Review of internet-of-things enabled monitoring systems for tailings storage facilities

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Abstract

Water quality and geotechnical monitoring instruments have long-established designs that have become the backbone of monitoring. In recent years, advances in battery technology, radio communications, microprocessors and telecommunications have enabled the Internet-of-things to become an important part of water quality and geotechnical monitoring in and around tailings storage facilities. The introduction of several protocols such as LoRa, ZigBee or mesh-based TCP have increased the connectivity of instruments from individually programmed point-to-point communications to fully integrated systems. Several parameters have to be optimized concurrently to design robust internet-of-things (IoT) systems. Despite the opportunities offered by these new developments, a compromise has to be reached between radio functionalities such as bandwidth and response time, range and power in order to fulfill the requirements of any given monitoring project. Radio range is proportional to the electrical power required by the radio modules, yet power consumption should be minimized in all situations as solar power is often the only option for systems that are remote and isolated. In addition to these core concerns, compatibility has to be met with a wide range of instruments signal types such as vibrating wire, thermistors, RS-485, SDi-12, 4-20 mA and time-domain reflectometry. Expanded compatibility often demands more powerful microprocessor that increase the drain on the power supply of the system and thus needs to be accounted for when designing the entire system.

IoT best practices such as interconnectivity and the possibility to bring disparate technologies into a single framework will be discussed. Other IoT practices such as self-configuration and intelligent monitoring will be discussed in the context of water quality monitoring on mining sites. In some circumstances, smart sensors that reconfigure automatically for high-speed acquisition under pre-defined conditions would take advantage of IoT practices but at the expense of extra load on the microprocessor and power supply. The balancing act between processing, radio and the power supply will be expanded upon with experience drawn from several mines in northern and eastern Canada. These new IoT practices also lay the groundwork for future developments such as the use of machine learning and AI for more proactive monitoring of assets.

INTRODUCTION

Unfortunate events in recent years have increased the general awareness of the issues posed by tailings and tailings dams. Several major failures have shown that deploying remote monitoring techniques improves safety by providing engineers and mining companies with relevant data. Industry 4.0 practices such the Internet of things (IoT) paradigm into monitoring of tailings storage facilities (TSF). The IoT is a set of methods in which devices are connected to a network automatically and with a unique identifier. In many industries, the IoT sees success as a way to collect data from monitoring points, instruments, and the status of machines and data logging systems. Geotechnical instruments have proven designs that have become the backbone of tailings storage facility (TSF) monitoring but in recent years, advances in batteries, radio technologies, microprocessors and telecommunications have enabled the IoT to become an important part of TSF monitoring.

IoT best practices such as interconnectivity and the possibility to bring disparate technologies into a single framework will be explored. Other IoT practices such as self-configuration and intelligent monitoring will be discussed in various contexts. IoT practices also lay the groundwork for future developments such as the use of machine learning and AI for more proactive monitoring of assets. This review will cover the benefits of IoT systems and how the different hardware and software layers are interconnected. It will compare the features of several manufacturers of IoT hardware for TSF.

IoT Characteristics

Monitoring is an integral part of the culture surrounding TSF. Piezometers, water sampling, surveying and more have been used consistently to ensure the durability and safety of tailings for decades. For some older facilities, instruments such as piezometers have been in use for decades. Bringing an IoT framework to this field is an evolution prompted by the decreasing costs and increasing power of microprocessors and radio communications (RF) modules. By attaching specific devices to the instruments, an already-existing network of instruments can be converted to an IoT system. In the context of TSF and environmental monitoring at large, an IoT system is a system that monitors and controls sensors over a wide area, whose data are connected remotely and centralized in a server.

Dynamic and self-adapting

Instruments should be able to adapt to changes in the environment. A typical example of this is that wireless systems should provide redundancy for both the instruments themselves as well as for communications.

Self-configuring

By correctly designing the IoT hardware and its data connectors, adding instruments should be standardized in such a way that minimal technical knowledge is required for the field staff.

Interoperability

In tailings and environmental monitoring, there are different manufacturers of sensors, data loggers and instruments. An IoT system should accommodate many types of instruments and allow the instruments to interact as needed. At a higher level, using standard data connectors to move the data from the instrument to the database facilitates integration of any type of sensors into IoT-based monitoring systems.

Unique identity

Each instrument can and should have a unique identity built-in into the system. This acts as a redundancy compared manually tracking instrument locations, installation parameters, serial numbers and calibration factors.

Integration into larger data networks

An IoT system should be able to allow analysis and comparison of data from many different sources and sites. For instance, working on weather stations, ground-based radar, In-SAR and in-ground instruments can lead to insights that were previous unattainable.

