State-of-the-art Technologies for Structural Health Monitoring of Tunnels: an Overview

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16. Abstract
This report presents the findings for the project "State-of-the-art Technologies for structural health monitoring of tunnels: an overview." It consists of a literature review in which the journal articles, highway agency technical reports, and textbooks are utilized. The outline of the report is as follows. We first review current tunnel construction techniques and discuss the application of SHM techniques to each of them. After reviewing the tunnel types, we review different monitored parameters in current practice and sensors needed to monitor these parameters. In the review we classified the sensors into two groups, following ACI PRC-444.2-21 [1]: 1) Sensors for Structural Response and 2) Sensors for Environmental Conditions and Loads. They were discussed in detail in the document, followed by conclusions and general observations.

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Table of Contents

Disclaimer ii
Abstract iii
Acknowledgments iv
Table of Contents v
Introduction 1
Review of Types of Tunnels 2
  Cut-and-cover Tunnels 2
  Rock Tunneling 2
    Drill and Blast 3
    Mechanized Tunneling Using Tunnel Boring Machines (TBM) 3
    Mechanized Tunneling Using Roadheaders 3
    Sequential Excavation Method (SEM) / New Austrian Tunneling Method (NATM) 3
  Soft Ground Tunnels 4
  Immersed Tunnels 4
  Jacked Box Tunnels 4
Current Monitoring Technologies for Tunnels 4
  Sensors for Structural Response 4
    Displacement (Contact and Contactless) 5
    Strain 5
    Tilt/Rotation 5
    Cracking/Fracture and Crack Motion 6
    Acoustic Emission 6
    Acceleration 6
    Velocity 6
  Sensors For Environmental Conditions and Loads 7
    Pressure 7
    Force/Load 7

Temperature 7
Humidity 8
Corrosion 8
Chloride Content 9
pH Value 9
Precipitation 9
Conclusions 10
References 11

Introduction

Tunnel monitoring is a unique field of Structural Health Monitoring (SHM). Tunnels are large-scale structures of crucial importance to transportation networks. The interactions between tunnels and their surroundings have a profound effect on both the tunnel and structures close by. The monitoring of tunnels thus consists of many different applications aimed at understanding the structural response of the tunnel and the interactions between the tunnel and its environment. Tunnel monitoring is regularly performed during the construction to guide the process. Different motivations for monitoring during construction can be found in practice. A reason for monitoring could be the optimization of support structures, as is the case with the New Austrian Tunneling Method (NATM), which is based on sequential excavation and real-time adjustment of the construction process based on monitoring information. Another reason is to protect the surrounding structures from the negative effects of large-scale excavation, for example by monitoring pore pressure reduction that can lead to excessive ground settlement nearby. Monitoring could be also done to improve the safety of the excavation process, for example by monitoring the state of the ground surrounding the excavation.

In terms of monitoring technologies used, many applications utilized traditional methods such as strain gages, fiber optic sensors, thermistors, and accelerometers. However, applications of more modern techniques such as computer vision and remote sensing can be found in the literature. It seems likely that these technologies would gain a more prominent position in the future. This is driven by two factors. First, the artificial intelligence (AI) technologies that are prerequisites of such applications are constantly evolving and diffusing to widespread use across industries. Second, tunnels are often extensive structures, possibly extending over several hundred yards or even multiple miles, making the installation of sensors both expensive and time-consuming. However, because of the many times superior accuracy of the physical sensor and the inability of imaging-based technologies of measuring some quantities such as some of the environmental factors, physical sensors will most likely remain in use for the foreseeable future.

This report presents the findings for the project *State-of-the-art Technologies for structural health monitoring of tunnels: an overview*. The aim of the project is to understand the current state of the art in structural health monitoring (SHM) of tunnels as well as to get a sense of the future tendencies. In the review, journal articles, highway agency technical reports, and textbooks are utilized. The outline of the report is as follows. We first review current tunnel construction techniques and discuss the application of SHM techniques to each of them. After reviewing the tunnel types, we review different monitored parameters in current practice and sensors used to monitor them. In the review we classified parameters into two groups, following ACI PRC-444.2-21 [1]: 1) *Sensors for Structural Response* and 2) *Sensors for Environmental Conditions and Loads.* The report closes with the conclusions and general observations.

