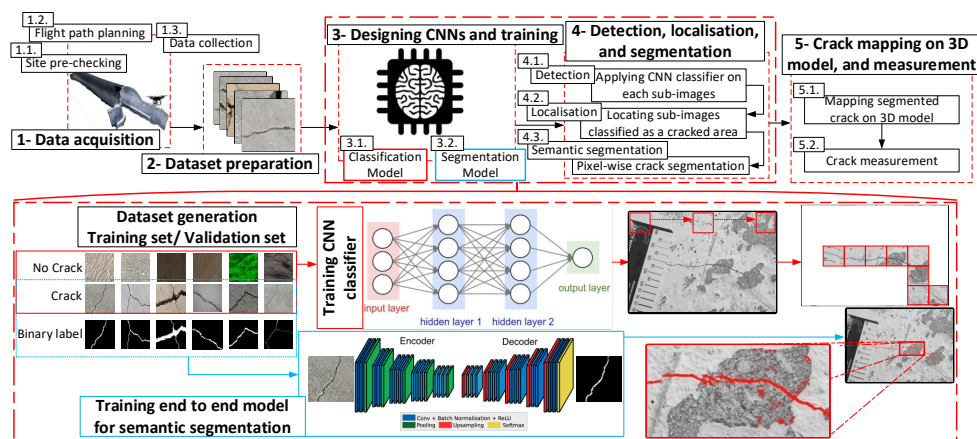


Figure 3-37 Workflow of the proposed method for automated damage detection and quantification.

However, the commercial product in both software and hardware for autonomous drone inspection of concrete structures is proposed by Qii.AI and Skydio as technology partnership and exist in the market.

Commercial product for remote inspection of concrete structure by drone scanning

Surveying nuclear assets presents inherent challenges, often necessitating inspectors to navigate confined and hazardous environments. By synergistically leveraging robotics alongside computer vision technologies, we not only enhance

operational efficiency but also establish a resilient framework for safeguarding the safety and reliability of nuclear power plants.

Qii.AI and Skydio have established a strategic technology partnership aimed at facilitating inspections with minimized risk to personnel. This collaboration offers a commercial solution enabling the utilization of drones for comprehensive survey imaging purposes. Subsequently, the cloud-based platform will meticulously organize the collected visual data and generate precise 3D digital replicas, providing an in-depth and accurate representation of assets (see Figure 3-38). These pioneering solutions serve as instrumental tools in mitigating the distinctive challenges encountered within the nuclear energy sector.

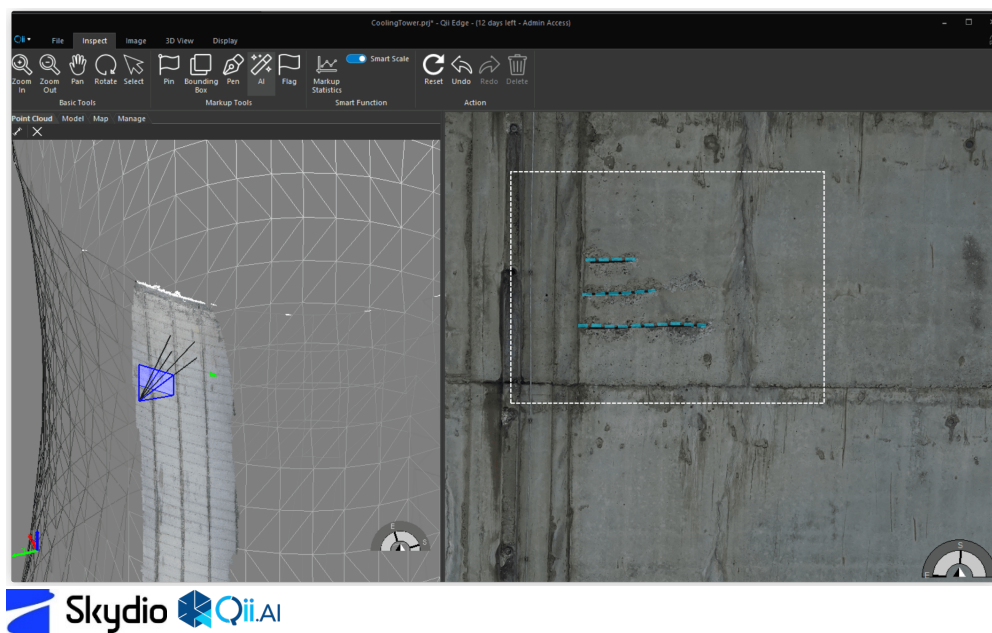


Figure 3-38 Survey cooling towers concrete shell.

