Article

Smart System for Utility Tunnel Management

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Abstract: This paper presents how the Smart Technology could help in addressing the challenges of the Utility Tunnel, which hosts in the same space several utilities. This technology offers large advantageous such as the possibility to inspect, maintain and extend easily urban utilities without excavation and then to eliminate disturbance related to urban excavation such traffic jams, noise, pollution and pavements degradation. However, the use of this technology is yet below expectations, because an incident in space could lead to a chain of incidents and to the interruption of basic urban services. The management of this space constitutes also a major challenge, which should be properly addressed in order to increase confidence in this space and to provide guarantees for utilities concerning the respect of their requirements as well as the transparency of the governance and economic model. The recent development in the field of Smart Cities offers new opportunities to improve the security and efficiency of complex urban systems. This paper presents how this technology could help both Utility Tunnel operator and utilities managers to address the challenges of the Utility Tunnel. After a presentation of the Utility Tunnel challenges and the Smart City concept, the paper presents the construction of a Smart System for the Utility Tunnel, with emphasis on the system architecture, monitoring, inspection & maintenance, information system, data analysis and system control. It shows that the use of this technology constitutes an effective response to the challenges of the Utility Tunnel.

Keywords: Utility Tunnel; Disturbance; Management; Smart City; Smart Grid; Information System; Smart Monitoring; Data Analysis; Intrusion; Artificial Intelligence; Utilities; Security

Introduction

The Utility Tunnel is an underground easily accessible space, which could host a wide range of urban utilities such as water supply, water drainage, electrical power, gas, heat and telecommunications as well as other public services. This space has also its proper equipment for lighting, communication, ventilation, drainage, access control, and firefighting. It offers the possibility to realize inspection, maintenance, renovation and extension of utilities in safe condition without the necessity to make excavation or street cuts [1-4]. Consequently, it reduces traffic congestion as well as working noise and pollution due to pavement cutting and trenching. It reduces also pavement maintenance expenses by increasing the pavement lifespan. It facilitates utilities inspection and reduces the cost related to their maintenance, because maintenance could be conducted more easily under any climate condition and use of the public space. The construction of utilities tunnels highly contributes to the sustainable development of the urban underground space, because it optimizes the use of this space for utilities and public services purposes [5-7].

Despite the large advantages of the Utility Tunnel technology, its implementation is below expectations, because of several barriers and disadvantageous, which were discussed in previous papers [8-10]. The major barrier concerns the security of hosted utilities and their Service Continuity. Indeed, an incident in the Utility Tunnel could lead to a chain of incidents and to the interruption of
urban services such as energy, telecommunication and water. Incidents could result from technical problems such as water leak, flood, gas leak, electrical outage and fire or from maintenance operations or vandalism and sabotage. The Utility Tunnel is subjected also to additional difficulties, which are related to the governance and economic model of this “shared” space [11-13]. Since utilities have specific requirements, they are generally worried about the respect of these requirements in this “shared” space. Difficulties concern also the quantification of the benefits of each utility and establishing an appropriate share of investment and exploitation expenses among beneficiaries.

The management of the Utility Tunnel constitutes a major challenge, which should be properly addressed in order to increase confidence in this space and to provide guarantees for utilities concerning the respect of their requirements as well as the transparency of the governance and economic model. The recent development in the field of the Smart Grids and Smart Cities offers new perspectives for the optimal and safe management of complex urban systems. These concepts are based on an interdisciplinary approach of urban systems including smart monitoring of urban systems as well as the use of advanced tools for data collection, analysis, learning and system control [14-18]. This paper presents how the application of this technology could help operators to address the challenges of the Utility Tunnel management. After a presentation of the Utility Tunnel challenges and the Smart City concept, the paper presents the application of the Smart Technology on the Utility Tunnel management with emphasis on the Smart Solution architecture, monitoring, inspection & maintenance, information system, data analysis, and system control.

Utility Tunnel Advantageous and challenges

The Utility tunnel is an accessible underground space, which aims at hosting a wide range of utilities such as water supply, water drainage, electric power, gas, heat and telecommunications. It could also host other public services, which are compatible with urban utilities.

