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2018

Seet, G., Yeo, S. H., Law, W. C., Burhan, Wong, C. Y., Sapari, S., & Liau, K. K. (2018). Design of tunnel inspection robot for large diameter sewers. *Procedia Computer Science*, 133, 984-990. doi:10.1016/j.procs.2018.07.078

<https://hdl.handle.net/10356/89245>

<https://doi.org/10.1016/j.procs.2018.07.078>

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International Conference on Robotics and Smart Manufacturing (RoSMa2018)

Design of Tunnel Inspection Robot for Large Diameter Sewers

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Abstract

The Singapore used water transport infrastructure comprises of three sewage systems: trunk sewer, link sewer network and the Deep Tunnel Sewerage System (DTSS). It is a solution towards Singapore's long-term water needs such as used water collection, treatment, reclamation and disposal. Environmental conditions and activities in and outside the tunnels can lead to deterioration of tunnel assets such as liner cracking, dislocated joints or even collapsed sections over an extended period. Leaks from sewer tunnels may contaminate the surrounding land and pose risks to public health. In order to prolong the service life of sewers and to protect surrounding environment, inspecting the structural integrity of the tunnel is an essential part of infrastructure maintenance.

The use of robots is one of the options being explored to assess underground spaces and to achieve enhanced inspection and maintenance capabilities. This option is desirable as it reduces the risk to humans resulting from prolonged incursions into a hazardous environment. The presence of biological contagions, hazardous and explosive gases (predominantly hydrogen sulphide, methane etc.) can pose a threat to the wellbeing of humans. Oxygen deprivation, absence of illumination and slippery conditions can further add to the risk level. In addition, automation promises greater reliability and manpower savings.

Deploying robots into modern-day sewer systems are not without its engineering and technological challenges. Frequently there are restrictions to access through manhole openings. Access tunnels may have further structural obstructions to permit the use of launch support mechanisms. In addition, the depth of service tunnels approaches 50 m with distances between adjacent accesses points approaching 2 km. Keeping the robots supplied with power is challenging and with conflicting operational advantages and disadvantages between on-board battery and surface supplied power. The paper provides insights to the identification of design considerations and field trial for our tunnel inspection robot.

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Peer-review under responsibility of the scientific committee of the International Conference on Robotics and Smart Manufacturing.

Keywords: Service Robot; Sewer Inspection; Inspection Robots;

1. Introduction

The Singapore used water transport infrastructure comprises of three sewage systems: trunk sewer, link sewer network and the Deep Tunnel Sewerage System (DTSS). It is a solution towards Singapore's long-term water needs

such as used water collection, treatment, reclamation and disposal. Environmental conditions and activities in and outside the tunnels can lead to deterioration of tunnel assets such as liner cracking, dislocated joints or even collapsed sections over an extended period. Leaks from sewer tunnels may contaminate the surrounding land and pose risks to public health. In order to prolong the service life of sewers and to protect surrounding environment, inspecting the structural integrity of the tunnel is an essential part of infrastructure maintenance.

The use of robots is one of the options being explored to assess hazardous and constraint spaces such as the site of a nuclear, fire or tunnel collapse disaster zone [1-4] and to achieve enhanced inspection and maintenance capabilities. This option is desirable as it reduces the risk to humans resulting from prolonged incursions into a hazardous environment [5]. The presence of biological contagions, hazardous and explosive gases (predominantly hydrogen sulphide, methane etc.) can pose a threat to the wellbeing of humans. Oxygen deprivation, absence of illumination and slippery conditions can further add to the risk level [6]. In addition, automation promises greater reliability and manpower savings.

Deploying robots into modern-day sewer systems are not without its engineering and technological challenges. Frequently there are restrictions to access through manhole openings. Access tunnels may have further structural obstructions to permit the use of launch support mechanisms. In addition, the depth of service tunnels approaches 50 m with distances between adjacent accesses points approaching 2 km. Keeping the robots supplied with power is challenging and with conflicting operational advantages and disadvantages between on-board battery and surface supplied power.