4 Suggestion for future assessment of nuclear power plants

Image acquisition using UAVs is potentially valuable in nuclear power plant, because it can facilitate data acquisition from areas that are likely to be damage-prone and hard to access. Moreover, UAVs allow images of regions of interest (ROI) to be captured at close range and thus at high resolution, leading to improved pattern recognition and more accurate geometric dimensions measurement. However, 3D model generation based on close-range imaging have the drawback of requiring the capture and analysis of more images than alternatives based on longer-range imaging, leading to higher computational costs. To overcome this problem, the suggestion for future image-based remote inspection in big-scale concrete structures, with interest to find small-scale defects like crack, is application of Intelligent Hierarchical Dense Structure from Motion (IDSfM). This method can help to create 3D model of the structures with higher resolution on the areas with existing defects and proposed by (Mirzazade, 2023).

Real-time defect detection and segmentation methods using computer vision technology enable prompt detection of any types of defect during data acquisition. Therefore, such methods could be useful for strategically data acquisition with higher resolution images in defected areas leading to decrease computational resources in remote inspection. This section therefore investigated the scope for using data-driven computer vision techniques for defect detection on long-range images, and pixel-wise semantic segmentation on close-range images.

The evolution of Intelligent Hierarchical Dense Structure from Motion (IDSfM) (Mirzazade, 2023) has potential to represent a significant leap in defect detection within civil infrastructures. This method has been tested before on a silo, which is a big-scale concrete structure, and there are similarities with nuclear power plants regarding the size and type of the structure.

4.1 OBJECT DETECTION ON LONG-RANGE IMAGES

In the context of computer vision, the YOLO (You Only Look Once) family of algorithms stands out for real-time object detector model. This model strikes a balance between speed and accuracy, making it ideal for real-time defect identification on images or video frames. As it is illustrated in Figure 4-1, real-time defect detection can be obtained by application of computer vision, YOLO v5 model in this case (Mirzazade, 2023), during image acquisition from the surface of the concrete structures.

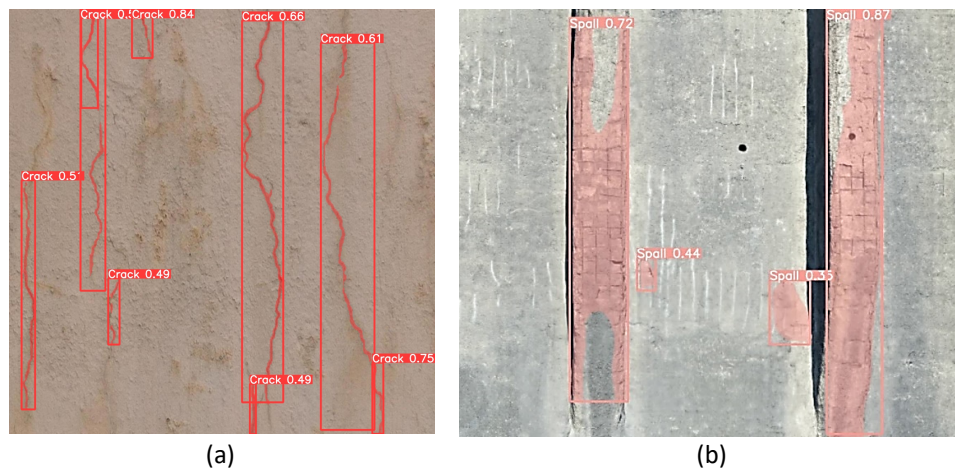


Figure 4-1 Detected cracks on the surface of inspected silo (a); Detected spalling (b) (Mirzazade, 2023).

Regarding the background of YOLO model, from the inception of this intelligent model in 2016 until the present year (2024), the YOLO family has continued to evolve at a rapid pace. Figure 4-2 presents the YOLO advancement timeline together with the popularity in using their GitHub repositories by researchers, engineers, or system developers. Over the course of its evolution, there have been 8 versions of the YOLO algorithm, of which YOLO v1, YOLO v2, and YOLO v3 originated from the YOLO research team (Redmon et al., 2016). Subsequent versions ranging from YOLO v5 to YOLO v8 were developed by other research groups and focused on real-time detection, classification, and segmentation with the aim of significantly reducing model size and improving performance.

