An Embedded System for Impedance Imaging of Permafrost Changes

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Overview

Abstract: Permafrost is permanently frozen soil in the near-surface. Impedance imaging techniques may enable monitoring of increased seasonal variation in land movement and slope stability wrought by climate changes. We explore the constraints on an open-hardware embedded system for long-term remote monitoring of permafrost enabling preventative action prior to a catastrophic infrastructure failure.

Permafrost is a layer of permanently frozen soil (< 0°C for 2 years) which covers 24% of the landmass in the North to a depth of 1.5 km in some locations [1]. Changing climatic conditions have led to structural changes in permafrost: seasonal heaving of formerly stable land upon which civil infrastructure resides. A key indicator of these changes are the formation of "ice wedges" as well as sub-surface pooling of melt water. Electrical Impedance Tomography (EIT), or equivalently Electrical Resistivity Tomography (ERT), is a promising technique for monitoring these localized changes in structure [2]. In warmer conditions, EIT systems tend to be designed for relatively low frequencies (1 Hz) and are often designed to be sensitive to humid soils and conductive ores. Frozen soils have much lower conductivities and temperature dependent permittivity, meaning current will propagate poorly unless stimulation frequencies in the 10's or 100's of kHz are used [3]. This means that the hardware design experience in the biomedical EIT community can be relevant to designing a multi-frequency system for permafrost EIT measurement. We explore the design constraints for an embedded system to be used in remote, long-term monitoring of seasonal changes in the resistivity of permafrost layers.

We have interviewed a number of hardware experts from the EIT community regarding their experiences designing EIT systems. We briefly summarize the design considerations identified during these interviews below.

Design Considerations Identified

An impedance imaging system can be broken down into a number of components as shown in Figure 1. Audio frequency analog circuits, low frequency A/D converters, and millivolt-range measurements imply a straight-forward design. The components are relatively well understood but are deceptively challenging to implement well at 100kHz frequencies [4, 5]. In implementing these functional blocks, design choices and trade-offs must be made: frequencies of operation, noise tolerance, complexity, and reliability.

For products manufactured at a commercially viable scale or remote installations where on-site maintenance costs can be very high, reliability plays a key role. How much calibration, testability, and repeatability should be built into a system or be available in some adjacent system?

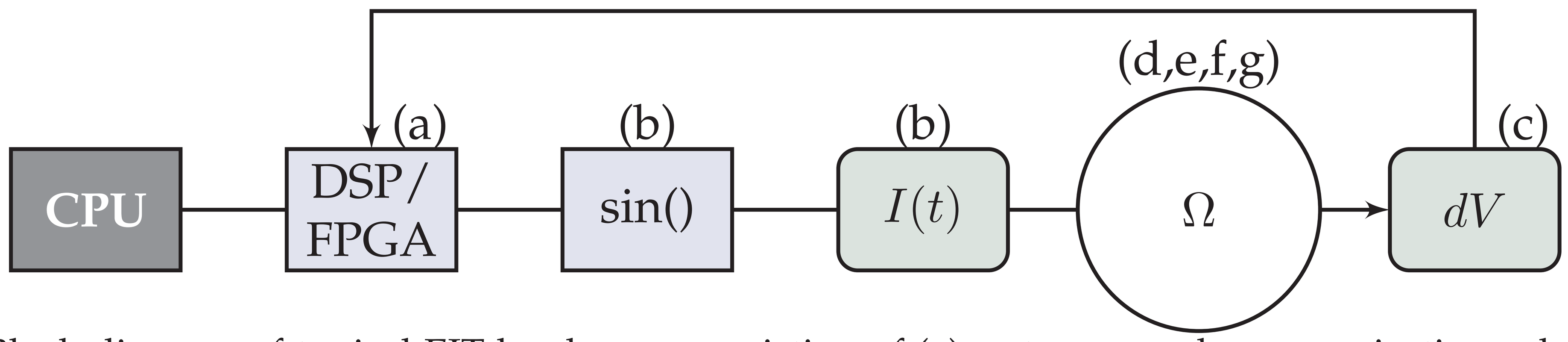

Figure 1: Block diagram of typical EIT hardware, consisting of (a) a storage and communication solution, typically some form of microcontroller or embedded processor and storage connected to the outside world, (b) digital frequency synthesis and modified Howland current source, (c) quadrature differential measurement, (d) analog signal chains for amplification, buffering, and filtering, (e) switching, (f) wiring, and (g) electrodes