Context awareness

Context varies little in TSF compared to other industries. A classic example would be vehicle trackers that are able to give the exact location of the equipment on a mine site and then have security features be enabled automatically according to that information. TSF are stable over years if not decade and this facet of IoT is not as relevant.

Intelligent *decision-making*

TSF monitoring systems should be able to lead to more intelligent decision-making by offering sizable amounts of data that can be used by engineers to build detailed models of their structure and perform preventative maintenance as needed.

IOT ARCHITECTURE

Table 1 summarizes the structure of an IoT project as used in TSF. The instrument layer is the instrument itself. An in-depth analysis of instrument types and technologies is beyond the scope of this review insofar as the instruments are largely decoupled from the IoT hardware with one important caveat. Instruments that have been installed for years or decades should be possible to add to an IoT network by attaching the proper hardware to it. This is not a new industry starting from scratch and in which continuity with older monitoring programs is critical. Moreover, instruments are often installed in the ground and as such cannot have any type of telemetry built-in. These two points are addressed at the node layer. It usually comprises a data logger, a radio module and a power source. The edge layer collects data from the nodes and pushes it to a local network or to the internet. The management layer is a software layer that assists in the data and inventory management of the instruments and nodes. The application layer is where all data is aggregated and used for monitoring, modelling and more. The layers are intended as framework rather than a strict set of recommendations: for instance, the node and instruments can be built into a single device in the case of tiltmeters or in other cases, the edge device and nodes are the same device.

Table 1 Examples of items part of each of the 5 layers of an IoT system for TSF

Instrument	Node	Edge Device	Management	Application
Piezometers	Data logger	Cellular	Instrument inventory	Graphing
Total station	Radio module	Satellite	Data archiving	Automated reports
LIDAR		Gateway	Security	Data analysis
Inclinometers		Distributed gateways	Traceability	Specialized tools

INSTRUMENTS AND NODES LAYERS

Instruments in TSF are often in remote locations with no external power and no network connection. The node layer is used to bridge the gap between the instruments and the network and databases. Nodes are network-enabled devices that can transmit readings over radio links, collect data from instruments and in most cases locally store the data. They may use a variety of protocols such as Zigbee, LoRa, Pakbus, and proprietary versions or implementations of each, as well as generic-purpose products such as WiFi and LTE.

These protocols can be sorted in two broad families: Star and mesh networks. Star topology relies on having a transmitter at each location that transfers directly to an edge device (see the following section), typically called a gateway (Figure 1 (a)). This link can be unidirectional (the instrument transmits its data on a schedule or when certain conditions are met) or bi-directional, in which polling and other operations can be initiated over the link. Star topology is simple to use, simple to understand and to manage but star networks have a few constraints that should be taken into consideration. There is no way to reroute the data around obstacles should the topology of a site change. It is also not typically possible to extend the range by adding repeaters. However, the most commonly used technology for star networks, LoRa, has a range of up to 15 km, easily covering even the largest TSF.

In mesh networks (Figure 2 (b)), nodes can communicate with each other and transmit relay data between them and all the way up to the gateway or edge device. These networks are often self-healing: if the radio link between two specific nodes is broken, data can be automatically rerouted. The radio technology behind this is more complex than what is required for star networks, but mesh networks tend to more resilient and have fewer points of failures than star networks.

Several manufacturers offer products that work under this principle to enable IoT practices. A comparison of the specifics of each technology can be found in table 2. This list is not exhaustive and is only meant to be representative of the author's professional experience working in North America.

The design of nodes has to balance several factors to be deployed successfully in TSF. It is critical that the transfer data over long distances with minimal battery requirements. Power draw can be influenced by radio power, radio duty cycle, power to the chip that reads the instruments, calculations that need to be done onboard and ambient temperature. All manufacturers make some compromise between all of the above to offer products that are appropriate for TSF monitoring.

