

Smart sensor-based geospatial architecture for dike monitoring

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Smart sensor-based geospatial architecture for dike monitoring

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Abstract. Artificial hydraulic structures like dams or dikes used for water level regulations or flood prevention are continuously under the influence of the weather and variable river regimes. Thus, ongoing monitoring and simulation is crucial in order to determine the inner condition. Potentially life-threatening situations, in extreme case a failure, must be counteracted by all available means. Nowadays flood warning systems rely exclusively on water level forecast without considering the state of the structure itself. Area-covering continuous knowledge of the inner state including time dependent changes increases the capability of recognizing and locating vulnerable spots for early treatment. In case of a predicted breach, advance warning time for alerting affected citizens can be extended.

Our approach is composed of smart sensors integrated in a service-oriented geospatial architecture to monitor and simulate artificial hydraulic structures continuously. The sensors observe the inner state of the construction like the soil moisture or the stress and deformation over time but also various external influences like water levels or wind speed. They are interconnected in distributed network architecture by a so-called sensor bus system based on lightweight protocols like Message Queue Telemetry Transport for Sensor Networks (MQTT-SN). These sensor data streams are transferred into an OGC Sensor Web Enablement (SWE) data structure providing high-level geo web services to end users. Bundled with 3rd party geo web services (WMS etc.) powerful processing and simulation tools can be invoked using the Web Processing Service (WPS) standard. Results will be visualized in a geoportal allowing user access to all information.

1. Introducing the EarlyDike project

Sea dikes and estuarine dikes are the main coastal protection structures in countries like Germany or the Netherlands. The reliability of these structures is therefore of prime importance to protect inhabitants and economic values. Today's monitoring and early warning systems for dike failures are mainly build on water level observations and predictions but lack in observing and simulating the structure itself. Furthermore, it is well known that other factors like wind, waves, currents and the resistance of sea dikes towards these external influences play also a pivotal role in dike safety.

The EarlyDike project focuses on a holistic monitoring and simulation of sea dikes in real-time considering not only the water level forecast but also other external factors like waves and currents. Simultaneously, the dikes are equipped with different types of sensors to implement a network of smart dikes alongside a coast line. By combining different sensor data, prediction models, marine data infrastructures and smart technologies an innovative and intelligent risk- and sensor-based early warning-system for coastal and estuarine dikes is developed to support authorities in making just-in-time decisions.

Such an intelligent risk- and sensor-based early warning-system has to incorporate different aspects of sea dike safety and failure consequences. Measuring wind or waves and monitoring the dike structure is just one part of a system which should predict dike failures with high-precision and in real-



time. Several research institutes with various key competences and knowledge are working on five different subthemes forming an interdisciplinary project consortium. Because this paper focuses mainly on the Sensor and Spatial Data Infrastructure (SSDI) and its architecture interconnecting all subsystems, the project parts dealing with simulations are briefly presented in the following section 2. Then, section 3 illustrates the intended geospatial architecture for the early warning systems. Section 4 describes the gap occurring between the low level-systems of sensor networks and high-level web services and our solution to close this gap. Further, in section 5 the concept of GeoPipes is introduced as a communication mechanism between geo processes, sensors as well as other subsystems and how this is used to make real-time processing chains possible. Section 6 gives a brief introduction into the dissemination channels of the recorded data and simulated findings with focus on the planned Dike GeoPortal. A conclusion and an outlook about further developments are given in section 7.

2. Monitoring and Simulating the Dike

Models and simulators have to be set up which decide about the risk of a failure, its probability, its consequences in inundation areas and the necessity of evacuating people and protecting economic values. These models and simulators are the following ones:

2.1. Storm Surge Monitor and Simulator

A storm surge monitor and simulator was created by the Research Institute for Water and Environment of University of Siegen (fwu), providing water level forecasts (up to three days ahead) for the entire German North Sea coastline with a high temporal (at least 15-minute values) and a high spatial resolution. A statistical storm surge model was developed coupling data driven empirical and numerical models in an innovative way.

2.2. Wave Monitor and Simulator

The Institute of River and Coastal Engineering at Hamburg's University of Technology (TUHH WB) implemented a system to simulate high accuracy wave impact data for now- and forecasts for the entire German North Sea coastline and to derive an integrated model for the assessment of the wave induced hydrodynamic loads on sea dikes' surfaces. In addition, an integrated (forecasting) wave gauging network will be realized.