Design decisions imply different cost, sensitivity to noise and interference, robustness and calibration requirements. Key challenges are to address drive, connectivity, and measurement needs while limiting interactions that complicate calibration. Quality of excitation is determined by quantization errors, current source matching, output impedance, and frequency range. Wiring, muxing and electrodes may limit system performance: crosstalk, stray capacitance, and leakage currents may be controlled with shielding. Electrode polarization can be managed through appropriate measurement strategies and careful control of excitation. Differential measurements are typically limited by Common Mode Rejection Ratio (CMRR). Measurement accuracy and speed is further limited by filter structures, A/D dynamic range, time source jitter and phase accuracy at measurement demodulation. Equipment must be able to report on the quality of measurements, as well as the measurements themselves. Increasing circuit complexity in an attempt to solve some of these issues tends to lead to increased calibration challenges.

Ice Wedges

Ice wedges form through repeated partial freeze-thaw cycles over many seasons, driving harder ice into cracked permafrost layers of mixed weaker material (Figure 2). Distinguishing types of ice may be possible by frequency-difference EIT (>10 kHz) or looking for anistropic resistivity regions.

Figure 2: (left) "Pingo" (a mound formed in permafrost regions) with geometric polygon shapes formed due to ice wedges in the permafrost, near Tuktoyaktuk, NWT, Canada; licensed public domain image, Wikipedia [6]; (right) An ice wedge associated with high-centred lowland polygons; reproduced Gov't Canada public domain non-commerical use image [7]

Water Interfaces

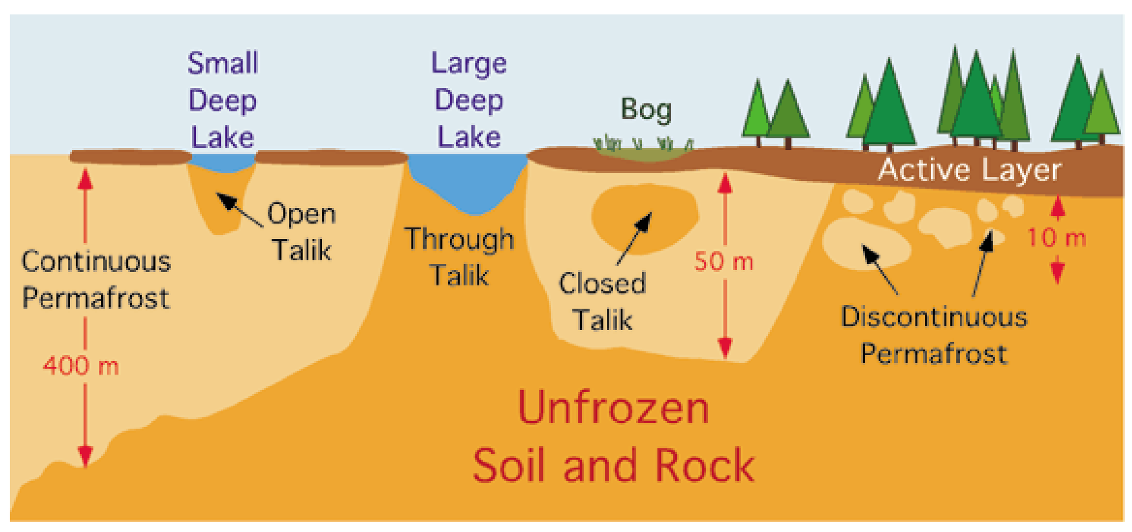

Figure 3: At the margins of permafrost regions there are pockets of permafrost interspersed with "talik" (regions of unfrozen ground) which may be associated with water which moderates heat transfer into the ground; image reproduced from [8], Figure 10ag-2

Distinguishing changes in permafrost boundaries (Figure 3) is important for designing local climate mitigation stratgies. Locating pooled and moving water at the surface, under snow layers, and in the near-surface, inform estimates of heat transfer and annual change in the permafrost layer.

Discussion

There are challenges in implementing an EIT system under new constraints. We aim to bring together the experiences of many in the EIT and ERT communities in designing these systems by working towards an open-hardware platform as a focal point for discussion of design constraints and trade-offs.

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