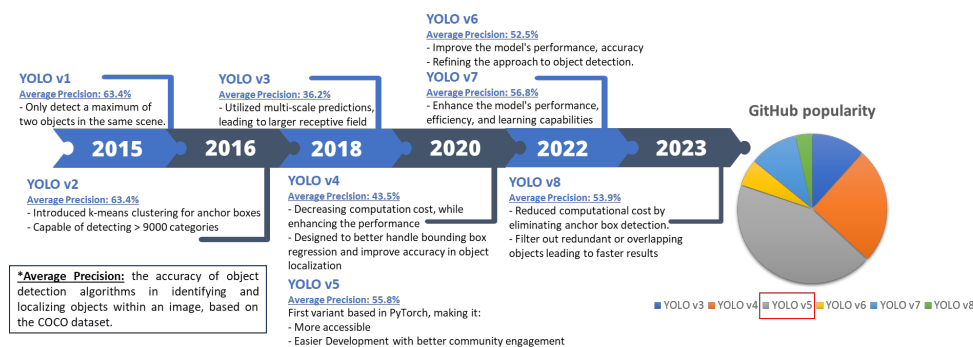


Figure 4-2 YOLO evolution timeline and GitHub popularity comparison.

In object detection, a rectangular box called a bounding box is used to find where an object is located (see bounding boxes in Figure 4.1 for crack detection). But when it comes to irregular shapes like cracks in existing structures, these methods don't work well because the cracks don't fit neatly into rectangular boxes. This means that while these methods can tell you where a defect is, they can't accurately identify the exact shape of the defect down to each individual pixel. To get more precise measurements of defects, we can use semantic segmentation methods, especially for close-range images. These methods help recognize defects on a pixel-by-pixel basis, giving us a more detailed understanding of the defect's shape and distribution.

4.2 SEMANTIC SEGMENTATION ON CLOSE-RANGE IMAGES

Semantic segmentation of detected defects in close-range images involves classifying each pixel within an image. Pixel-wise defect detection is helpful for accurately outlining and measuring defects. For this, End-to-End networks that consist of two cooperative sub-networks (encoding and decoding) can be beneficial to classify each pixel and thus segment the whole detected defect. For instance, U-Net (Ronneberger et al., 2015) showcase promising results in millimeter scale for concrete crack segmentation, as it is discussed by (Mirzazade, 2023) in big-scales concrete structures, Figure 4-3.

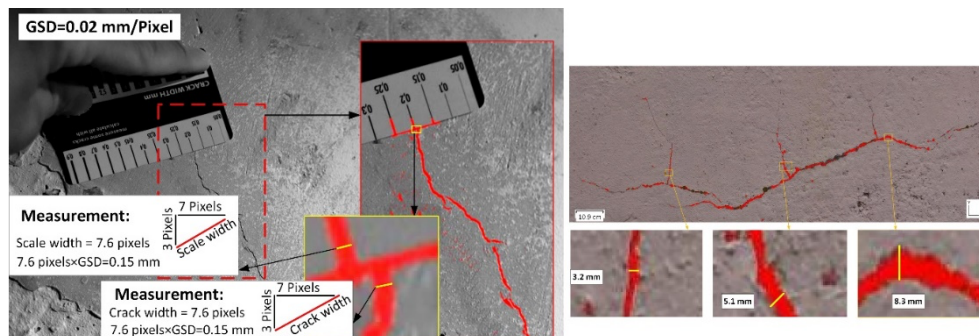


Figure 4-3 Crack measurement and validation, application of autonomous semantic segmentation (Mirzazade, 2023).

(Belloni et al., 2020) presented some preliminary findings that combines advanced deep learning techniques and innovative photogrammetric algorithms to develop a monitoring system. This method was based on the U-Net (Ronneberger et al., 2015) architecture which has been trained on a small available labeled dataset and tested on a large set of images acquired using a customized mobile mapping system. The results have shown that it is possible to effectively segment cracks in unseen imagery.

4.3 FIELD DEPLOYMENT

This part focused on the remote inspection of a concrete structure, a silo for this case, with application of IDSfM to enable more accurate defect measurement in sub-millimetre scale through the big-scale structure. Figure 4-4 shows the dimensions of inspected silo, while the objective is to detect and measure existing cracks in sub-millimetre scale. This approach complements traditional preliminary inspections by using drone scanning, to obtain images/videos of the entire silo's exterior (see Figure 4-5), and IDSfM approach.



Figure 4-4 Dimensions of the inspected concrete silo.

The fieldwork included the meticulous capture of images covering the entire external surface of the concrete silo; a total of 3,987 photos were taken to ensure the requisite 60% overlap in both the longitudinal and transversal directions. Notably, this drone-based scanning was done under predominantly overcast weather conditions. Although full access was available around the structure, specific areas, particularly those near pipes, conveyors, and other installations, presented operational challenges due to limited space for safe drone maneuvering.