Advantageous of the Utility Tunnel were discussed in many papers [1-7]. Figure 1 summarizes these advantageous. The great advantageous of the Utility Tunnel concerns the possibility to install, inspect, maintain and extend utilities in a safe environment without the necessity to operate street cut or excavation. Consequently, this technology reduces disturbances resulting from direct embedment of utilities in the underground. It reduces traffic congestion as well as working noise and pollution due to street cutting and trenching. It reduces also urban pavement maintenance expenses by increasing the pavement life span. It facilitates utilities inspection and maintenance under any climate condition or use of the public space. Consequently, it reduces the expenses related to their maintenance. The risk of utilities damage during excavation work is reduced, because blind digging risk is eliminated. Utility Tunnel reduces also corrosion of buried utilities, which results from the contact of corrosive utilities with humidity and chemical components in the soil [8, 10].
Figure 1. Main advantageous of the Utility Tunnel.

In addition, utilities built using traditional technology are subjected to damage risk due to soils settlement. This risk is eliminated by the Utility Tunnel [13]. Moreover, traditional utilities suffer from the high cost of their inspection and of the impact of inspection on the disturbance of traffic and other urban services. According to [19], lack in utilities inspection constitutes the principal failure hazard to utilities. The use of utility tunnels facilitates utilities inspection, and consequently, increases their reliability as compared to the conventional installation practice.

[5-7] consider that the Utility Tunnel highly contributes to the sustainable development of the urban underground space, because it optimizes the use of this “nonrenewable” space for utility and urban services purposes. Thanks to these advantageous, the Utility Tunnel has been used in many cities in the world [3, 20-24]. The Utility Tunnel technology is largely used in China. According to [25], about 69 cities in China are building underground utility tunnels with a total length of 1000 km; this length will exceed 1 600 km in 2020.

Utility Tunnel Challenges

Figure 2 summarizes the main challenges of the Utility Tunnel. Considering the role of this facility in providing basic urban services such as energy, water and telecommunications, it constitutes a critical infrastructure for cities. Consequently, the major challenge of the Utility Tunnel concerns the Service Continuity of hosted utilities and related services. Any serious incident in the tunnel could result in a chain of incidents and to the interruption of urban services. Incidents in the Utility Tunnel could result from technical problems such as water leak, flood, gas leak, electrical outage and maintenance operations. The Utility Tunnel could also be subjected to vandalism, sabotage and terrorism actions. Consequently, the security of the Utility tunnel constitutes a major concern for public authorities as well as for the tunnel operator and clients [8,10, 26]. Utility tunnels are highly complex systems with “synergistic” characteristics, which designates the occurrence of combined actions which have greater total effects than the sum of their individual parts [27].

Fire constitutes the major risk for the Utility Tunnel. Several papers showed the necessity to establish fire-safety strategy for the Utility Tunnel including restrictions on the use of materials in the tunnel construction and equipment, compatibility of hosted utilities, tunnel compartmentalization, tunnel access, escape means, use of fire early detection system, smoke control, fire extinguishment and ventilation [28]. According to a report of the Federal Highway Administration, flood constitutes also a serious risk for the safety of the Utility Tunnel [4].
Liability and management of the Utility Tunnel constitutes also a major challenge for companies who share the same critical space [7, 11, 12]. Generally, companies do not accept liability involving risk of explosion, flood, and the presence of other company working in the same space. Consequently, Utility Tunnel owner and operator should present guarantees about the safety and security of the Utility Tunnel exploitation.

The Utility Tunnels is subjected also to difficulties related to the governance and economic models of this “shared” space [11-13]. Since utilities have specific requirements, they are generally worried about the respect of their requirements and also to the transparency in the determination of utilities benefits as well as the share of investment and exploitation expenses.

The complex challenges of the Utility Tunnel constitute a major barrier to their development and use. The Smart Technology allows to meet these challenges through the construction of a comprehensive management system including monitoring, control of security equipment and advanced data analysis, that allow to detect quickly any incident in the tunnel and to apply adequate procedures to confine this incident, repair its origin and re-establish the system functioning. The system ensures that hosted services do not fail or that their failure is recovered within acceptable time limits. The following sections show how the Smart Technology will help in the construction of this comprehensive management system.

