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Autonomous Inspection and Maintenance of Linear Assets

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***Abstract* – Linear assets have linear properties, for instance, similar underlying geometry and characteristics over a distance. They show specific patterns of continuous inherent deteriorations and failures. Therefore, remedial inspection and maintenance actions will be similar along the length of a linear asset, but because it is distributed over a large area, the execution costs are greater.**

Autonomous robots can be programmed for repetitive and specific tasks. Unmanned aerial vehicles and remotely operated vehicles are currently used in different industrial settings in ad-hoc manner for inspection and maintenance purposes.

This manuscript provides a conceptual framework for the use of autonomous inspection and maintenance practices for linear assets to reduce maintenance costs, human involvement, etc., whilst improving the availability of linear assets by effective utilization of autonomous robots and data from different sources.

I. INTRODUCTION

A linear (or continuous) asset is an engineering infrastructure that usually spans long distances and can be divided into different segments, all of which perform the same function but may be subject to different loads and environmental conditions. Typical linear assets include railway lines, roads, pipelines and cables. Modern society relies heavily on linear assets and distinguishing feature of these assets, given their large scale, linear assets play an important socioeconomic role and therefore imperative to manage them effectively.

Research on linear asset management has attracted considerable attention from asset management practitioners and academic researchers, although previous research has focused on specific types of linear assets. For example, Ahern and Anandarajah [1] developed a model for prioritizing railway investments using weighted integer goal-programming. Li et al. [2] developed a management information system for mining railway transportation equipment. Brito and Almeida [3] attempted to rank risks for natural gas pipelines based on multi-attribute utility theory. Their model can incorporate the decision-maker's preferences and behaviors quantitatively. To model the variable condition of pipeline segments along a route, such as the pipeline failure rate, the pipelines were divided into a number of smaller sections. To address failure issues, Cagno et al. [4] conducted a case study to estimate the prior distributions of gas pipeline failures using the Analytical Hierarchy Process (AHP) and a Bayesian approach. Coffen-Smout and Herbert [5] presented an overview of submarine cable management challenges, while Jones and McManus [6] conducted a life-cycle analysis of five different 11 kV electrical power cables. Finally, Link [7] studied the renewal costs of motorways in Germany using an econometric analysis but did not explicitly consider the road's condition.

Conventional asset management systems or decision support tools are not suitable for linear assets; their hierarchical asset structure uses parent–child relationships to link system, assembly, component, and part type hierarchies and is not suitable for managing linear assets [8]. To address linear asset issues, Maximo developed a tool called the linear asset manager [9]. However, this tool does not integrate inspection and maintenance data and decision analysis functions.

While these research results are useful for maintenance management decision support, an effective framework for linear asset management inspection and maintenance needs to be developed to integrate field operations into decision support. Such an environment can be generated using the emerging ICT technologies, for instance, big data technologies.

The paper discusses a framework to incorporate inspection data with maintenance data using big data technologies to manage linear assets by means of autonomous robots. The paper is arranged as follows. Section 2 discusses current industrial practices; section 3 explains the industrial challenges; section 4 discusses autonomous inspections and maintenance and explains the framework for the autonomous inspection and maintenance of linear assets; section 5 provides conclusions.

II. CURRENT INDUSTRIAL PRACTICE

In today's industrial setting, engineering assets are divided into three categories:
(1) Non-linear assets: Non-linear assets can be further classified as component based assets, which include production assets such as machines, mobile assets such as vehicles, and fixed physical assets such as facilities [8].
(2) Linear assets: Linear assets can be defined as engineering structures or infrastructures that often cross a long distance and can be divided into different segments that provide the same function but are subjected to different loads and conditions.
(3) Hybrid systems: These comprise a combination of linear and non-linear assets.
The differences of the asset categories are summarized in Table 1.
Linear assets have the following characteristics:

• Linear assets often form networks which consist of a number of 'lines'. These lines are functionally similar, but can have different characteristics due to various construction materials, operational environments and geometric sizes.

• Linear assets may not have a clear physical boundary. For example, a pipeline is often partitioned using technical, jurisdictional and organizational criteria and different criteria can result in different, perhaps overlapping, 'pipelines' being identified for the same pipeline network.

• Linear assets usually span long distances and are divided into segments. These segments are often virtually defined based on maintenance activities and may vary among different maintenance actions. An example is given in Fig. 1. Even though linear assets are constructed of basic elements such as individual pipes in a pipeline, the segments are not necessarily the same as the construction elements. Failures, maintenance events and associated costs are usually recorded for segments, not for the whole linear asset.

• Linear assets are usually long-lived assets. As a result, when conducting reliability analysis, we may have sparse failure records for a few segments only, as the majority of segments have not failed.

• If any single section of a linear asset malfunctions, the entire asset will not function properly.