2.3. Dike Monitor and Simulator

The dike monitor and simulator were developed by the Institute for Textile Technology and Chair for Textile Machinery (ITA) and the Institute of Hydraulic Engineering and Water Resources Management (IWW), both of RWTH Aachen University. The system covers the real-time monitoring of the dike construction by sensors for e.g. soil temperature, soil moisture and newly developed smart geo textiles to detect stress and deformation. Further, the impact of the storm surge and wave forecasts on the dike can be simulated.

2.4. Flood Simulator

Finally, the IWW sets up a flood simulator to predict real-time flooding scenarios and damage potentials as a function of the dike's failure probability. This simulator gets implemented by the "Hyd" module of PROMAIDES which incorporates the theory of diffuse waves and the "Dam" module to predict the damages of the flooding [1]. This way, local-based threats can be diagnosed and alerts are emitted to local authorities.

3. Smart sensor-based geospatial architecture

A holistic and reliable early warning system for dike breaches needs a smart sensor-based geospatial architecture acting as an interface between existing spatial-temporal data, real-time measurements, the mentioned models and simulators and suitable dissemination channels for the findings.

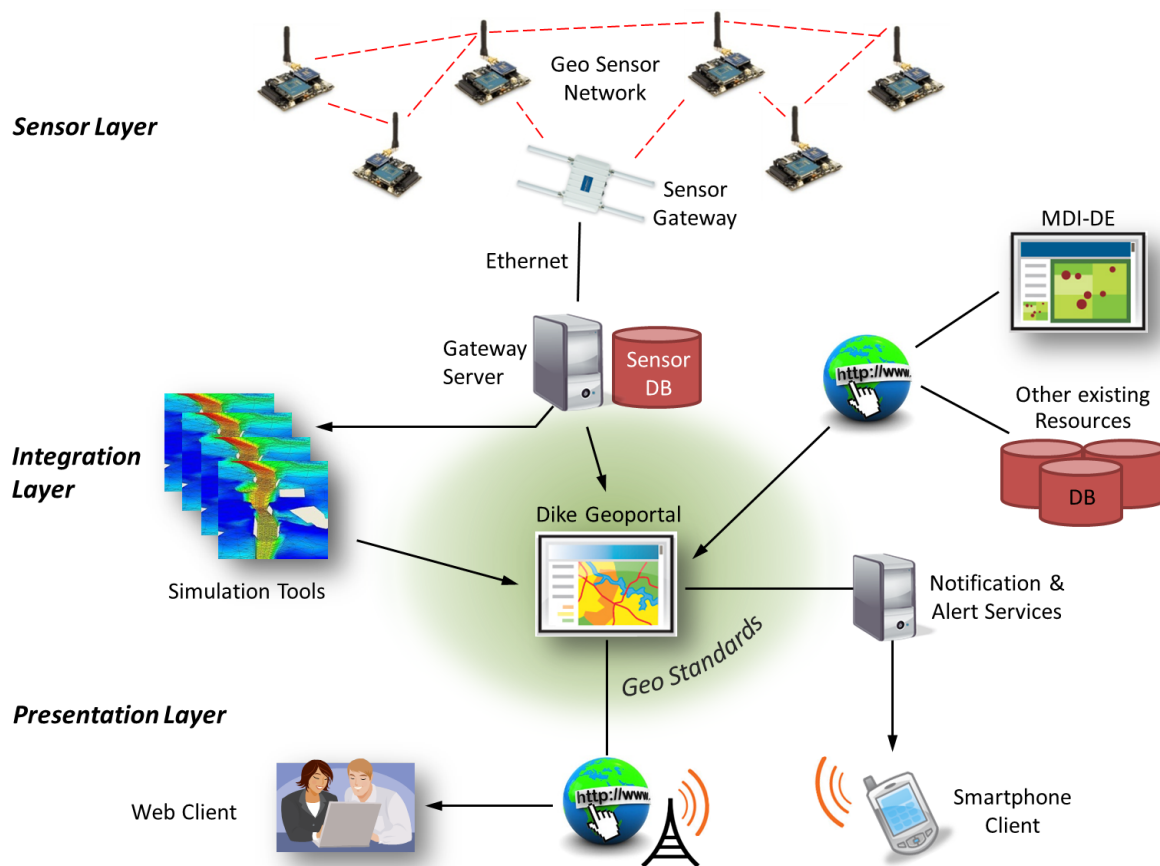


Figure 1: Sensor and Spatial Data Infrastructure for dike monitoring

Our intended architecture is composed of a three layer stack – a sensor, an integration and a presentation layer (Figure 1). First, the sea dikes themselves must be equipped with in-situ sensors measuring e.g. soil temperature, soil moisture or the stability of the structure via intelligent geo textiles [2]. Modular designed sensor nodes serve as platforms for different sensors and are additionally equipped with communication modules and power supply forming a set of wireless geo sensor networks (WGSN) along the coastline. The sensor nodes collect the measurements with a reasonable temporal resolution and send the data to a network sink where it gets processed and forwarded to persistent storage services in the next layer.

The architecture's integration layer is implemented according to the service-oriented architecture pattern (SOA). As a consequence, a Sensor and Spatial Data Infrastructure (SSDI) is realized which facilitates data and model retrieval via web services. International standards for geospatial content and services of the Open Geospatial Consortium (OGC) and the EU INSPIRE directive are utilized to ensure interoperability. Widely used data exchange standards like the Web Map Service (WMS) or the Web Feature Service (WFS) provide e.g. access to maps or vector data. Furthermore, the Sensor Web Enablement (SWE) initiative of the OGC has already developed standards for accessing sensor data archives via web services like the Sensor Observation Service (SOS) [3]. In other research projects like OSIRIS [4], SLEWS [5] or FluGGS [6], SWE services have already been successfully used to manage and access sensors and sensor data.

Consequently, with the help of the SSDI relevant data can easily be disseminated, integrated and rendered into the presentation layer of our architecture. It is envisaged to use different communication channels for the data, model results and issued warnings. The central access point will be a web-based geoportal whilst a smartphone client is also planned (see section 6).

4. Interoperability gap between sensor and integration layer

The main exchange format of many SSDI services is the Extensible Markup Language (XML). In environments with limited resources like sensor nodes in WGSNs using XML is a huge disadvantage. The common installed hardware is not suitable for processing and transmitting large XML documents which lead to an interoperability gap [5].