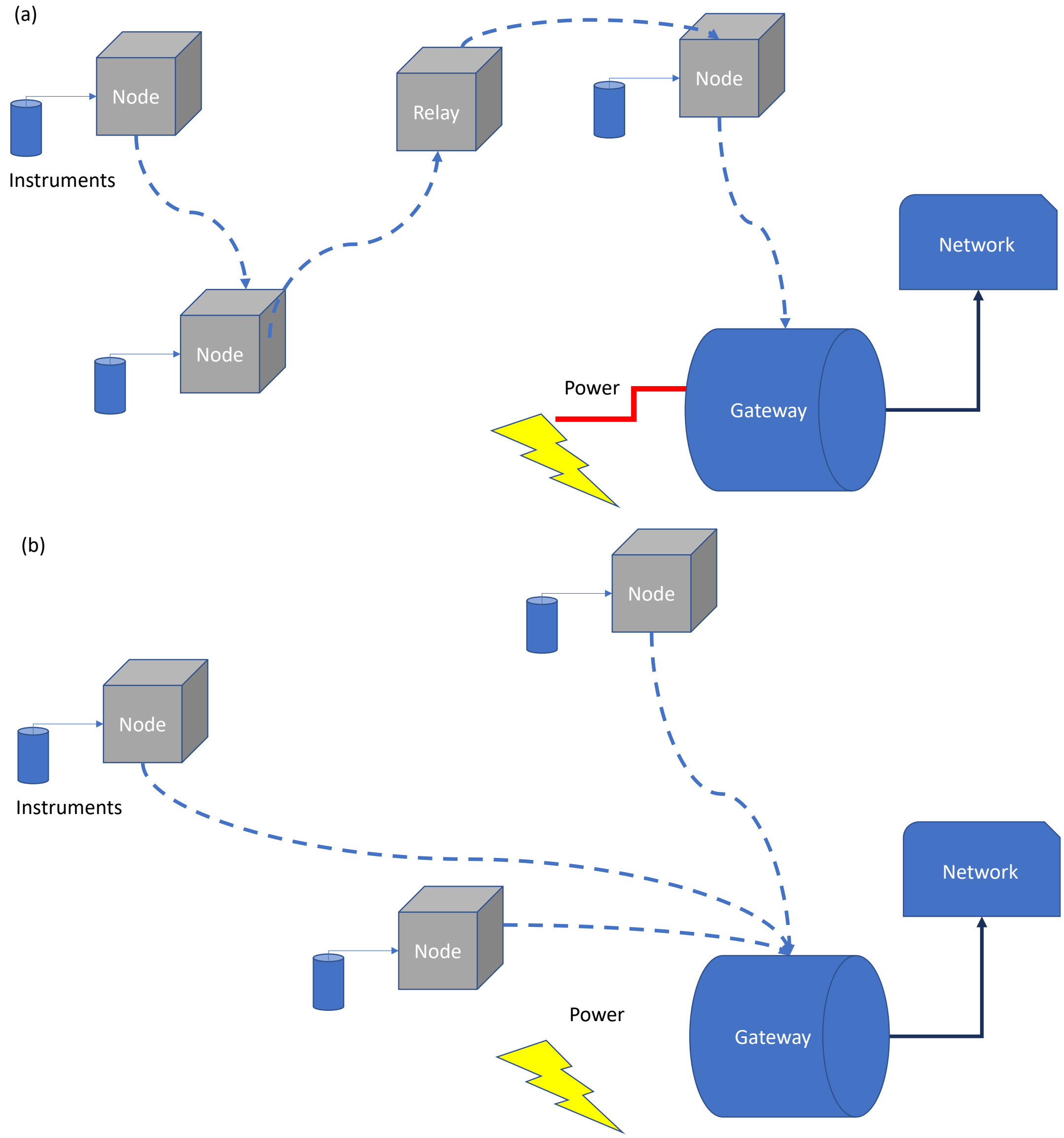

Figure 1 (a) Schematics of a star network. (b) Schematics of a mesh network.

Table 2 Summary of key specifications of IoT node hardware for TSF

	Protocol	*Net. type*	*Self-healing*	*Nb. of hops*	*Range outdoor*	*Range indoor*	*Edge device*	*Instr. Per node*	*Batt. Life*
Ackcio	Mesh-LoRa	Mesh	Yes	>10	10 km	1 km	Prop. Gateway	1-8	10 yr.
Geokon	Mesh	Mesh	Yes	4	6 km	300 m	Prop. Gateway	1-8	1 yr.
Campbell Scientific	Pakbus	Cust.	N/A	>10*	40 km	1 km	Any	Many	1 yr.
Senceive	Prop. Mesh	Mesh	Yes	>25	500 m	200 m	Prop. Gateway	1-4	10 yr.
Sensemetrics	Prop.mesh	Mesh	Yes	?	12 km	1 km	Each node	Many	Solar
Worldsensing	LoRa	Star	Yes*	N/A	15 km	1 km	Prop. Gateway	1-5	10 yr.

*Limited by end-user programming.

Delving in specifics of each technology is beyond the scope of this paper but a few key differences are highlighted in this section. All products are compatible with vibrating wire instruments such as piezometers. All but Geokon's Geonet are compatible with analog output instrument such as barometers or temperature sensors. Digital instruments are on a case-by-case for each instrument for every manufacturer as the drivers have to be programmed on demand.

