**Major points of extension**

1. Introduction

To address linear asset issues, IBM began to develop a generic approach to dynamic segmentation using existing standards such as ISO 19133 (Information Technology Geographic Information Framework Data Content Standard) [9]. They discussed this idea among several development partners, including infrastructure managers, academics and government authorities, and decided to segregate the assets into linear and non-linear ones, making them more easily controlled by users. The Maximo Linear Asset Manager 7.1 was released after 3 years; it is based on the concept of ‘treating linear assets differently than pumps’ through the dynamic segmentation of the former [10][11]. However, this tool does not integrate inspection and maintenance data and decision analysis functions.

Various types of engineering systems have been developed to acquire data on inspections or to perform maintenance tasks. These are mostly semi-automated systems, i.e., robotic applications. The fields of application range from welding rails to inspecting steel bridges, railways or nuclear power plants. In general, robots need to be developed for specific tasks and fields of application, as these define which locomotion principles or adhesion systems are suitable and which dimensions the robot must have.

1. CURRENT INDUSTRIAL PRACTICE
   1. A. Asset Registry Models

In asset intensive industries where there are strict regulations, the use of a top/down or hierarchical approach to the management of linear assets is both challenging and multifaceted. These types of assets have exclusive requirements that demand a unique asset management approach, often called continuous or linear asset management [12].

1. INDUSTRIAL CHALLENGE
   1. Challenges of Linear Assets

The main areas of linear asset use include railways, roads, pipelines, electricity distribution networks, canals and waterways. The major challenges of linear asset management are the following [13]:

1. *Structure*. Long and straight linear assets are different from up and down ones.

2. *Use of GIS*. Linear asset management requires data from different sources. Geographic Information Systems (GIS) is one method to acquire data and information. But the reporting of maintenance activities should combine linear asset management data and GIS data.

3. *Dynamic segmentation*. This is the ability to define changing characteristic features along the length of an asset. For example a segment of pipeline will have changing features along its length. Pipe line is the asset and the features can dynamically change across with piping segment which is maintained.

4. *Linear reference methods*. The location on a linear asset can be signified in a several ways. The location can be absolute point (start of the segment) or relative to some defined marker such as a kilometre or mile post or distance from a known marker. This referencing is useful to identify faults in the system (see Figure 4).

5. *Mass changes*. Tools are needed to effect mass changes to the linear assets under management – this is particularly relevant where costing boundaries change and both the linear assets and point assets need to be updated with new cost collectors.

6. *Location information.* This can vary depending on the asset type, e.g.:

Roads: Markers, e.g. mileposts/kilometre posts, lanes, direction, offsets, bridges, tunnels, signs etc.

Rail: Mile or chain markers, track number, offsets, switches, crossings, signals etc.

Pipelines: Kilometre points, compressor stations, valves, pig stations etc.

Transmission lines: Substations, traces etc.

Waterways: distribution points, gates, wires, dams, barrages, bridges, culverts, banks etc.

7. *Reflection of linear asset*: The linear aspect has to be reflected in:

Inspections

Condition monitoring

Maintenance and repair



Figure 4. Different methods used to record distance on a linear asset.

The maintenance of any linear infrastructure bring many challenges [14]:

1. *Modelling linear assets*: Modelling is the major challenge as assets are not limited to a single location and may span geographical areas.

2. *Assigning non-linear assets to linear assets*: Inclusion of non-linear assets within linear assets is difficult as it affects the behaviour of the latter.

3. *Parallel networks*: With parallel networks, a failure of any one has consequences, such as work stoppage.

4. *Intersecting networks*: Networks can cross one another, so maintenance carried out on one asset will have an impact on another network. This happens, for example, when road and railways intersect pipe lines, waterways and transmission lines.

5. *Planned maintenance time*: Stoppage for maintenance will result in an increased load on other networks as traffic is diverted; more usage may lead to reductions in performance.

6. *Skilled personnel to perform maintenance*: Maintaining linear assets requires groups from different departments to work on the same assets and coordination may be difficult.

7. *Special equipment for maintenance*: Maintaining these assets may require special equipment.

8. *Work order planning and execution*: The planning and execution of maintenance tasks with multidisciplinary teams is a challenge.

10. *Maintenance analytics*: In addition to planning and executing the work, other analytics may be required, for example, determining the downtime trend, cost of maintaining the network, allocation of costs to different networks etc.