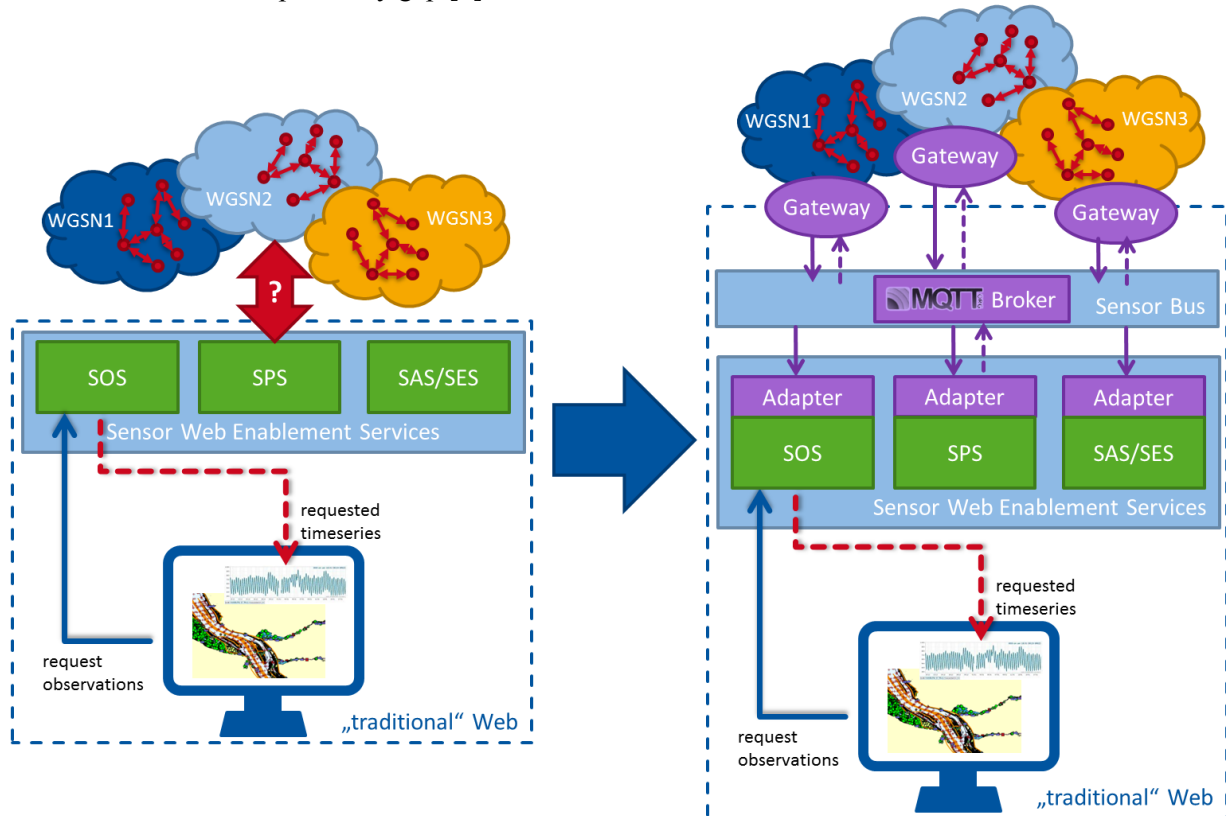


Figure 2: Closing the interoperability gap with a Sensor Bus

This interoperability gap between the low-level protocols used in WGSNs and the high-level protocols of e.g. a SOS for inserting or accessing the sensor data archives needs to be closed in a sophisticated way. Therefore, data measured and collected in-situ with WGSNs has to be transferred into the high-level architecture of the SWE. Broering et al. [7] suggest an intermediary layer to bypass the gap between the two systems. They introduce a so-called sensor bus which follows a message bus pattern. With that layer, sensors can be easily integrated into the SWE infrastructure. Adapter applications are connected to the sensor bus waiting for new sensor data to arrive and forwarding the data into the SWE services via the service compliant methods. For instance, arriving data is persistently stored in the database which is accessible by the “InsertObservation” method of the SOS service (Figure 2).

The message bus pattern and, thus, the sensor bus, can be implemented using a bunch of different protocols. For example, Broering et al. [7] are using four different technologies: Internet Relay Chat (IRC), Extensible Messaging and Presence Protocol (XMPP), Java Message Service (JMS) and Twitter. GEIPEL, J. et al. [8] are also using XMPP to notify clients in the sensor bus.

In our architecture, we need to consider different functional requirements which narrow down the list of protocol alternatives for the sensor bus implementation. First, the sensor nodes in the WGSN should act like clients in the message bus and therefore should also be able to receive messages. Since the WGSNs rely on connectionless transmission protocols like ZigBee, notification protocols which use exclusively TCP/IP for transmission and communication (e.g. IRC or XMPP) are not suitable for