Pipelines maintenance robots have been developed mainly for small and medium bores [7-13]. Capabilities for large-diameter sewer tunnels, more than 3 meters, are less well developed. In the recent past, man entry was the mode of inspection and maintenance. The challenges of maintaining a large-diameter tunnel are different from those of the conventional small pipes. Large diameter tunnels are normally in partially or completely filled condition during normal operation, the robot's dynamic adaption to external disturbances like water and gases flow is more significant in large-diameter tunnel. The illumination intensity needs to be high enough to illuminate the tunnel surface and high resolution cameras are required to produce high fidelity images suitable for real-time visual inspection. Invariably, there is limited opportunity for a single design robot. Accesses to the tunnels are invariably also more challenging to existing equipment. The conditions in large bore tunnels can be significantly different at the start and end of the network. There is great variation in the level of liquid fill and also in the flow conditions. The presence of obstacles deposited on the bottom of the tunnel is also to be considered.

In this paper, our interpretation of the operational requirements and constraints as well as their effects on design choices are described and discussed.

2. Design Considerations and Challenges of Tunnel Inspection Robot

The basic objectives of a sewer inspection robot are to navigate into the tunnel, capture high resolution images and backtrack to the entry point for extraction depending on the depth of tunnels, permitted hazard level, and limited or no human intervention is allowed. When no human presence in the tunnel is permitted, a launch cage [14] is required to deliver the robot to the main sewer and provide additional support to the robot. With the need for a tether, the launch cage must also provide the necessary tether guides and support for cage stabilisation. Tether guides are required to prevent damage to the fibres of the tether and to transmit the pull force should a force extraction be necessary. In some cases, access constraints may also not allow the use of a launch cage and necessitate man entry.

2.1 Tether and Power Delivery Considerations

Robots require a communication link for real time status and control. With extended inspection (with the possibility of repair) battery power becomes challenging. Tethers providing communication, power and extraction capabilities are normally desirable for tunnels with larger diameter. However, long tether length can be a significant drain on the traction requirements of the robot. Another factor in the specification of tether is its density. Neutrally-buoyant tethers may be an advantage in a partially submerged environment but become a disadvantage at low levels of fill. The larger diameter can be a significant volume to deal with at lengths of 1-2 km. A smaller diameter and

lower density tether is desirable in enhancing deployment, controllability and motor power requirements.

The effects of copper losses over distances of 500 m and above can be considerable when the diameter and weight of the tether needs to be minimised. In an effort to reduce losses, the voltage needs to be increased. In our design, we opted for a 415VAC 3-Phase supply from the ground surface. This specification exploits high voltage and multi-phase power transmission efficiencies. Whilst a battery powered system may appear an advantage, the real time updates and control typically necessitates the need to include a communication tether, albeit a smaller bore tether is possible. The tether serves as a contingency in the case of a need for manual extraction. Failed robot may be pulled out without human incursion into the tunnel.

2.2 Robot Size Considerations

The initial objective was to design and develop a sewage inspection robot to inspect concrete sewage tunnels with internal diameter of 3 m or larger and for incursions of up to 400 m. The robot was specified to operate in a partially filled tunnel with the possible presence of explosive gases. The robot was also required to be resistant to corrosion and be compact in size. The size restrictions were to facilitate the deployment and launch into existing infrastructure. The typical manhole access are less than 60cm x 60cm. The manhole in Fig. 1, less common, is circular in profile and diameter 0.71m. Pass the manhole, the access tunnel diameter opens to 1.8 meters, with the main sewer diameter of 2.5 m at a moderate depth of about 18 m. In addition, access tunnels are frequently impeded by intermediate platforms which were installed based on safety considerations.

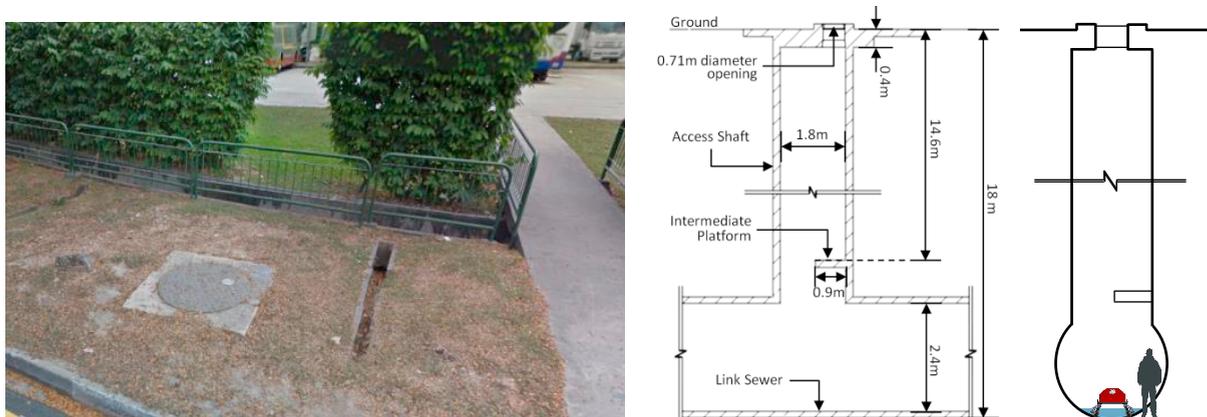


Fig. 1. Access Constraints on inspection robot.