**Smart City concept**

The Smart City concept is based on an interdisciplinary approach of urban systems [14-18]. It consists in using both digital technology as well as social and economic innovations for the optimal and safe management of cities. The focal point of this concept concerns the efficiency of urban systems, quality of life for citizens as well as development of friendly urban environment, that preserves natural resources and reduces pollutants emission. The Smart City concept includes a friendly digital environment, that provides citizens with pertinent information about urban systems and services. In addition, the Smart Technology offers the capacity to confine a local fault and consequently to prevent its extension to larger areas. This technology provides public authorities and city stakeholders with pertinent data and information concerning the real performances of urban systems as well as stakeholders’ response to urban crisis or disasters. These data are crucial to improv the city capacity to address resiliency challenges.

Figure 3 summarizes the implementation of the smart city concept. It includes data collection from different urban systems including infrastructures, services and environment [7-11]. Collected data are then verified, cleaned and stored in an information system, which constitutes the heart of the Smart City system. Data could be enhanced by images, videos and audios resulting in the construction of urban Big Data [29, 30]. Analysis of real-time and historical data includes different issues such as identification of general trends in urban systems responses, security and performances analysis, machine learning, development of prediction models and their use to improve the city management.
Figure 3. Implementation of the Smart City concept.

Utility Tunnel Smart System Management

Specifications

The smart management system of the Utility Tunnel aims at developing an inclusive digital system that uses the latest technology in smart monitoring, data collection, data analysis, system control and data share to meet the requirements presented in figure 3.

Figure 4 summarizes the specifications of the Smart System Management. It should perform data collection concerning the tunnel and hosted utilities assets and exploitation using smart sensors as well as smart tools for the tunnel inspection and maintenance.

The system should also perform real-time and historical data analysis using conventional engineering and security tools as well as advanced ICT tools such as BigData, Artificial Intelligence and Augmented Reality.

The system should also incorporate advanced tools for resilience management such as establishing smart procedure for incident management, incident early detection as well as for effective incident response to ensure the Service Continuity. The ACT tools such as Artificial Intelligence are used to enhance the Utility Tunnel resiliency. The system should edit and diffuse incidents reports as well as performances reports.
Figure 4. Specifications of the Utility Tunnel Smart Management System.

Architecture

The architecture of the Smart Management System is presented in figure 5. A Smart Management Platform ensures the coordination of the system, which includes the following layers: managers layer, physical layer, monitoring layer, inspection and maintenance layer, information system, analysis layer and control layer.

Figure 5. Architecture of the Utility Tunnel Smart Management System.
Managers Layer

The managers layer includes the operator of the tunnel as well as the managers of hosted utilities. The tunnel operator is in charge of the management of the tunnel, which consists in ensuring the tunnel security as well as the operational conditions for utilities according to the agreement between the tunnel owner and utilities managers. The Utility Tunnel management requires the creation of a Management Committee, which is composed of the tunnel operator and utilities managers. This committee shares information about the exploitation and security requirements of each utility as well as the general requirements for the tunnel exploitation and security. This committee is in charge of analysis of utilities interactions, in particular the impact of any incident in the tunnel on utilities. It establishes procedures to be followed in case of any incident.

Physical Layer

The physical layer corresponds to the tunnel and hosted utilities as well as their equipment. This layer is subjected to strict exploitation and quality control requirements, including operational conditions and performances as well as monitoring, inspection and maintenance.

A 3D digital model is constructed for the digital representation of the tunnel and utilities assets. This model includes digital identification as well as geo-localization of the tunnel and hosted utilities components. Each component is equipped by RFID tags, which provide dynamic information about the component including manuals, guides, photos and videos. BIM is used for the construction of this model as well as for the asset management and 3D visualization.

Monitoring Layer

The monitor layer concerns both the tunnel and hosted facilities.

Tunnel Monitoring

Figure 6 illustrates the smart monitoring of the tunnel. It includes smart sensors to follow indoor conditions such as temperature, humidity, air quality, smoke, gas emission and water infiltration.

Survey cameras are used to track illegal intrusions in the tunnel. Staffs access to the tunnel is controlled using digital identification system for each staff member. This system provides information about the identity of the member, his contact and hierarchy as well as the authorized area in the tunnel. In addition, each presence in the tunnel is tracked using internal geo-localization system [31, 32]. At each instant, the system provides the identity of staff members in the tunnel as well as their positions. This information is crucial for security requirements. The system provides also the history of presences in the tunnel.

