Abstract—We introduce a new computing and communication architecture, Reflex-Tree, with massive parallel sensing, data processing, and control functions suitable for future smart cities. The central feature of the proposed Reflex-Tree architecture is inspired by a fundamental element of the human nervous system: reflex arcs, the neuromuscular reactions and instinctive motions of a part of the body in response to urgent situations. Our multi-layered architecture mimics human neural circuits to achieve the high levels of scalability required for efficient city-wide monitoring and feedback. To demonstrate the utility of our architecture, we present the design, implementation, and experimental evaluation of a prototype simulation. We show the effectiveness of the architecture and verify the feasibility of implementation.

I. INTRODUCTION

The “Smart City” is an emerging concept aimed at dramatically enhancing the efficiency, sustainability, and safety of tomorrow’s urban communities. Integrating infrastructure and services into a cohesive whole allows them to be both monitored and managed using intelligent devices and systems [1]. Accurate, distributed, and real-time sensing platforms with high performance computing and communication structures are the core components of the smart city concept, enabling municipalities to monitor and respond to changing conditions within the community in real-time. A prime example is the use of a large amount of multiplexed sensors to monitor critical elements of public infrastructure (bridges, tunnels, gas and oil pipelines, etc.) and massive parallel and distributed computing infrastructures to intelligently process vast amounts of data collected [2]. Such infrastructure enables both appropriate and efficient resource allocation during normal operation and quick response in real-time to storms, earthquakes, or other natural disasters. To tackle the challenges involved in the creation of a highly complex distributed city monitoring system, we propose a transformative computing and communication architecture specifically suitable for smart cities, the Reflex-Tree.

II. OVERVIEW OF REFLEX-TREE ARCHITECTURE

The Reflex-Tree architectural approach is inspired by the human nervous system, which uses several distinct hierarchical layers to process and react to millions of data streams of biological sensory information in real-time [3]. The key element of the reflex-tree concept is the inclusion of automated “reflex” circuits in the sensing and distributed computing architecture. Physiologically, the myotatic (or stretch) reflex, acts as a direct neural circuit to maintain muscle position without the need for centralized control input from the brain. Similarly, drawing a parallel to a city management application, the detection of a burst pipeline governed by an edge device or intermediate computing node could trigger an automatic valve closure, providing immediate action that minimizes potential damage without necessarily waiting for direction from a centralized command center. Through coupling both afferent (sensor input) and efferent (control output) elements to individual edge devices and intermediate computing nodes in a multi-level hierarchy, we should be able to develop feedback loops to effectively and efficiently stabilize important parameters at the appropriate levels of the system in question.

The envisioned Reflex-Tree architecture, as seen in Fig. 1, is comprised of a 4-layer hierarchy. Each layer is capable of implementing a certain level of immediate “reflex arc” feedback. At the leaves of the tree, layer 4 contains a distributed sensor network with numerous sensory nodes, which monitor public infrastructure by acquiring and processing critical data in parallel and in real-time, allowing for unprecedented temporal and spatial resolution. Layer 3 consists of a vast array of low-power, high-performance computing nodes, or edge devices. Each edge device is directly connected to a local sensor network (covering a neighborhood or a small community) and is responsible for raw data processing tasks, such as data classification and pattern recognition. A cluster of such edge devices is
connected to an intermediate computing node that forms the next level of the hierarchy, layer 2. The key to this layer is make spatial-temporal associations based on the inputs from lower layers to support decision-making. Layer 1, the top level at the root of the Reflex-Tree, is the cloud with the high computing power necessary to provide city-wide monitoring and control functions. This layer will use the inputs from the second layer to perform complex system behavior analysis and execute any required dynamic decision-making algorithms. This allows for a city-wide response in the event of a natural disaster or other potential cause of service outage. The end result of our architecture is a new computing platform with massive parallelism across all four layers, providing the necessary computing power and intelligence demanded by smart cities of the future.

III. CASE STUDY IN CITY MANAGEMENT

Gas pipeline systems play an essential role in supplying energy within cities. Several threats can affect pipeline integrity, which can significantly hinder/endanger pipeline function, leading to damage, leakage, and pipeline failure. It is known that in a gas pipeline, local temperature drop is an indication of leakage owing to the Joule-Thomson effect: local pressure release induces a cold spot in a compressed gas line, allowing for the quick determination of the precise location of a leak. Also, detection of heat can be indicative that an explosion has occurred. In our simplified simulation we use temperature to determine burst and cracked pipelines.

The top half of Fig. 2 depicts the gas pipeline system used in our simulation. The pipeline itself is represented by the blue lines in the figure. X and Y axis markings are distance measurements given in meters. A distributed layer 4 fiber-optic sensor network, utilizing Rayleigh backscatter extracted by optical frequency domain reflectometry (OFDR) as a sensing mechanism for temperature is deployed in the vicinity of the pipeline. A multitude of layer 3 edge devices are located on a meter level alongside the pipeline. Each edge device performs periodic support vector machine (SVM) pattern classifications on the incoming raw data, grouping it as either “normal”, “hot”, or “cold” and provides the results to the next higher layer. All edge devices in the figure are attached to a single layer 2 intermediate computing node. Here we have employed the density-based spatial clustering of applications with noise (DBSCAN) clustering algorithm to detect whole sections of damaged pipes. The local grid covered by this computing node is, along with multiple other layer 2 nodes, interfaced directly to the cloud. The server cluster representing the cloud layer is not connected to an intermediate computing node that forms the next level of the hierarchy, layer 2. The key to this layer is make spatial-temporal associations based on the inputs from lower layers to support decision-making. Layer 1, the top level at the root of the Reflex-Tree, is the cloud with the high computing power necessary to provide city-wide monitoring and control functions. This layer will use the inputs from the second layer to perform complex system behavior analysis and execute any required dynamic decision-making algorithms. This allows for a city-wide response in the event of a natural disaster or other potential cause of service outage. The end result of our architecture is a new computing platform with massive parallelism across all four layers, providing the necessary computing power and intelligence demanded by smart cities of the future.

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For the case study we run a simulation of both a fire and ground tremor that increase in area over time, a frame of which can be seen in Fig. 2. The fire results in a pipeline explosion, and the tremor is intended to produce pipeline leakage over time. “Reflex arc” feedback is disabled in the simulation such that detections at higher layers can be clearly observed.

IV. RESULTS

A visualization of our full simulations can be found in the video files located at [4]. For our simulation, SVM classification in the layer 3 edge devices was found to predict nearly all simulated pipeline states correctly over the duration of the simulation. The clustering algorithm present at layer 2 was able to accurately detect portions of the pipeline/power line that were at risk once enough individual layer 3 classifications became available.

In a deployed system with feedback, layers 3 and above would detect events and respond in real-time. Layer 3 would be capable of sensing small disturbances such as leakage, layer 2 could detect significant perturbation such as a ruptured pipeline, and layer 1 would identify major hazard events such as earthquakes, fires, and adverse weather.

V. CONCLUSIONS AND FUTURE WORK

To the best of the authors’ knowledge, we have presented the first hierarchical approach to city infrastructure management modeled after the human nervous system. Through simulation of a realistic case study, we have verified that the concept appears to be both feasible and highly reliable in detecting potential issues at multiple stages in the hierarchy. In an actual deployed system, the “reflex arc” feedback should aid in performing timely adjustments to city infrastructure, prior to cloud-level intervention.

REFERENCES