our implementation. Secondly, the resource constraints restrict the abilities of sensor platforms to process, create and transmit large data formats like XML and, thus, rule out the use of protocols like XMPP. Our approach utilizes an adaption of the lightweight Internet-of-Things (IoT) protocol Message Queue Telemetry Transport (MQTT) which has a small code footprint and, with its add-on for sensor networks (MQTT-SN), it is also applicable in connectionless transmission environments [9].

4.1. Message Queue Telemetry Transport (MQTT)

The MQTT protocol is a perfect fit for the intended architecture since it is an extremely lightweight publish/subscribe messaging protocol, running in connectionless as well as connection-orientated networks and, thus, easily connects different devices of different size and hardware resources.

An MQTT system basically involves two components: clients which can publish and receive messages and a broker which disseminates incoming messages. A topic string is used for addressing, so that clients can subscribe to a topic or publish data to a topic. The broker forwards the incoming messages to all clients which are subscribed to the messages' topics. Topic subscriptions are hierarchically structured meaning topics may have subtopics. In addition, clients are able to subscribe to sets of different topics by using wildcard characters in the topic string.

MQTT Version 3.1.1 is standardized by OASIS and heavily used as one communication protocol in the IoT. The whole list of features is described in [10].

4.2. GeoMQTT

In the EarlyDike project, we are using an own adaption of the MQTT protocol which incorporates a geospatial and temporal component respectively. Hence, the extension GeoMQTT also uses the topic filter and a payload for the publish/subscribe pattern like the original MQTT, but additionally integrates the functionalities of a temporal filter and a spatial filter.