Tunnel monitoring concerns also the tunnel equipment such as tunnel access (open/closed, identity of users), compartmentalization equipment, ventilation system (debit, temperature..) and the lightening system (on/off, color).
Utilities Monitoring

The smart technology achieved a high maturity level for utilities management. The use of this technology in the Utility Tunnel is facilitated by the ease access to utilities and favorable environmental conditions for the monitoring system. Figure 7 summarizes the smart monitoring of the following systems: drinking water, water drainage, district heating and electrical grid.

The drinking water system is monitored by AMRs (Automatic Meter Reading) to measure water debit, pressure cells to record the water pressure and water quality sensors for on-line control of the water quality (Turbidity, pH, Temperature, chlorine, conductivity,...). This system allows rapid detection of water leakage and water contamination.

The drainage system uses sensors to follow the water level and flow in the tunnel, water quality (turbidity, temperature, pH, ..) and pumping equipment. This system allows early detection of flood in the tunnel and faults in the pumping equipment.

The electrical grid is monitored by smart sensors to measure the electrical tension, current and frequency as well as switches status (on/off) and the electrical wires temperature. This system allows early detection of faults in the electrical grid.

The heating system is monitored by sensors that record fluid temperature, pressure and flow as well as the state of valves (open/off). This system allows early fault detection in the heating system as well as the improvement of the system performances.
The inspection and maintenance of the Utility Tunnel constitute a major concern for the tunnel and utilities safety and performances. Requirements and procedures for the smart inspection and maintenance of each component of the tunnel and hosted utilities should be established and coordinated by concerned managers. Each inspection and maintenance intervention should be controlled and result in an on-line “intervention report”, which is transmitted to concerned staffs and authorities.

Figure 8 illustrates how the Smart Technology could help in improving the quality of inspection and maintenance of the tunnel and hosted utilities. In addition to the digital identification and geo-localization of the tunnel and utilities components, each component is equipped by inspection and maintenance RFID tags, which are connected to the “Tunnel Management Platform” via mobile application.

The inspection tag provides both inspection historical data and procedure. It allows via specific protocol to control the inspection quality as well as on-line reporting. The inspection report could include sheets, images and videos. The report is then automatically transmitted to staffs concerned by the inspection, with alerts in case of any need for urgent intervention.

Robots could be used for the inspection of the tunnel using inspection cameras as well as tags for the localization of the tunnel and utilities components.

The maintenance tag is used to improve the quality and control of maintenance. The RFID maintenance tag is used in the same way as the inspection RFID tag to improve and control the quality of maintenance.
Information System

Data and information concerning the tunnel and utilities assets as well as their monitoring, inspection, maintenance and exploitation are stored via the management platform in an information system. Any new data is first controlled and eventually cleaned according to specific protocols before integration into the information system. The information system includes structured data such as sheets, time-series data as well as unstructured data such as images, videos, audios...

The management of the information system is complex, because of the critical nature of this system for the security of the tunnel and for the Service Continuity of hosted utilities. An organization of the information system in clusters allows to meet the operational and security requirements of the tunnel and hosted utilities. Figure 9 shows this organization. It includes three types of clusters. The tunnel cluster, which includes data and information related to the tunnel and utilities assets and the digital identity of staff members involved in the tunnel or utilities exploitation. It includes also data concerning the tunnel monitoring, inspection and maintenance. Each Utility cluster includes data related to the utility asset, monitoring, inspection and maintenance. The security cluster includes data related to the Utility Tunnel security and incident management, such as indoor conditions, fluid leak, illegal intrusion, faults in the security system (ventilation, fire frightening, compartmentalization, access control…) and human presence.

A “key actor” is designated for each cluster. His role is to work with other key actors as well as with the tunnel and utilities managers to establish procedures related to data purchase, verification, cleaning, validation, processing, share, exploitation and quality control. The procedure should also cover data use for incident and security management.
The control layer includes electronic devices, switches, valves, motors, pumps and locks, which could be remote-controlled via the platform.

Electronic locks are used for the on-line control of the tunnel access. Smart pumps are used for the control of ventilation, smoke extraction, fire-frightening and water evacuation. Smart motors are used for closing/opening the tunnel compartmentalization doors and tunnel access. Smart valves are used to control the water flow or pressure in the drinking water and district heating systems. Smart switches are used for the control of the electrical grid.