Ackcio

The gateway synchronizes the mesh network and offers an ethernet connection, a wifi connection and a cellular network connection. The self-healing mesh network appears to work best in constrained areas such as underground mines as opposed to open-air TSF. This product's strength is its compatibility with a large number of digital instruments from all leading manufacturers.

Geokon

Gekon's Geonet product deploys a mesh network with a limited range and a limited number of hops compared to other options such as Ackcio and Senceive. They are compatible with vibrating wire instruments and Geokon digital instruments. The gateway synchronizes the network and can be configured to contain a cellular modem with either an LTE-M or 3G connection. The limited compatibility with instruments from other manufacturers can make it a less desirable choice for systems with digital instruments or legacy instruments from other suppliers.

Campbell Scientific

Campbell Scientific is lagging behind their competitors to introduce fully integrated IoT solutions. However, the PakBus radio technology (Campbell's proprietary protocol) is flexible and can be made to work as a mesh network. The loggers are completely customizable and programmable, allowing for compatibility with all types of instruments available on the market. Campbell Scientific loggers now include built-in data connectors to interface their internal memory into IoT databases. These products are often the most cost-effective approach when a large number of instruments is to be connected to a single location. Most other systems discussed here can only accommodate a few instruments per node, whereas Campbell Scientific loggers can be easily expanded to read hundreds of instruments.

Senceive

Senceive's line of products offers the most robust mesh network in terms of range, number of hops, number of nodes and stability of the products discussed in this review. They offer compatibility with vibrating wire and analog instruments but have limited compatibility with digital instruments. The nodes have a long battery life. Of the products discussed here, they are the only that do not have memory backup on the nodes themselves. This sets up the gateway as a single point of failure but several gateways can be deployed at once as backups with automatic rollovers.

Sensemetrics

The nodes (THREADS) are all gateways with an ethernet connection that can also communicate with each other with a mesh network architecture. Each THREAD is compatible with most digital instruments and analog instruments. They also offer a STRAND product that is designed to exclusively read vibrating wire instruments and which connects in a star pattern to individual THREADS. It is also the only system discussed in this review that has a proprietary cloud platform for configuration and management of the loggers and instruments. The battery life of individual THREADs is low (on the order of weeks) and they typically require a solar panel for continuous operations.

Worldsensing

Worldsensing products (Loadsensing) work on a purely star network (LoRa) with a very long radio range. The nodes require little power and have a battery life of years or more. Nodes are compatible with vibrating wire instruments, analog instruments and a select number of digital instruments.

EDGE DEVICES LAYER

Edge devices layer comprises the device that connect the local IoT network to the internet. In other industries, instruments themselves have their own connectivity, but the lack of local networks and power supplies on TSF makes impossible direct connection of each instrument. Many products, such as Senceive, Worldsensing, Ackcio and others use a gateway that acts both as the collection point for the local IoT network and as a connection point to the internet.

Other products, such as Sensemetrics' THREADS distribute the edge connectivity with each THREAD being a data logger, radio transmitter and internet connection point. This gives the most flexibility and redundancy but increases operation costs. It's usually preferable to have fewer edge devices that aggregate data from several nodes due to the extra cost and power requirements incurred by cellular modems, built-in or external.

In a few cases, the instruments themselves connect to the internet or a local server but this is unusual in the tailings monitoring. Cellular modems are commonly built-in into strong motion sensors or seismographs. The typically large amount of data generated by this type of instrument makes it impractical to transmit measurements over local radio links.

MANAGEMENT LAYER

The management layer is both a benefit and a core component of an IoT system. In TSF and geotechnical monitoring, the standard is to know exactly why an instrument should be at a given location, what is expected to be learned from it and how to handle its data. Even with these widespread precautions, it is not rare for practitioners to lose track of the instrument inventory, of historical data or to ignore data. Large mining companies are showing interest in fully automating their monitoring systems in tailings across the world. This compounds the aforementioned data and instrument management issues as tens or hundreds of sites will be managed concurrently by small off-site teams.

The management layer can be split in two main categories: off-the-shelf specialized software and generic IoT platforms. Specialized platforms are usually designed from the ground up to be used specifically with geotechnical instruments. They include software such as Vista Data Vision's VDV or Canary's Multilogger or Trimble's T4D. They include tools that are made to specifically integrate data from text files as generated by commonly used loggers and edge devices, as well as direct, custom-made, connections to many of the same devices. Furthermore, they offer an application layer that contains tools typically used for TSF, such as displacement graphs (used with inclinometers), geo-localization of instruments and integration of weather station data. This category of software has the advantage of being simple to use and is often the best solution for small operations that cannot invest in setting up their own IoT infrastructure. This software tends however to be more closed-off, making the export of data to other tools more complicated than the software included in the next category.