Review of Types of Tunnels

According to the FHWA[2], the main types of tunnels, as grouped by construction techniques are:

1. Cut-and-cover tunnels
2. Bred or mined tunnels, built without excavating the ground surface
3. Rock tunnels
4. Soft ground tunnels
5. Immersed tunnels
6. Jacked box tunnels a monitoring example

Below, we review the main characteristics of these tunnel types and discuss the application of SHM for each tunnel type.

Cut-and-cover Tunnels

In the Cut-and-cover tunneling method a trench – the "Cut" in the method's name referring to its excavation – is first excavated and the tunnel structure is constructed in this excavation. After the construction the excavation is backfilled – this is what the "Cover" in the method's name refers to. [3]

Due to the large-scale excavation involved in Cut-and-cover tunneling, the effects on adjacent structures can be significant, as the excavation may significantly perturb the stability of soil and adjacent structure foundations. Because of this, monitoring campaigns to evaluate the effect on adjacent soil and structures are required. For this purpose, both ground movements and the adjacent structures themselves can be monitored.[2] Xiao et al. have demonstrated that in case of new cut-and-cover tunnel excavations, it is very useful to monitor in the vicinity of the tunnel the ground water level and soil settlement as well as structural element deformations in adjacent structures.[4] According to Chi et al. monitoring excavation support systems is beneficial for safety during construction.[5] Holmes et al. highlighted the importance of sufficient planning of monitoring campaigns. They present a case study where the monitoring systems are used to control the construction process. In their approach, the monitored parameters were grouped into primary and secondary parameters. The primary parameters had set trigger values and were used to control the construction. The purpose of monitoring secondary parameters was to improve the understanding of structural behavior of the tunnel itself.

Rock Tunneling

FHWA[2] presents the following classification for the major rock tunneling methods:

1. Drill and Blast
2. Mechanized tunneling using Tunnel Boring Machines (TBM)
3. Mechanized tunneling using Roadheaders
4. Sequential Excavation Method (SEM) / New Austrian Tunneling Method (NATM)

In this section, we will provide an overview of the rock tunneling methods above, except for SEM/NATM, which is considered both rock and soft soil tunneling method and which we will discuss in a separate chapter. In addition to providing an overview of the methods, we will discuss aspects of tunnel monitoring in relation to these methods.

Drill and Blast

Drill and blast tunneling method is a method based on drilling holes into the rock and filling these holes with explosives to remove rock. The holes are drilled in a pattern to control the shape of the resulting excavation. [2] The method is suitable for a wide range of rock types. [3]

The use of explosives (blasting) creates ground vibrations, which can have adverse effects on existing structures nearby. This risk necessitates monitoring during the project. [3] Because of the vibrations damaging effect, Peak particle velocity (PPV) is an important parameter to monitor [6][7].

Mechanized Tunneling Using Tunnel Boring Machines (TBM)

Tunnel Boring Machines are full face excavation machines that utilize a chipping of the rock material under shear stresses to remove the material and create space for the tunnel. The shear stresses are induced by the machine's rotating cutterhead that is thrusted against the excavation face. [2][3] TBM method can also benefit from monitoring methods. Because the method is based on using the machine, in addition to monitoring surrounding ground and structures, the machine itself can be monitored. One important parameter to monitor is wear of the cutter. Accurate knowledge of the cutter wear status is important to avoid unnecessary stoppages of works and reducing the need of inspections of the cutters that are risky for the workers health and safety.[8], [9] Jin et al. propose monitoring TBM cutter wear using chirped fiber brag grating (CFBG) method.[9] In tunnels excavated using TBM, the tunnel is often constructed of concrete segments [10], and the opening of the joints between these segments is an important monitoring parameter, to control leakage.[11]

Mechanized Tunneling Using Roadheaders

The TBM utilizes rotating tool, and because of this it is only suitable for excavating circular cross-sections. A machine called roadheader, or partial face boring machine, does not have this limitation. [3][2] It contains movable arm that enables positioning of drilling head so it can follow virtually any designed shape of the tunnel cross-section. The monitoring needs are similar to TBM.