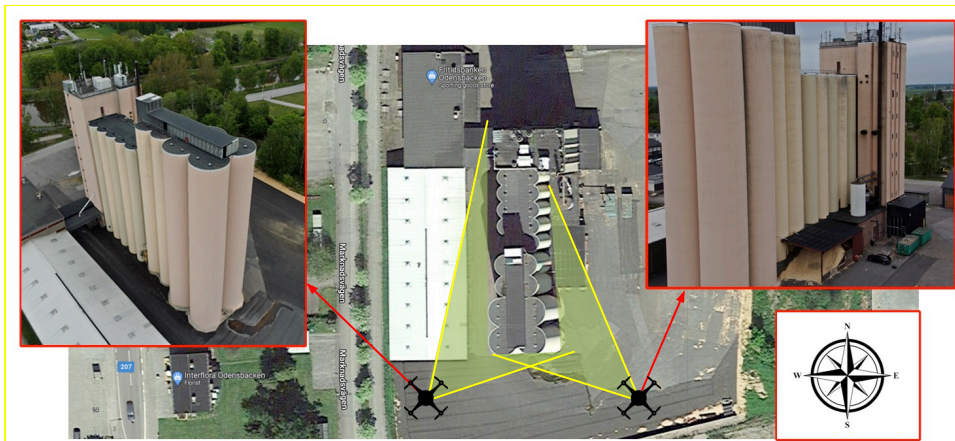


Figure 4-5. Aerial photos from the case study, a concrete silo.

Image acquisition was performed with a Matrice 300 RTK drone equipped with an H20T sensor, as shown in Figure 4-6. The H20T sensor comprises four distinct sensors that support the implementation of IDSfM. During the scanning phase, the drone captured long-range images through the wide lens, which were then analyzed using the real-time object detection model, YOLO v5. If cracks were identified within the field of view (FOV), the zoom lens captured close-range images of those specific areas. Subsequently, the collected images underwent processing using Agisoft PhotoScan Pro (LLC, 2017), a robust software package based on the Structure from Motion (SfM) methodology.



Figure 4-6 Matrice 300 RTK drone equipped with a H20T Quad-Sensor Solution unit.

A zoom lens is an excellent tool for capturing high-resolution images up close, while a wide lens excels at capturing images with a broader field of view. Real-time defect detection could thus potentially improve the generated 3D model by sending trigger to the data acquisition system to switch from the wide to the zoom lens when a defect is detected. This would enable the capture of high-resolution close-up images of the identified defects while the remaining areas of the structure are captured in less detail with the wide lens.

Converting images into a realistic 3D model of a structure allows inspectors to inspect it visually on a computer without having to worry about safety or time constraints in the field. The application of IDSfM facilitated the measurement of existing defects, even down to the sub-millimeter level depending on the camera's resolution, in large-scale structures, Figure 4-7. It also helps manage computational resources and memory usage effectively.

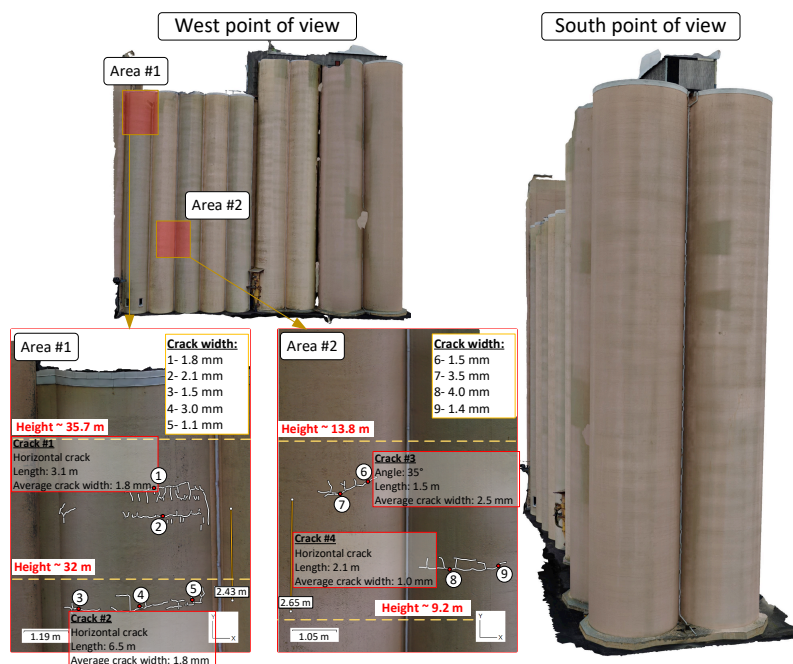


Figure 4-7 3D model with IDSfM approach, generated for remote inspection (Mirzazade, 2023).