These characteristics of linear assets mean that their registry (categorization), reliability and cost analysis, and maintenance decision modelling methods are different from those of non-linear assets.

A. Asset Registry Models

In current industrial practice, engineering assets are registered using a hierarchical approach representing a 'parent–child' model. Using this model, maintenance attributes, such as maintenance history, repair costs, replacement costs and operational history, are directly linked to individual systems, subsystems, equipment or components. The traditional 'parent–child' hierarchical model works well for most non-linear assets, as there is normally a clear fixed physical boundary between components. However, a parent–child hierarchy is not suitable for linear assets with their virtually defined and dynamically changing segments. A network model approach may be useful in addressing these issues [8]. Fig. 2 applies the parent-child model to the non-linear asset hierarchy.

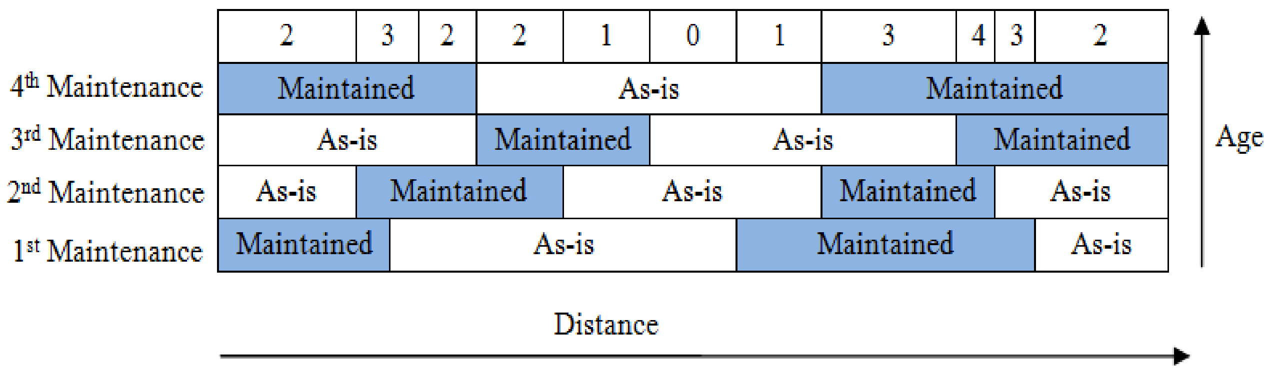

Fig. 1. Dynamic maintenance segment boundaries of a linear asset.

Table 1. Three asset categories

Category	Example	System configuration	Characteristics
Linear assets	Roads, railway tracks, pipelines, power cables, canals and waterways	Tree structure or networks	-Maintained and renewed in place and in segments -No clear physical boundary for segment -All segments normally play the same function -Maintenance costs, failures and maintenance and operational events are associated with segments -segments can be dynamic, usually long lived.
Non-linear assets	Pumps, cars, machine tools	Complex physical structure	-Installed and replaced as a whole, but maintained at basis maintainable unit(BMU) level, often in workshops -BMU has clear physical boundaries -BMUs often play different functions -Maintenance cost, failures and maintenance and operational events are associated with BMUs -BMUs are usually static -Lifetime varies
Hybrid assets	Power plant boilers, refrigerators, refineries	Complex physical structure, but linear and nonlinear parts have a clear	-Installed, maintained and replaced in parts for large assets and as a whole for small assets -Linear subsystems and nonlinear subsystems can often be separated

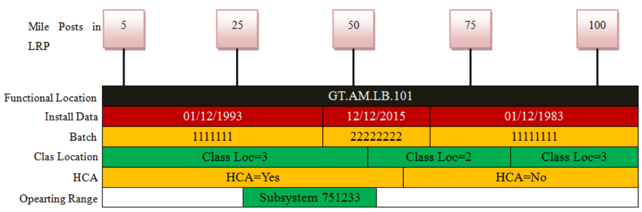

Fig. 2. Hierarchical parent-child approach for non-linear assets.

B. Data Processing and Segmentation of Linear Assets

Data grouping plays an important role in the management of linear asset inspection and maintenance. The data grouping demands can be divided into:

- Dividing linear assets into proper segments.
- Correctly grouping segments.

Important data on inspection and maintenance can be gathered by investigating the major influencing factors of asset degradation and failures. For example, such factors for water pipelines could include pipe materials, soil types, water pressure, ages, and pipe diameters.

Segment grouping is critical for scheduling the maintenance of linear assets. A major challenge is how to group similar, but geographically-separated, segments, and how these groupings influence maintenance decisions and executed maintenance, e.g., sending a repair team out to replace all segments made of the same material and with the same amount of wear in a particular locale.

Making maintenance decisions for a linear asset network involves the following:

- Determining which parts of the asset should be renewed together (i.e., a contiguous line or a group of separated but similar segments).
- Determining the best time to renew each part.