Sequential Excavation Method (SEM) / New Austrian Tunneling Method (NATM)

SEM is a tunneling method where the fundamental principle is to utilize the supporting action of the ground combined with a thin shotcrete lining, instead of a thick lining. [2][3] The method has monitoring in its core. In the times of early applications stability of the lining could not be decided using computations, so displacement monitoring was used.[3] Monitoring is necessary for this tunneling technique, as it is based on continuous monitoring of the deformations caused by the excavation and adjusting the process accordingly.[2]

Soft Ground Tunnels

In general, large-scale tunnels in soft ground are realized using the SEM method, described earlier, or using shield tunneling methods, which we will discuss in this section. [2]

Shield tunneling is based on excavating the ground and constructing the tunnel support under a special structure called the **tunneling shield.** [3] The support structure typically used in shield tunnels is precast concrete lining, consisting of multiple segments.[3] The integrity of the joints between the segments is a key monitoring goal and Zhang et al presented a method of monitoring segment joint deformations using Distributed Fiber Optic Sensing (DFOS). [12]

Immersed Tunnels

Immersed tunnels are a type of underwater tunnel. In this technique, the tunnel structures are constructed on dry land and later submerged and placed into an underwater trench. [3] The tunnel structure consists of shell segments that are joined together after submerging. The segments are constructed using steel or concrete. [2] Chou presents an example of immersed tunnel deterioration assessment monitoring parameters such as: tunnel leveling, vibration, corrosion testing, joint displacement monitoring.[13]

Jacked Box Tunnels

Jacked box tunneling is a technique where a precast tunnel section (box) is jacked through ground that is excavated in small steps in front of the box using a shield. The method is beneficial because it offers a way to construct a tunnel with minimal interruptions to surrounding structures.[3] Structural monitoring can be utilized to protect the surrounding structures. In case of Central Artery and Tunnel ("Big Dig") project, monitoring was utilized to protect nearby railroad tracks during a jacked box tunneling operation.[14] In construction of the vehicular under-bridge, M1 motorway, J15A, monitoring settlements was used to protect the highway above the jacked box tunnel.[3]

Current Monitoring Technologies for Tunnels

In the review of monitoring technologies, we have classified the sensor technologies (and monitored parameters) into two groups: 1) Sensors for Structural Response and 2) Sensors for Environmental Conditions and Loads. In categorizing the measured quantities, we have applied the categorization of ACI PRC-444.2-21 [1], as applicable to tunnels.

Sensors for Structural Response

Here we present a review of the current applications of monitoring technologies for tunnels with respect to measurements of structural condition. We have subdivided the literature according to the measured quantity.

Displacement and Deformation (Contact and Contactless)

Displacement and deformation monitoring in tunneling is an important topic. Key motivations for monitoring displacements are to protect adjacent structures from the effects of tunnel construction or the tunnel from the effects of construction/excavation that is happening nearby. Another reason for monitoring the deformation of tunnels is as part of routine maintenance to guarantee safe operation by having an understanding of the structural changes over time, especially if the tunnel is crossing land-sliding area or if it was exposed to hazards such as earthquake, flooding, or fire. Two main displacement and deformation components of interest are convergence (local deformation of tunnel's cross-sections) and longitudinal deformation (when the tunnel is observed as long linear body).

Typical contact-based sensors are extensometers anchored deep in soil with the assumption that there is no movement of soil at their end point. However, these are discrete sensors installed with relatively sparce spatial resolution. To allow a convenient and cost-effective method of inspecting tunnel networks, that can be long so that contact-based measurements might not be feasible, different vision and laser-based solutions have been proposed. For example, Yue et al. present a displacement calculation method based on mobile laser scanning of railway shield tunnels. [22] They verified the method in subway tunnels. Monitoring tunnel displacements can also be achieved using remote sensing. Rocchegiani et al. present a study of ground displacements during tunnel construction using satellite imaging in the form of synthetic aperture radar multi-temporal interferometry (MT-InSAR). [23] Global deformations of the tunnel can also be inferred from strain measurements by applying appropriate data analysis algorithms [1].

Strain

The role of strain measurements in tunnel systems is to aid in the evaluation of the structural condition for safety reasons. The most frequently, strain is converted to stress, which in turn serves as the basis for evaluating structural safety. For this purpose, short-gauge, long-gauge, and distributed strain sensors can be used. Distributed strain sensors can be especially effective as they can cover the entire length of the tunnel and provide measurements with spatial resolution of 10 cm [1].