1. AUTONOMOUS INSPECTION AND MAINTENANCE
   1. Smarter Drones

Unmanned aerial vehicles (UAVs) have attractive features, such as flexibility, adaptability, and a range of payloads. Sensors include high-resolution digital and infrared cameras, Light Detection and Ranging (LiDAR), geographic information systems (GIS), sonar sensors, and ultrasonic sensors; most can be adapted to a UAV platform. A close-up photograph of a structure on an offshore platform, difficult for inspectors to reach, will show maintenance personnel how much corrosion/erosion has built up and suggest the situation of welds and other structural elements.

Drones equipped with forward-looking infrared (FLIR) or ultraviolet sensors can detect hot spots or corona discharge on conductors and insulators, signalling a potential defect or weakness in the component. LiDAR can be integrated with drones to survey a proposed right-of-way, show the infrastructure situation when seismic conditions are changing, or monitor the encroachment of vegetation. There are many more potential uses and the examples are only a small fraction of the possible applications.

At present, UAVs are remotely operated; the next phase of UAV technology will be to deploy ‘smarter’ machines that can fly autonomously. This technology will allow UAVs to sense and avoid other objects in their path, recognise features or components through various sensors (including cameras) using complex software algorithms such as image processing algorithms, and achieve situational awareness. This advanced technology will foster calculated decision making, such as initiating focused inspections, issuing work orders for repairs, and starting maintenance work with the same robot or another autonomous robot integrated in the system.

In any industry, safety and cost are two of the most significant drivers of operation and maintenance and, thus, are always of high importance. Many industrial work areas are hazardous, so measures must be taken to secure the safety of users. HSE indicators can mitigate the risks, but the situation remains challenging when new technologies are introduced.

For instance, working on energised high-voltage transmission lines, sometimes hundreds of feet up in the air, can make the consequences of a mistake deadly. According to the US Bureau of Labor Statistics, 15 linemen were fatally injured in 2013 as a result of ‘exposure to harmful substances or environments’ [15].

Unmanned systems have the potential to greatly reduce the amount of risk exposure of the operational workforce. The safety of personnel involved in risky operational tasks can be ensured with this new technology.

* 1. Autonomous Robots

Many different robots have been developed to handle various situations on linear assets, buildings, ship hulls, or other human-made structures. But most are limited to special situations or applications. To execute the desired tasks, autonomous robots, as well as all other technical systems, have to fulfil certain requirements. The requirements and their importance and focus depend on the individual application or tasks. However, we can formulate a general set of requirements as follows:

1. *Velocity and mobility*: Vehicle speed and dynamics (ability to move) are two main aspects of robot design. Depending on the dimension of the linear asset, it may have to reach a relatively high velocity for sufficiently fast navigation between inspection areas or similar points of action. Another requirement is related to the desired manipulation and positioning capabilities of the system. This includes the precision of locomotion and its trajectory, since some inspection sensors need to be moved in a smooth and continuous way over the surface. The robot may also need to move sideways or to turn 360° to position sensors or tools. The system dynamics should be able to handle the various terrains and reach all positions of the asset.

2. *Payload*: Depending on the application, the system must be able to carry payloads of different weights. For example, in the case of steel piping, a payload of 5 kg or more is mandatory to carry ultrasonic inspection sensors. This requires a much bigger robot than a system which just needs a simple camera with a weight of several hundred grams. In other words, the dimension, adhesion, and motion components of the robot need to be adapted for the application.

3. *Reliability and safety*: A further important non-functional aspect is the robustness of the system. If the autonomous robot fails frequently during one inspection task, it is not usable in practice. The requirements of reliability and safety include robust hardware, optimal controllers, and methods to detect and handle hazardous situations and to recover from them.

4. *Usability*: Velocity, manoeuvrability, and the capability of carrying a certain payload are important, but they are only the basis of the general operability of the system. To bring a robotic system into application, it has to be more powerful, more efficient, and less dangerous than common approaches, e.g., in terms of inspection devices. This includes aspects of maintainability and a broad range of other tasks. Therefore, it must be able to carry different payloads (e.g. inspection sensors or tools) depending on the desired task, parts need to be easily replaceable, and the operation must be faster and less complicated than existing approaches. Aspects like energy consumption, weight, or dimension of the system can be important as well. Based on the individual task, a robot developer has to decide which requirements have to be fulfilled and select a suitable locomotion and attraction principle.

* 1. Conceptual Framework



Figure 5. Proposed ICT infrastructure for the autonomous inspection and maintenance of linear assets.

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