The second category includes software that are first and foremost IoT platforms but that can be adapted for TSF and the mining industry at large. At its core, the IoT platform should act as a bridge that connects the edge devices or nodes into a database. There are however hundreds of IoT management platforms and each extend into data collection and into applications to varying degrees, and each offer functionalities that are relevant for specific industries. The database then becomes the central repository of instruments, instrument definitions, loggers, nodes and the raw data. This database itself is where software such as business intelligence software collect data and information for advanced analysis. Examples of software that fill this management layer to control the instruments and consign data include Osisoft's Pi, Inductive Automation's Ignition, Google's IoT core thingsboard.io and Microsoft's Azure IoT.

Whichever software or IoT platform is selected, it should help with several key concerns of TSF monitoring. Inventory management of both instruments and nodes is a challenge for long-term monitoring. In TSF monitoring projects that last decades, there may be handoffs between engineering teams, contractors or mine operators. A properly set-up management layer will ensure that each instrument exists as an entity with all its relevant information attached to it such as installation the installation date, instrument name, serial number and more.

Similarly, long-term management of data can be made a lot more resilient. The authors have worked with mining operations that had decades worth of data lost because they were improperly stored in text files or excel spreadsheets. Similarly, there have been cases where the exact process by which the calculated values were reached was lost, making it nearly impossible to re-analyse data or re-use it in more up-to-date models. Historically, instruments data has been collected manually and stored first on paper and then on computers in a completely ad hoc process creating this situation out of circumstances. However, properly storing the data in a secure database, along with a long-term management plan for said database, is now feasible to prevent data loss or degradation over time. Using a generic IoT platform creates a database with which other IoT platforms could interact and more importantly, from which database can be extracted and backed up at any moment.

Similarly, the management layer should give end-users an overview of the current status of the instruments network with real-time updates of parameters such as battery levels, uptime, crashes, data losses, etc. This leverages the advantages of using an IoT framework by lowering the risks of data loss due to hardware failure or communications issues.

APPLICATION LAYER

The foundation of the application layer can be the user interface of off-the-shelf products as described in the previous section or the software used to extract and analyse data from the database generated by an IoT platform. Commonly found functions such as graphing of historical data or report generation data have been introduced for TSF specifically over a decade ago by software companies such as Vista Data Vision or Geoexplorer and are standard in any modern business intelligence or analytics software.

Some commonly-used instruments require specific tools for plotting and interpreting data. In-place inclinometers and manual inclinometer probes have notoriously tricky data to analyse that can't be displayed accurately on regular time graphs. Distributed monitoring such as ground-based radar and total stations also require specialized tools for plotting. The application layer chosen for an IoT system should include the necessary tools for the instruments of a given TSF monitoring plan. Off-the-shelf platforms usually contain them as one of their selling points.

Because industry 4.0 offer a more direct integration of geotechnical data, functions often found in manufacturing and utilities are now recommended to be added to TSF monitoring system. Any complete IoT system should offer real-time alarms on readings, trends and data loss. An alarm log should also be tied in and be accessible for future reference.

Data distribution and control over access rights is another key component of the application layer: the exact views, graphs or reports available for each user and stakeholder can be tailored according to the needs of each.

The application layer encompasses emerging technologies such as machine learning and artificial intelligence. Access to large data sets is necessary to train most machine learning and AI algorithms and the IoT will finally generate the amount of data needed. Training a machine-learning algorithm requires both success and failure states; engineers work tirelessly at preventing failure states so datasets for these are currently limited. However, as more IoT systems are built and more researcher pool their data, more complete models of TSFs should eventually arise.

CONCLUSION

The IoT and industry 4.0 are trends in TSF monitoring that are going to change the face of the industry. They open the door to automated monitoring of the TSF themselves, but also of the instruments, data loggers and data quality. This review has given an overview of what an IoT system for TSF should look like. A growing number of providers offer hardware compatible with instruments such as vibrating wire piezometers and in-place inclinometers. The hardware now offers standardized data exports, making their data available online for management and analysis. The hardware is the first component forming the basis of the various layers of an IoT system as the nodes transform the instruments into IoT points of data collection. Through the integration of large amounts of data from the hardware and instruments, the management layer opens up possibilities that were not usually seen in previous iterations of monitoring plans such as long-term resiliency of the data, real-time alarms, inventory management and distribution of the data. These tools are really what set IoT systems apart and what will help usher along a new era of TSF monitoring.