Tan et al. propose a real-time monitoring system based on fiber-optic strain sensors and water pressure sensors to function as an early warning system for underwater shield tunnel failure. [24] Wang et al. present a similar application of distributed fiber sensors for underwater shield tunnel structural performance evaluation. [25]

Tilt/Rotation

Another way to monitor deformation of the tunnel is indirect, through tilt monitoring. Wang et al. present an application of tilt sensors to monitor the structural condition, more accurately they measure the convergence of the tunnel, of a shield subway tunnel where the lining is constructed of precast segments. [26] Monitoring systems utilizing tilt sensors can be used not only to monitor the structural performance of the tunnel itself but also to assess the effect tunnel construction might have on surrounding structures. Acikgoz et al. used tilt sensors in conjunction with displacement and strain sensors to evaluate the effect of nearby tunnel construction on a heritage structure. [27]

Cracking/Fracture and Crack Motion

Identification of cracks and monitoring of crack progression is an important task of tunnel monitoring. Modern machine-learning methods have enabled the development of imaging-based crack monitoring methods. Some of the main benefits of these novel methods are due to their relative ease of setup and their non-contact nature.

Zhang et al. used high-speed complementary metal-oxide-semiconductor (CMOS) industrial cameras together with a machine-learning based image processing techniques to monitor and classify cracks in a subway tunnel. [20] Li et al. developed a convolutional neural network-based method for crack detection using imaging. [21] The data they used contained images of cracks in the walls of seven different tunnels.

Acoustic Emission

Acoustic emission method is used mostly to study different damage processes such as cracking in either concrete elements of tunnels or the rock surrounding the tunnel.

Manuello et al. studied damage progression in precast concrete arch elements [18]. Cheng et al. studied the physical state of the brittle rock in the excavation area using AE with the aim of producing data that would be helpful during the excavation process [19].

Acceleration

Acceleration measurements in tunnels is mostly used for studying the vibration response. This type of measurements can be useful in special situations such as studying blast loads or earthquake loads.

Li et al. used a wired accelerometer network to study the vibrations of an underwater shield tunnel [15]. Their work was had an interesting approach of applying edge computing to monitoring of tunnels. Yu et al. studied the vibration response of a soft soil tunnel subjected to blasting loads [16] Liu et al. present an application of acceleration monitoring to study microseismic events such as rockbursts to improve the safety during TBM tunnel construction. [17]

Velocity

Similar to acceleration monitoring, velocity is often measured to study structural behavior in special situations involving vibrations and dynamic loads, such as earthquakes and blast loading. It is important to note that these studies can be done not only for the sake of the tunnel itself, but also to protect important adjacent structures such as pipelines from the tunnel construction induced loads.

Liu et al. studied the peak particle velocity in the lining of a highway tunnel in a situation where adjacent construction involves blasting. [28] In their work they establish limits on the blast parameters that can safely be used in the adjacent construction. Guan et al. utilized velocity sensors to study the effect of tunnel blasting excavation on a nearby pipeline. [29]

Sensors For Environmental Conditions and Loads

Here we present a review of the current applications of monitoring technologies for tunnels with respect to environmental conditions and loads. We have subdivided the literature according to the measured quantity.

Pressure

Monitoring of pressure is done in order to evaluate the interaction between the tunnel construction and its surroundings. Quantities to monitor include mechanical pressure, and pore pressure.

Zhang et al. installed pressure cells between the primary lining and the secondary lining of a railroad tunnel constructed using the NATM tunneling method. [42] Their aim was to study the interaction between the first and second lining. Their results show that the interaction between the two layers develops over time. They show that due to the development over time of the loading on the second lining, curing of concrete and removal of formwork is a process that requires great care. This indicates that the use of load cells as they have presented might have some benefits in controlling the curing and formwork removal process. Zhao studied a subsea tunnel. [43] They monitored pore pressure in the surrounding soil, the contact pressure between the two linings of a subsea tunnel and the stresses in the circumferential reinforcement of the inner lining to understand the proportion of the hydrostatic pressure the tunnel lining is experiencing. Langford et al. reviewed data from 44 tunnel projects focusing on pore pressure reduction caused by tunnel construction. [44] Pore pressure reduction is a significant problem because it can lead to settlement and damage to structures near the tunnel construction. They recommend real-time pore pressure monitoring in future tunnel projects as a means to control the pore pressure reduction and protect adjacent structures from excess settlement.

Force/Load

In tunnel construction and design, ground loads and support loads play an important role. This is a particularly important consideration in NATM, where the ground support is crucial for supporting the tunnel structure. For this purpose, several types of sensors were developed, and the most frequently used are load cells.