A large robot footprint is necessary taking into consideration of its stability and ability to travel over sediment, deposited on the bottom of the tunnel. However, the manhole of the access tunnel imposes constraints on the size of the robot in order to pass through the opening. In addition, the robot must also negotiate the available space between obstruction such as intermediate platform and walls of the access tunnel. The ability to fold in the extremes of the robot is a perceived as a design advantage.

3. Concept Solutions

Fig. 2 illustrates the details of the sewer inspection robot that was designed based on the assessment of needs and optimal considerations from conflicting needs. The main subsystems include an imaging array as an integral unit to illuminate and image the tunnel surfaces. A semi-circular frame contained three HD cameras and four focused LED light sources. It forms an inspection array radially in the tunnel and is capable of capturing a 270° of the tunnel's interior surface above the water line. The coverage of each camera and LED overlaps to provide seamless images and illumination. Additional post-processing stitches the images to form a panoramic view of HD image of the tunnel surface. A front pan-tilt camera and a rear camera are also provided for navigation purpose. Other major subsystems include power converters and drive systems. The mechanical drive system comprises of four 200 mm

diameter hub motors, which eliminates the need for external gearbox and transmission components. The power converter converts the high voltage 415 VAC 3-phase supply to regulated 24 VDC. In addition, the robot is integrated with a flammable gas sensor, and laser profiler.



Fig. 2. Compact Mobile Robot for Sewer Inspection.

By way of mechanical novelty, the wheel frames of robot fold to permit a compact profile for its passage past access tunnel obstruction. At the base of the access tunnel, the wheel frames are extended to increase its footprint for better stability. The wider track width lands the drive wheels above the waterline, at the designed level of fill. This provides better traction and avoids sediment that may be deposited at the floor of the tunnel.

4. Field Tests



Fig. 3. Compact Mobile Robot for Sewer Inspection.

The compact mobile robot was deployed over a number of occasions. During each of the test, the design concept was evaluated as well as a refinement of deployment procedures. The mobile robot was manageable using a single-man assisted deployment. Human intervention was required to guide the mobile robot passing through the access obstruction and unfold the wheel frames in the tunnel. Human extraction of the mobile robot over 100 meters was also found to be physically manageable. The outcome of the field tests were encouraging and identified a better understanding of design issues. Whilst the use of neutrally buoyant tether was found to reduce the dragging force of tether on the tunnel floor, spooling and releasing the tether on the spool of winch became more difficult due to its diameter and stiffness. A problem we encountered was the failure of power carrying copper cores. The effective capacity of the copper wire was lower than that indicated by our design calculations. This could be attributed to

material impurities. More probably, failure occurred due to too much mechanical stress imparted onto the tether during the robot deployment to access tunnel.

In order to overcome the rough handling of the robot and tether, modification to the robot design and the launching procedures was required. A tether guide was required to maintain a minimum bend radius and camera lens covers were required to protect cameras from abrasion during the lowering and extraction phase. An additional issue was moisture condensation on the lens covers due to the relative changes in humidity and temperature on the ground surface and at the bottom of the tunnel. Fig. 4(a) shows a HD image of sewer tunnel taken from the front PTZ camera. Fig. 4(b) shows a screen capture of our Graphical User Interface (GUI) in our laboratory.