The temporal filter allows the clients to subscribe to a topic for time periods. GeoMQTT introduces a subscription message in which the client includes a specific time span by setting start and end timestamps or repetitive periods by specifying a temporal pattern with a Cron expression and an interval length. Of course, it is also possible to deactivate the filter. Besides that, a spatial filter is added to the subscription message enabling clients to subscribe to a 2D or 3D bounding box. Currently, this bounding box is specified by two coordinate values in World Geodetic System 1984 (WGS84). However, it is planned to replace this feature with a more comfortable solution using Extended Well-Known Text (EWKT). This way, clients would be able to subscribe to more complex geometries specified by other coordinate systems, too.

Corresponding to the new subscription mechanism, a geo-publish message is introduced consisting of a topic string, a timestamp and a geographic location (2D or 3D) as well as the message payload. The broker forwards the message to a client only if the client's subscription matches all three filters meaning the timestamp is in the specified period of time, the location is within the bounding box and the topic strings match.

The GeoMQTT extension is fully compatible to the MQTT broker. The broker handles conflicts between MQTT and GeoMQTT subscriptions with different strategies. For example, if a client is subscribed to MQTT topic and the broker receives a geo-publish message which matches the topic filter, the latter one would ignore the temporal and the spatial filter and forwards the message to the client. Furthermore, the newly introduced messages do not collide with the original message types. Brokers that do not implement the extension simply ignore the GeoMQTT messages.

A GeoMQTT broker, a Java client and a Python client are already implemented. In addition, a QGIS plug-in is realized to stream data into a GIS. Currently, the GeoMQTT extension for sensor networks (GeoMQTT-SN) is under development.

5. Interfacing real-time processes using an Event Bus & GeoPipes

Real-time dike monitoring and simulation in the EarlyDike project involves different in-situ sensors,

data, services and processes which has to be interconnected and invoked in a push-based way. For example, before persistently stored in a database, raw measured sensor data must be processed further which sometimes cannot be accomplished by sensor nodes themselves. So, a post processor must be aware of the new measured data, process the data and write it to a database. Ghobakhlou et al. [11] suggest a so-called Sensor Data Processing Service (SDPS) which subscribes to a MQTT topic on which the raw sensor data is published by the sensor node. If the message matches a specific pattern, the raw data is post processed by the service and stored in a SOS database.

In our architecture, we adapt this idea, transform the entire sensor bus into an event bus and introduce the concept of GeoPipes which is basically a spatial notification and data stream transfer mechanism using GeoMQTT (Figure 3). (Post-) Processing services log in the event bus and subscribe to the (Geo-)MQTT topics on which the sensor data are published. The results of the processing service are republished to the event bus on a different topic. Data storage services like SOS subscribe to the post processed messages and only store this data persistently. That way, e.g. outlier or erroneous data can be filtered easily or data aggregation functions can be applied to reduce data for storage.