He et al. monitored the ground loads in a tunnel and showed that the observed ground load in the weathered sandstone setting their tests were conducted does not agree with some of the theoretical approaches used to evaluate ground loads. [34] Their results show that monitoring methods have the potential to improve design procedures in form of more accurate load specifications. Ma et al. explored how force monitoring together with the application of intervention load can be used to improve the load distribution in the tunnel supporting structure. [35]

Temperature

The motivation for temperature monitoring in tunnels results from the needs to control the construction process and to separate the thermal influences from the mechanical influences after construction.

Yan et al. present an interesting application of temperature monitoring.[45] They present a case of a subway tunnel being excavated using artificial ground freezing to stabilize the soil. They monitor the ground temperature around the tunnel by using four 76 m long thermometer chains with thermometer spacing of 3m. They monitor the ground temperature for a period of 285 days. Zhang et al. present another interesting application of temperature monitoring to investigate the frost heave forces, which can damage tunnels in cold regions. [46] They explain that the measurement of the frost heave force is complicated because it needs to be separated from the original surrounding rock pressure. They apply a combination of temperature sensors in the surrounding rock and soil pressure cells to infer the frost heave force.

Humidity

Humidity monitoring in tunnels seems to be mainly related to understanding the conditions so the performance of lining materials and surface membranes can be investigated.

Wang et al. studied measured the temperature and humidity in a tunnel setting where geothermal energy could be expected to influence concrete curing. [36] They use the measurements to conduct laboratory tests of the strength development in such conditions. Holter and Geving conducted a similar study, except their purpose was to study moisture transport in tunnel linings, which in cold weather can suffer from freeze-thaw degradation. [37]To study moisture transport, they monitored temperature and humidity in a tunnel for two years. In addition, they took core samples from multiple tunnels and utilized a laboratory model of tunnel lining.

Corrosion

Corrosion is one of the most important environmental deterioration mechanisms affecting concrete structures. Many concrete tunnel linings have to withstand particularly aggressive corrosion environments, for example, subsea tunnels, tunnels in corrosion-inducing soil composition, or highway tunnels that can be influenced by deicing salts. Thus, corrosion monitoring is an important consideration for long-term management of tunnel condition and safety. However, available technologies are limited in application and performance.

Zheng and Lei show the application of three different types of corrosion sensors in the long-term corrosion monitoring of a large subsea tunnel. [32] The sensors were installed during the construction of the tunnel. Their monitoring campaign is ongoing, and the results should provide an understanding of the long-term performance and durability of corrosion monitoring systems. At the time of the writing of their article, the sensors had survived five years. Hire et al. present an interesting study in corrosion monitoring where the corrosion process itself is used to power the transmission of data from the wireless sensors to the data collection location. [33] Their result is important because it shows that monitoring systems could potentially operate long times without the need for intervention in the form of changing batteries, even if a fixed power supply is not installed. This is a particularly important consideration in tunnel settings because tunnels are almost by definition difficult locations for any type of intervention.

Chloride Content

Chloride penetration into concrete is a major cause of corrosion. Because of this, concrete-lined tunnel long-term performance management can benefit from the utilization of chloride content (penetration) monitoring. While the sensing technologies for continuous non-destructive chloride content monitoring exist, there is a space for improvement in terms of their accuracy, and the developments are ongoing (e.g., see [47]).

An interesting application presented by Mayer et al. is to utilize chloride monitoring systems to decide when a protective surface treatment needs to be reapplied.[30] Mayer et al. present a case study of a highway tunnel where they measure electric resistivity to understand the depth of chloride ingress in concrete tunnel walls. [30] The study in question is done in order to understand the long-term performance of concrete surface treatment applied with the purpose of stopping chloride penetration. Raupach and Schiessl developed a monitoring system able to measure the depth of critical chloride content in concrete and deployed the system in a tunnel located in soil with high chloride content. [31]

pH Value

PH value is an important parameter for the corrosion of reinforcement steel. Zheng et al. implemented a multiparameter corrosion monitoring campaign in a subsea tunnel. [32] PH level was one of the parameters they chose to utilize for corrosion monitoring of the tunnel. It is important to note that in some applications, pH might be a more important parameter than in others. For example, sewage tunnels are subjected to microbiologically induced corrosion, in which pH is an important parameter. [38]

In addition to its importance to corrosion processes, pH value monitoring can be utilized to evaluate or safeguard against the environmental effects of tunnel construction – mainly effect on water quality. The concern over adverse environmental effects can be explained by either worry about the harmful chemicals used in construction or the sensitivity of the environment in which the tunnel construction is taking place. Hedrick et al. present a case of tunnel construction in the Great Smoky National Park. [39] They monitored the water quality in sensitive streams in the area of the tunnel construction, which in this case was not a new construction but a reconstruction of old tunnels. One of the key parameters monitored was the pH level of the streams.