The current industrial segmentation of linear assets is generally not suitable for maintenance management statistical analysis, as the assets can have various lengths, and the subdivisions relating to maintenance requirements may overlap. See Fig. 3.

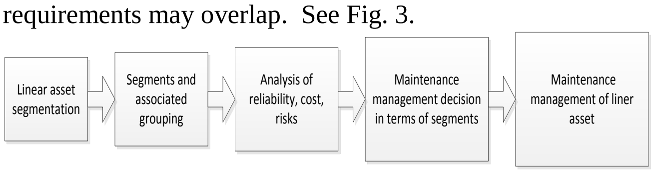

Fig. 3. Segmentation of linear assets for maintenance management.

III. INDUSTRIAL CHALLENGES

A. Challenges of Linear Assets

- The location information can vary depending on the asset type, e.g.:
  Roads: Markers, e.g. mileposts/kilometer posts, lane, direction, offsets, bridges, tunnels, signs etc.
  Rail: Mile or chain markers, track number, offset, switch, crossings, signals etc.
  Pipelines: Kilometer points, compressor stations, valves, pig stations etc.
  Transmission lines: Substations, traces etc.
- The linear aspect has to be reflected in:
  Inspections
  Condition monitoring
  Maintenance and repair
- Linear assets need to be managed as a single continuous asset with dynamic segmentation

B. Typical Attributes of a Linear Asset

- A linear asset has an associated length dimension represented by means of start points and end points or by asset length. Components (or features) can be 'installed' along its length.
- Attributes can change frequently along its length.
- It is typically connected with other linear assets to represent an infrastructure network or route.
- A linear asset is subject to dynamic segmentation; multiple sets of attributes can be associated with any portion of an existing linear feature independently of where it begins or ends.
- A linear referencing method is required to describe and locate a position along its length.
- Permanent referencing locations (markers or referencing locations) plus offsets are used to describe an exact position along the linear asset.

C. Challenges in Inspection and Maintenance

Industrial maintenance service providers find that creating a technical structure to accurately represent the linear assets in their infrastructure network is a highly complex process, making maintenance and inspection strategies difficult to plan and report. Yet maintaining the integrity of these assets ensures performance optimization and compliance with HSE regulations.

Managing linear assets, such as waterways or rail networks, comes with a unique set of requirements. Asset management functionality is associated with conducting detailed inspections, planning maintenance schedules, devising overhaul schedules and prioritizing work to meet safety, budget and customer expectations. To maintain linear assets, asset managers must do the following:

- Split assets into sections based on a definable length breakdown.
- Add records for associated assets along lengths, such as locks, gates, footpaths etc.
- Record multiple ownership records for single assets.
- Import historical maintenance records, images and any additional data in a dynamic manner.
- Perform on-site, roaming Inspections using autonomous devices to record defects, identify issues, add images, log GPS data and add any other information required.
- Perform maintenance activities through a remotely operated interconnected environment.

IV. AUTONOMOUS INSPECTION AND MAINTENANCE

Remotely controlled and autonomous inspection and maintenance devices are used in different sectors for different purposes. For instance, the military uses unmanned aerial vehicles for inspection, and offshore oil and gas industries use underwater robots for maintenance. The following list mentions some autonomous or remotely controlled devices used in the inspection and maintenance of linear assets:

Railways:

- Identification of obstacles and track irregularities using drones (Autonomous Inspection Robot (UAV)).
- Inspection of rail profile, cracks, irregularities, missing components using an autonomous robot vehicle (Autonomous Inspection Robot).
- Replacement of missing components, crack welding, etc. using an autonomous maintenance robot vehicle.

Roads:

- Identification of obstacles and damage using drones (Autonomous Inspection Robot (UAV)).
- Inspection of roadway, road alignment, road profile etc. using an autonomous robot vehicle (Autonomous Inspection Robot).
- Repair of roadway (placement of asphalt/concrete), repair of pavement, maintenance of embankments, maintenance and cleaning of ditches, etc. using autonomous maintenance robot vehicle.

Canals and Waterways,

- Identification of debris, obstacles and damages for the infrastructure through drones (Autonomous Inspection Robot (UAV)).
- Inspection of waterway, sidewalls, berm, gates, etc. using an autonomous robot vehicle, both land and water (Autonomous Inspection Robot).
- Removal of debris and obstacles, repair of sidewalls, berm, etc. using an autonomous maintenance robot vehicle (both land and water).

Power Lines,

- Identification/inspection of power line damage, insulator defects, tower damage using drones (Autonomous Inspection Robot (UAV)).
- Cleaning of insulators and repair of line damage using an autonomous drone robot vehicle.