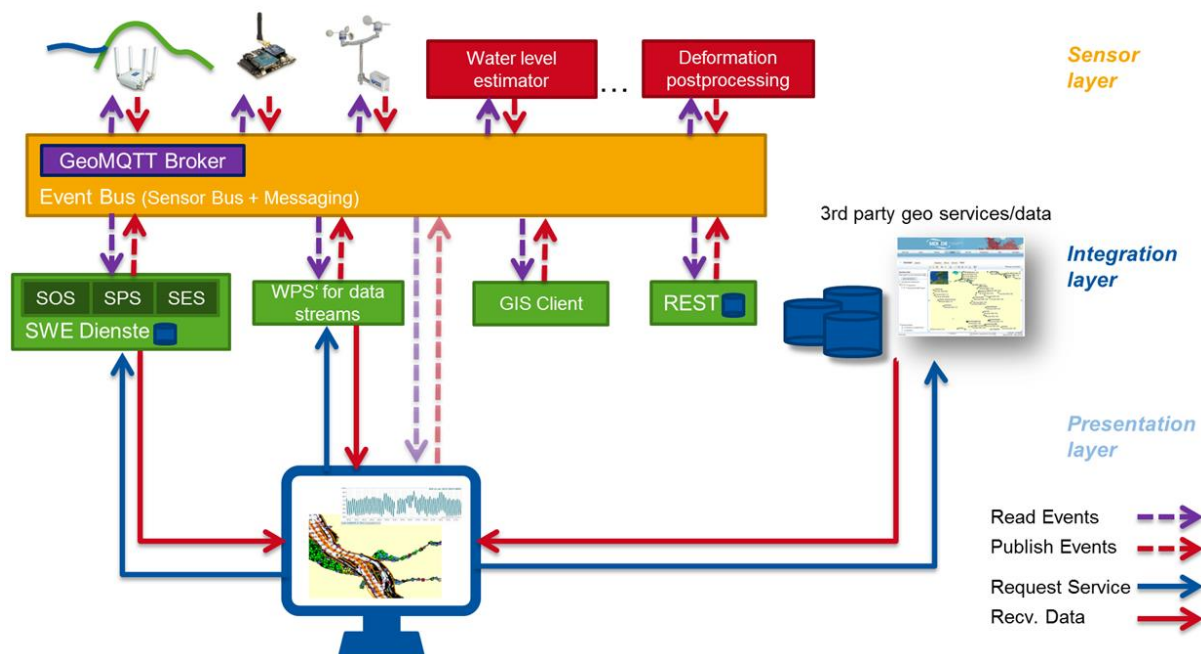


Figure 3: SSDI architecture with an Event Bus

In addition to process raw sensor data, the concept of GeoPipes adds also benefit to simulations and models which have to be invoked as soon as new data or results become available. Producers of data and processes acting on geo data streams can be connected easily to new event-driven process chains. In the EarlyDike project such an process chain could be the following: Installed anemometers publishes the wind speed in real-time using the GeoPipe mechanism; the storm surge simulator subscribes to the GeoPipe, computes the current wind field with the real-time data and republishes the result as an event on the bus; another process takes the computed wind field as well as real-time water level measurements and simulates the prevailing swell which serves as input to the dike simulator itself. The final result of the process chain is again published in the event bus enabling the subscription by any GeoMQTT client.

The example illustrates an event-driven invocation of the process chain. It is also possible to invoke a processing chain and, hence, run models and simulations by user request. We utilize the Web Processing Service (WPS) standardized by the OGC which enables spatial analysis of geospatial data via the Web. However, like most of the OGC web services it is based on synchronous HTTP and, thus,

not suitable for asynchronous real-time processes. To overcome this issue, first solutions have been developed [12,13]. The introduced concept of GeoPipes using GeoMQTT allows the user to define input and output (geo-)data streams in his WPS request and also to subscribe to the streams to receive continuous data and processed interim results.

6. GeoPortal

In the presentation layer a web-based geoportal is implemented and serves as a central information access point called “Dike GeoPortal”. The JavaScript application is created with common open source geospatial libraries. For example, the popular map viewer OpenLayers is used for load, display and render maps in the application. That way, the standardized services like WMS, WFS or SOS are deployed in the integration layer and can be utilized to request the data. Spatial data are rendered as maps in the map viewer while time series of e.g. water gauges are visualized by dynamic tables and/or graphs. Additionally, real-time sensor data can be displayed by either connecting directly to the event bus using GeoPipes or register to other services like the Sensor Event Service (SES). As mentioned before, authorized users might also invoke processes and simulations utilizing WPS as a standardized interface. In addition, 3rd party services also issued with OGC standards can easily be added to the geoportal creating a powerful analyzing tool.

Besides the web-based geoportal, a smartphone client is planned for alert and notification services. Local authorities might be warned early enough in case the monitoring and simulators detect anomalies or emergencies.

7. Conclusion and outlook

The EarlyDike project addresses the holistic monitoring and simulation of sea dikes in real-time, taking different data sources, models and simulations into account. Therefore, a smart sensor-based geospatial architecture is implemented to combine data collection with sensor networks, data storage and data processing in a Sensor and Spatial Data Infrastructure (SSDI). The concept of an event bus and GeoPipes is realized by GeoMQTT, an extension of the Message Queue Telemetry Transport (MQTT). With the introduction of a temporal and a geographical component in data streams, complex spatial processing chains from collection to visualization can be invoked. This way, the measured sensor data can be linked up with the simulators producing results in real-time.

GeoPipes can already been used with different simulators. A java and a python client have been implemented and a JavaScript based client using WebSockets is currently under development. The latter one will enable the push-based retrieval of simulation results in the Dike GeoPortal. Further, we are planning to add stream data mining capabilities to support highly spatially and temporally resolved data processing on-the-fly.

The illustrated approach and the future developments are going to facilitate a whole new bunch of applications especially in civil engineering and environmental informatics. For instance, possible use cases for our smart geospatial architecture might be energy or traffic management.

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