Precipitation

The motivation for precipitation monitoring is the development of models and mitigation measures for water inflow into the tunnel during rainfall. This is in some cases a significant problem and a safety hazard, especially during tunnel construction. It is not clear from literature if individual monitoring is required for each tunnel to create mitigation measures, or can general principles be created.

He et al. utilized precipitation modeling as part of a monitoring campaign with the purpose of investigating the conditions leading to water inrush situations during tunnel construction. [40] Their results show that there is a lag between rainfall and the induced water inrush. Lin et al. utilized precipitation monitoring combined with monitoring of tunnel water inflow to develop and verify a model to predict water inflow during heavy rain. [41] They verified the model in the area of a tunnel where construction had to be halted on multiple occasions due to water inrush.

Conclusions

This work reviewed the literature on SHM techniques in tunnel settings. We first reviewed majority of the tunnel construction types in contemporary practice and the typical SHM applications connected to each tunnel type. After this, we reviewed the most typical parameters monitoring in tunnels. In reviewing the monitoring parameters, we followed the taxonomy presented in ACI PRC-444.2-21. According to the taxonomy of ACI PRC-444.2-21, monitoring parameters are divided into 1) *Sensors for Structural Response* and 2) *Sensors for Environmental Conditions and Loads.*

In terms of sensors for the structural response, the monitoring of tunnels to a large extent resembles other applications of SHM. An overarching motivation for measurements of quantities describing structural response, such as strain and displacement is the evaluation of safety and detection of potential damage and tracking of damage evolution. We could identify two factors differentiating the monitoring of tunnels from general SHM. First, in evaluating the structural response and potential damage, in tunnel construction, in addition to monitoring the structural response of the tunnel itself, large importance was placed on the monitoring of adjacent structures during tunnel construction. This is viewed as important in the practice because tunnel excavation has the potential to damage structures nearby. Second, in addition to monitoring the structural response of the tunnel structure itself, monitoring the soil or rock around the tunnel is also important. For example, the acoustic emission method can be used to evaluate the state of the rock around the tunnel, which might have implications for the construction process. In addition, the NATM method of tunneling is based on monitoring the response of the ground around the tunnel, as the real-time construction decisions are made utilizing measurements of the ground response.

The relationship between a tunnel and its environment is complicated and important. On one hand, tunnels are often in demanding environments that have the potential to affect the condition of the tunnel adversely. On the other hand, the construction of tunnels can have adverse effects on its surroundings. The monitoring aim of monitoring campaigns related to parameters categorized to "environmental conditions and loads", will typically be around understanding, and mitigating the adverse effects caused by the surrounding environment to the tunnel, or vice versa. Like in other applications of SHM for concrete structures, applications include monitoring of critical long-term deterioration parameters, mainly factors influencing corrosion of reinforcement. The parameters monitored that are more specific to tunnel applications are mainly related to the interaction of the tunnel with the ground, such as pore pressure decrease caused by tunnel construction and monitoring of precipitation to improve mitigation of water inrush risk.

In terms of monitoring technologies used, many applications utilized traditional method such as strain gages, fiber optic sensors, thermistors, and accelerometers. However, applications of more modern techniques such as computer vision and remote sensing can be found in the literature. It is likely that these technologies would gain a more prominent position in the future. This is driven by two factors.

First, the artificial intelligence technologies that are prerequisites of such applications are constantly evolving and diffusing to widespread use across industries. Second, tunnels are often extensive structures, possibly spanning multiple miles, making the installation of contact-based sensors both expensive and time-consuming. Contactless monitoring technologies such as the ones based on computer vision or remote sensing have a significant benefit for tunnels because of that advantage. For example, there exist applications for monitoring subway tunnel lining deformations using an imaging system mounted on an inspection vehicle. Such a vehicle can conduct inspections of large tunnels rapidly. The benefit of these systems is also that the same monitoring system can be utilized in multiple tunnels, unlike physical sensors that are installed permanently or semi-permanently into a specific tunnel. However, because of the many times superior accuracy of the physical sensor and the inability of imaging-based technologies to measure some of important parameters, e.g., some of the environmental factors or subsurface parameters, physical sensors will most likely remain in use for the foreseeable future.

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