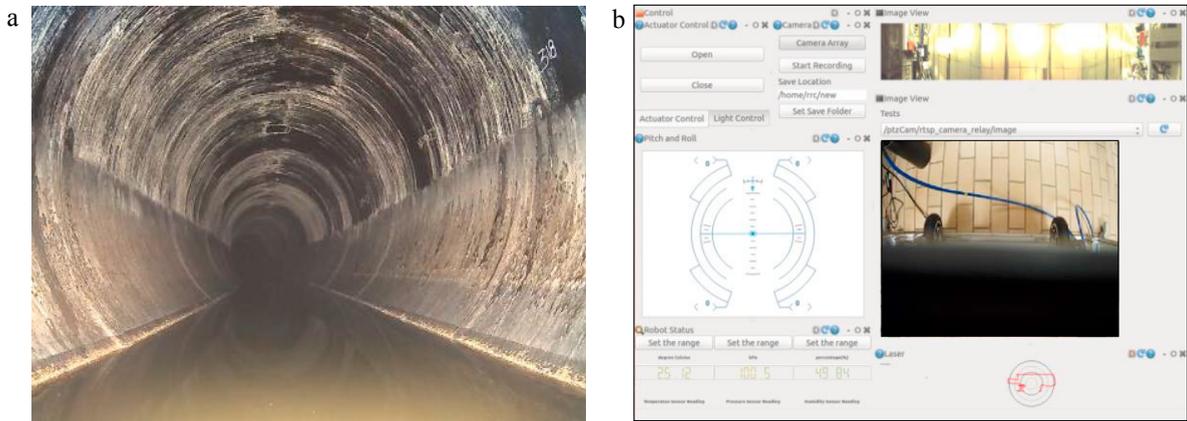


Fig. 4. (a) Tunnel Image from Front PTZ Camera; (b) User Interface.



Fig. 5. “Stitched Image” from Imaging Array.

5. Conclusion

The use of robots for sewer tunnel inspection is relative new, particularly in deep tunnels with limited access. The design considerations and specifications for sewer inspection robots are numerous and frequently opposing. The operating conditions are also varied from one deployment from another. Beside the access issues, there are considerations for simplicity and desirability for the exclusion of humans in the sewer tunnel environment. System reliability and extraction of equipment needs to be a major consideration. As with all engineering systems, the requirements and more importantly, the relative importance have yet to be fully identified.

In our design, we considered the tunnel condition to be minimally filled. At high levels of fill, floating platforms need to be considered. Water fill levels also affect considerations on the density and size of preferred tether specifications. Tethers are preferred as it provides a contingency in the event of robot failure in the tunnel. Mechanical extraction is possible by pulling on the tether winch. Tethers can frequently support a pull of over 10 tons.

In our implementation, the use of stitched multi-HD image allows the inspection processes to be automated for defect identification and location. A panoramic image captured by the imaging array, as shown in Fig. 5, can be converted to a large flat map of the tunnel surface. This facilitates the location of defects and its changes can also be effectively tracked.

Whilst much attention was made to identify the design specifications of all subsystems, overall reliability was compromised by the current capacity of the supporting umbilical/winch subsystem. The actual field measured current load was very close to the estimated design specifications. Unfortunately, the high mechanical stresses on the umbilical, coupled with manufacturing imperfections of the copper wires resulted in the manifestations of “hot spots” in the wire. This resulted in localized electrical failures. This was identified to be the most prominent mode of overall system failure and a severe compromise to reliability. This issue is being resolved with a 100% increase in the cross-section area of the copper wires. This expensive lesson highlights the importance of providing sufficient “safety factor”, especially at the proof-of-concept stage of design. Tab 1. Shows the power consumption of the various subsystems and how operations were enabled under the constraints of the lower than desired power capacity. In field-operations, the maximum power was limited by reducing the acceleration rates. This necessitated operations at a level lower than designed.

Table 1. Power consumption of each subsystem on the tunnel robot

Item	Power Consumption	Remarks
Lighting System	60W	Forward and Ceiling illumination
Camera System	27W	3 x ceiling, 1 x forward looking on pan-tilt mechanism and 1x rear facing camera
Sensors	6W	Lidar profile sensor and flammable gases detector
Motors	1000W	4 x hub motors
Others	16W	Cooling fans, voltage regulators and miscellaneous electronics

Fig 6. Shows the robotic platform attached to the umbilical and winch system, which handled the uncoiling of the umbilical and for powered extraction should the need arises, in the event that the robot platform is unable to make its powered exit.



Fig. 6. Robotic Platform Attached to Umbilical-Winch System

Continuous power is always desirable, in comparison to on-board battery, but copper losses need to be managed. With tether lengths of up to 500 meters, our specification of tether, with nominal diameters of 25 mm for neutrally buoyant and of 20 mm for negative buoyancy seems ideal for partially filled tunnel deployments. With deployments

in access of 1 to 2km, tether constraints would be more challenging to optimize. This problem would be even more challenging for systems requiring the need to perform maintenance and repairs.

With the challenges to land use in developing countries, deep sewer system appear to be the way ahead and an increase in interest amongst the engineering and utility services community is envisaged.

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