This approach has the potential to complement the autonomous identification of defects and facilitates high-resolution texture acquisition of defect-prone areas and can be beneficial in the remote inspection of power plant infrastructures.

5 Conclusion and recommendations

The exploration of remote inspection methods for concrete structures has revealed the immense potential of advanced technologies in revolutionizing maintenance practices. Through advancements in remote visual inspection methods bolstered by techniques such as photogrammetry, laser scanning, and infrared thermography, combined with cutting-edge technologies like enablers and computer vision, it is evident that remote inspection technologies offer advantages in terms of accessibility, safety, and operational efficiency.

Recommendations for Current Application:

Drawing from the report's outlines, several remote inspection methods are recommended for immediate application in NPP concrete structures:

1. **Aerial and Terrestrial Photogrammetry:** Leveraging both aerial and terrestrial photogrammetry methods can provide high-resolution imaging and detailed 3D models for structural assessment. Both methods have demonstrated high accuracy, ranging from a few centimetres to several millimetres, depending on factors such as camera quality, flight altitude, and ground control points. These techniques are effective in identifying concrete cracks of various widths, leveraging high-resolution imagery and sophisticated processing methods.

Photogrammetry offers several advantages in remote inspection, including non-contact measurement, high accuracy, cost-effectiveness, rapid data collection, and accessibility to inaccessible areas. However, it also faces limitations such as sensitivity to environmental conditions, the requirement for skill and expertise, time-consuming data processing, accuracy degradation with distance, and limited depth perception.

2. **Infrared Thermography:** Utilizing high-quality infrared cameras can enable the detection of subtle temperature differences as low as a fraction of a degree Celsius and indicative of defects such as crack, delamination, moisture intrusion, and thermal bridging. High-quality infrared cameras offer spatial resolutions ranging from a few pixels to sub-millimetre levels, enabling precise detection of even sub-millimetre crack width depending on the working distance.

Infrared thermography offers advantages such as non-contact measurement, rapid inspection, early detection of anomalies, and non-destructive testing. However, it faces challenges such as surface emissivity variations, environmental factors affecting imaging results, limitations in resolution and sensitivity, and the requirement for specialized training and expertise.

3. **Laser Scanning:** Employing laser scanning technologies, including triangular, time-of-flight (TOF), and phase-based scanners, provide accurate measurements for capturing surface details and small features. TOF scanners offer longer range data collection, making them preferable for scanning large structures, with accuracies ranging from millimetres to

centimetres. Phase-based scanners offer high precision and accuracy, capable of detecting surface features with sub-millimetre accuracy and concrete cracks as narrow as a fraction of a millimetre. Careful consideration of scanner technology, range, speed, resolution, and accuracy is essential for optimal results.

Recommendations for Further Development:

While current remote inspection methods offer significant benefits, there are promising techniques that can potentially warrant further development and investigation in NPP concrete structures with hard to access inspection areas:

1. **Robotics and Autonomous Vehicles:** Existing enablers and robot, like climbers, drones and ground-based inspection robots were explored in the report showing promising ability to reach hard to access areas. Advancing robotic systems integrated with sensing technologies can enhance inspection capabilities, particularly in challenging environments within nuclear facilities. Continued research should focus on improving customized autonomy, mobility, and sensor integration for more efficient inspections based on project necessities.
2. **Machine Learning and Artificial Intelligence:** Application of computer vision technique in concrete structure inspection is explored in real case studies. Since, there are few real case projects in this area for concrete structures in nuclear power plants, further exploration of machine learning algorithms for automated defect detection augmenting the capabilities of remote inspection methods is needed. Research efforts should aim to refine algorithms and optimize data processing techniques for enhanced accuracy and reliability.
3. **Sensor Fusion and Augmented Reality:** Integrating sensor fusion techniques with augmented reality platforms can provide inspectors with enhanced visualization and decision support tools. Future research is recommended to explore the integration of these technologies to enable real-time inspection and analysis.

In conclusion, while current remote inspection methods offer significant benefits, ongoing research and development efforts are crucial to address remaining challenges and unlock the full potential of these technologies in ensuring the safety, reliability, and sustainability of concrete structures in nuclear power plants.

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REMOTE INSPECTIONS OF CONCRETE STRUCTURES

The development of remote inspection technologies is reshaping the possibilities for inspection and data collection for many types of large concrete structures. This report includes state-of-the-art and state-of-the-practice technologies within remote inspection of concrete structures. It showcases new solutions that address conventional constraints, including accessibility issues, environmental risks, and the imperative to reduce operational downtime.

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