Poster Abstract: HERMES - Heavy Element Real-time Monitoring for Environmental Safety

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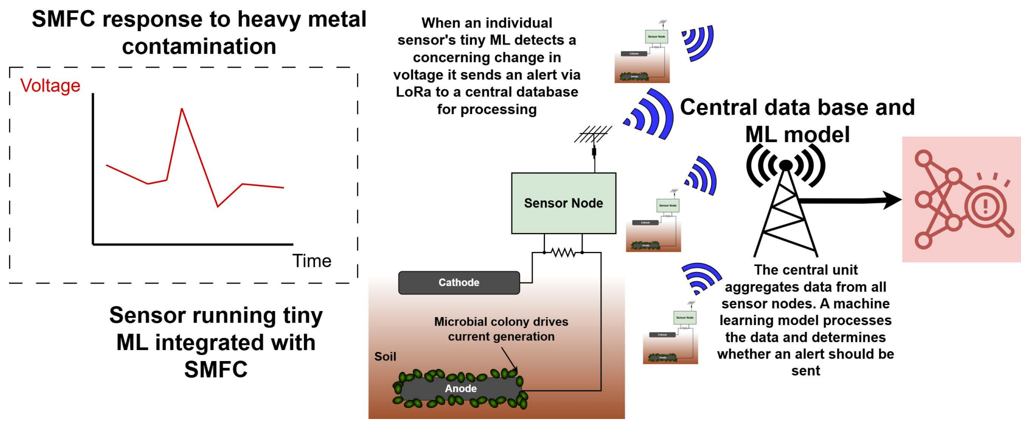

Figure 1: SMFC-Based Early Warning System for Heavy Metal Detection: Monitoring, Transmission, and Processing

Abstract

Heavy metal contamination in soil presents substantial risks to public health, industry, and the larger biosphere. Current methodologies for detecting heavy elements rely on labor-intensive sampling methods and time-consuming laboratory analysis, limiting temporal and spatial resolution. We present HERMES, an in-development heavy metal monitoring system that can be placed around high risk areas. HERMES leverages soil microbial fuel cells as autonomous biosensors. These biosensors when deployed as a sensor field, can monitor soil conditions and transmit data using a distributed machine learning framework. By providing improvements in the speed and resolution of heavy metal contamination detection, HERMES aims to enable earlier intervention and mitigate long-term damages.

CCS Concepts

• **Computer systems organization → Embedded and cyber-physical systems**.

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1 Introduction

The presence of heavy metals in water and soil poses a significant threat to the well-being of crops, ecosystems, and human health [2, 4]. Human activities, including agriculture, mining, and industrial processes, are recognized culprits for the release of heavy metals into both water and soil [2]. Soil systems near areas of heavy industrial activities are particularly vulnerable to damage by heavy metal contamination [7]. Workers and residents in proximity to areas of high industry activity are at greater risk of adverse health effects due to heavy metal exposure [4].

Currently, there are no in-situ, real-time methods available for sensing heavy metals. Detection can only occur retroactively via labor intensive soil sampling and time consuming external laboratory processing. Soil microbial fuel cells (SMFCs) offer a solution.

In its most general form, an SMFC comprises an anode submerged in the soil that houses a community of bacteria and a cathode exposed to air. As these bacteria respire, they generate electricity, which can be used as a novel sensing signal. In controlled, laboratory settings researchers have identified a direct correlation between SMFC power output and the concentration of specific heavy metals, namely zinc, cadmium, mercury, and lead [6]. This implies that in principle SMFCs could serve as on-site heavy metal detectors.

2 Hypothesis

We hypothesize that SMFCs can be used as the first in-situ heavy metal biosensors, and by extension can be developed as the sensor nodes for the first wide area heavy metal early-warning detection system. We call this system HERMES - Heavy Element Real-time Monitoring for Environmental Safety. Currently, SMFCs are not reliable enough to be deployed as sensor nodes in uncontrolled environments. To address this, we are characterizing SMFC response to ambient soil and environmental factors. This will then allow us to isolate SMFC response to heavy metal contamination. Finally, we will build and deploy remote sensor networks of SMFCs in outdoor environments.

Each individual sensor will operate a compact machine learning model (e.g. TinyML [1]) trained on data from the intial SMFC characterization work to detect potential heavy metal contamination events. When the compact model detects a potential contamination, the sensor will automatically upload its data to a central database for further analysis. A more extensive, centralized machine learning model will evaluate the data collected from all SMFC nodes in the network to determine whether an alert should be issued.

An overview of the platform is illustrated in Figure 1. The prototype sensor network will be deployed around Mission Bay, San Diego, CA, a region experiencing rising levels of heavy metal contamination. We have identified domain science partners at University of San Diego and Naval Information Warfare Center Pacific who are actively studying local contamination to assist with deployments and characterizing the platform's efficacy.

3 Research Plan

3.1 Phase 1: Eliminating Environmental Confounds (In progress)

The first step to developing SMFCs as heavy metal biosensors is developing technology to robustly isolate the signal from heavy metal intrusion. This is challenging as many environmental factors affect SMFC electrical output, confounding variables not present in the initial lab-based results that first demonstrated the sensitivity of SMFCs to heavy metals [6]. We have developed a standardized SMFC construction and experimental procedure to compare local soils across the country to a controlled "synthetic" soil. This procedure currently is being implemented by collaborators at UC San Diego, Northwestern, UC Santa Cruz, and Georgia Tech. This data will inform models to filter soil-type and environmental noise.

3.2 Phase 2: ML Model Creation

Once we have the initial native and "synthetic" soil data sets, we will incubate a substantial quantity of SMFCs in the "synthetic" soil, along with an equal number of SMFCs incubated in native soils. We will collect a database of responses to heavy metals, this database, when paired with the Phase 1 dataset, will be used to train both the compact ML model and the centralized machine learning model which will determin overall contamination risk.

Phase 2 will yield a baseline dataset and model for SMFC voltage responses to heavy metals. While it would be ideal to conduct this phase in a variety of outdoor real-world soils, exposing native soils poses significant environmental and public health risks. This is why both Phase 1 and Phase 2 are necessary. By pairing diverse baseline data from varied soil types with controlled heavy metal exposure tests, the model will be better equipped to detect contamination signals despite the natural variability in soil composition.

3.3 Phase 3: Deployment

We will deploy a sensor network using SMFCs attached to an enhanced version of the ENTS platform[3, 5] with support for performant, on-device ML. In steady-state, edge nodes will periodically upload sparse, down-sampled voltage traces. When an SMFC sensor detects a concerning power change, it will transmit full-fidelity voltage traces via LoRa to a central database. The centralized machine learning model will analyze the data from the entire sensor field. If the model determines that there is a significant cause for concern in any part of the network, it will generate an alert.

To validate the system, indivridual sensors will be placed in Mission Bay, San Diego, an area with known heavy metal contamination. As well as in nearby regions with minimal contamination and the boundary in-between. By comparing performance across these settings, this phase will test the system's ability to accurately identify contamination events. The outcome of Phase 3 will be the validation of whether a heavy metal early-warning system based on SMFCs is feasible.

4 Future Work

In the longer term, SMFCs have previously been studied as energy harvesters to provide trickle power for traditional sensors [8]. This work instead focuses on leveraging SMFC power output as a signal to sense, complemented by an external, battery-powered monitoring system. A natural next question then is whether SMFC power output can be both the sensor signal and the sensor power source. In principle, this could realize a maintenance-free, self-sustaining, wide area heavy metal detection system with unbounded lifetime.

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