Data analysis concerns the transformation of real-time and historical data into operational data, that improves the efficiency and security of the tunnel and hosted utilities.

Security analysis aims at improving the early detection of abnormal events such as water or gas leak, water infiltration, unusual increase in the temperature, illegal intrusion as well as faults in the tunnel equipment related to access control, ventilation, smoke extraction and firefighting. It aims also at operating rapid execution of security procedures including automatic actions such turning off/on some equipment, closing/opening accesses, closing/opening compartmentalization doors, putting-on firefighting system, smoke evacuation, alerting staffs inside the tunnel, sending alerts to staffs and authorities concerned by incident.

Early incident detection is based on the comparison of real-time data with references values or base-line values, which could be completed or enhanced by cross data analysis and Artificial Intelligence. According to the degree of violation of the reference values, a risk degree is attributed to the event and an appropriate procedure is activated. This procedure could include simply additional verification, alerts, turning off/on some equipment or emergency service intervention.
The incident post-analysis is crucial. It concerns analysis of data collected during the incident as well as pre- and post-incident data. It includes also staff response to the incident and the interaction among the tunnel and utilities operators. This analysis allows to understand the real-response of systems and staffs concerned by the incident. It allows also to check the efficiency of incident-management procedures and to improve these procedures including incident detection and response strategies.

Since the Utility Tunnel is very complex, historical and real-time data are used for the training and use of the Artificial Intelligence for the tunnel and utilities safety and optimal management. The Artificial Intelligence is mature for complex data analysis including, image processing, cross data analysis, faults early detection and system control.

**Construction of Utility Tunnel the Smart Management System**

An effective governance and management model is crucial for an efficient management of the Utility Tunnel. It is based on a governance committee, which is composed of the tunnel operator, utilities managers and other authorities concerned by the Utility Tunnel. It requires also clear rules for decision-making, responsibilities and rights of the Utility Tunnel stakeholders. It also defines the organization of the management team.

The specifications part aims at defining the specifications for the components of the Utility Tunnel concerned by the Smart System, such as monitoring, tunnel access rules, inspection, maintenance, information system, data analysis tools and system control.

The system construction consists in building the components of the system according to the specifications defined in the 2nd step. It concerns construction of the management platform, construction of the 3D digital model of the tunnel and hosted utilities, installation of the monitoring and control systems, digital installation of procedures for maintenance and inspection, implementation of analysis tools and software, including the Artificial Intelligence tools.

The last phase concerns the verification and regular evaluation of the system. It includes verification of vertical layers, which correspond to utilities, as well as horizontal layers, which concern the tunnel as well as security. Performances of these layers are evaluated regularly according to performances indicators. The system is regularly updated to enhance the system security and efficiency.
Conclusion

The Utility Tunnel offers large opportunities to cities. It allows an ease inspection, maintenance, renovation and extension of urban utilities under any environmental condition without the necessity to operate pavement cuts and excavations. Consequently, it eliminates urban disturbances related to utilities works such as traffic jams, noise, pollution and pavements degradation. It reduces also expenses related to maintenance of utilities and pavements. However, the use of this technology is yet below expectations, because of security and management challenges related to the exploitation of this critical space.

This paper presented a Smart Solution that allows the Utility Tunnel operator to improve security and efficiency of this space, and consequently to provide guarantees for utilities concerning the respect of their requirements as well as transparency of the governance and economic models. The great advantageous of the Smart Solution concerns the establishment of an efficient governance and management system, use of the latest technology to collect and share data and information related to the exploitation and security of the tunnel and hosted utilities, use of advanced technology, including Artificial Intelligence, for data analysis as well as for the enhancement of the tunnel resiliency. This solution provides at each moment a multi-scale fine picture of the tunnel and utilities functioning and environment. It allows early detection of abnormal events and a rapid application of advanced procedures to confine these events and to preserve the Service Continuity of hosted utilities. In addition, the construction of the Smart Solution allows a real involvement of the tunnel leaders.
stakeholders in the design, construction and use of this comprehensive solution. This involvement constitutes a major key success in the optimal and safe management of the Utility Tunnel.

Author Contributions
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