A. Autonomous Inspections

Traditionally, electric power suppliers have inspected power lines for encroaching trees, damage to structure and deterioration of insulators by having employees traverse the lines on foot and climb the poles. This is time-consuming and arduous, with a considerable element of risk. Now the task is often carried out by crews in manned helicopters using binoculars and thermal imagers to detect the breakdown of insulators. This too is not without hazard.

Recently, trials have tested the use of UAVs to inspect power lines, with considerable success. UAVs offer lower costs, do not create a hazard for aircrews, can operate in more adverse weather conditions, and are less obtrusive to neighboring communities or animals. Hover flight is essential for the inspection task. The UAV carries an electro-optic and thermal imaging payload, the data from which are available in real-time to the operator and recorded. The UAV is automatically guided along the power line within a limited volume of airspace close to the lines using a distance measuring device. An important requirement of UAVs deployed in this role is that they must be flown close to high voltage power lines, that is, within their electromagnetic fields, without adverse effects upon their control system or payload performance.

Oil and gas supplying companies are interested in UAVs for inspection and exploration purposes. UAVs offer a less expensive means of surveying the land where pipe lines are installed. They also offer a means of patrolling the pipes to look for disruptions or leaks caused by accidents such as landslides or lightning strikes or for damage caused by vehicles or falling trees. In certain areas of the world, sabotage is not uncommon.

UAVs could be used in road and railway inspections and for certain maintenance purposes by traffic infrastructure agencies. In addition to being less expensive to operate than manned aircraft, they are more covert and will avoid distracting drivers.

Irrigation projects, river authorities and water boards could use UAVs to monitor cannels, waterways, pipelines and rivers. UAVs could be used to monitor reservoirs for pollution or damage or to monitor pipelines for security purposes.

However, the use of UAVs in many of these cases will depend on the approval of the relevant regulatory authorities.

B. Autonomous Maintenance

Autonomous maintenance activities are mainly associated with robotic applications. Various industries, especially those dealing with high risk activities, are already using remotely operated robots for maintenance activities, for instance, marine repairs (repairs of ships offshore, offshore oil and gas platform maintenance, deep sea pipeline and cable maintenance), oil refinery repairs, nuclear power plant repairs etc. At the moment, because of the limited development of robots for maintenance purposes, complete maintenance cannot be performed in the above mentioned industries.

C. Conceptual Framework

With autonomous inspection devices and autonomous maintenance robots, a dynamic asset maintenance and management plan can be deployed with the help of big data technologies and available analytics. Right now, industries are using the devices separately for inspection and maintenance; the two have not yet been integrated. By integrating the two operations with the available ICT technologies, the asset maintenance and management process can be automated. Moreover, the incorporation of artificial intelligence tools can make the whole process dynamic and autonomous.

Since linear assets have a common behavior and architecture across their length, the implementation of the above concept may reduce costs, ensuring more effective operation and maintenance. The proposed framework is shown in Fig.4.

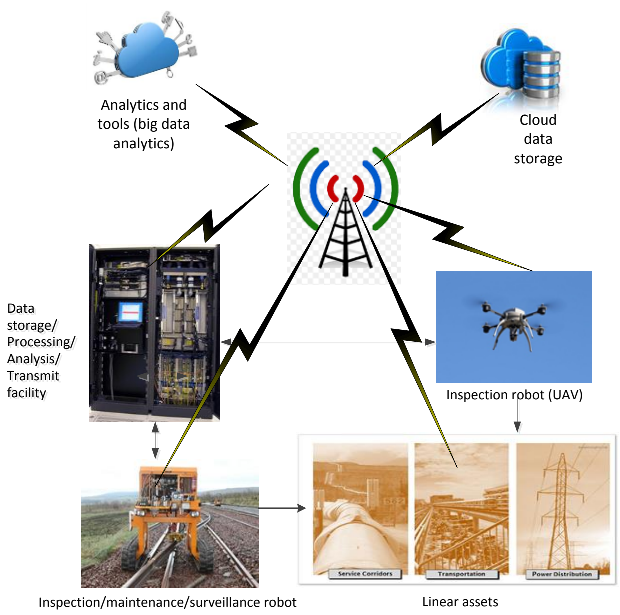

Fig. 4. Proposed conceptual framework for autonomous inspection and maintenance of linear assets.

V. CONCLUSIONS

The importance of autonomous inspections and maintenance in linear assets is increasing because these assets are often aging and asset managers are struggling to operate effectively and maintain costs. Reliable inspection and maintenance methodologies incorporating new technologies, specifically, the emerging ICT technologies, would facilitate cost effective and efficient asset management.

The industry movement towards new and more sophisticated inspection, condition monitoring, analysis and maintenance technologies, together with the development of autonomous robotics, will provide a platform to maintain large assets (i.e. liner assets) more efficiently. The technology is available but integration remains a key concern.

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