Demonstration: Real-Time Volcanic Earthquake Localization

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1 Introduction

We are demonstrating a wireless sensor network designed to automatically detect and localize volcanic earthquakes. The network consists of several wireless sensor nodes equipped with seismic and acoustic sensors, a middle-tier gateway node for computing wavefront arrival times, and a base station laptop calculating source locations. We will deploy our network in the University of Colorado football stadium, a space large enough to accommodate an array aperture permitting source localization. As we do not anticipate a reliable source of seismic activity at the demo site, we will actuate the system with an infrasonic source (e.g., gunshot or small explosive) and use the acoustic signal for localization.

This demonstration builds upon our previous work on monitoring volcanoes using wireless sensor networks [3, 4]. For the last two years, we have been collaborating with seismologists from UNC, UNH, and the Instituto Geofísico, Ecuador, to develop wireless sensors for monitoring active and hazardous volcanoes. Wireless sensors are lighter, smaller, and consume far less power than existing volcanic monitoring equipment, permitting studies with a large number of sensors distributed over a volcanic source region. In addition, wireless communication permits real-time data acquisition, which is essential in assessing the level of volcanic activity and determining potential hazards.

As part of this project, we have deployed two sensor networks on volcanoes in Ecuador: Tungurahua (July 2004) and Reventador (August 2005). These networks collected seismic and infrasonic (low-frequency acoustic) data on volcanic earthquakes, tremor, and explosions. The Tungurahua network was intended as a proof-of-concept, while the Reventador network consisted of 16 sensors deployed over a 3 km aperture, delivering real-time seismoacoustic data on nearly 300 volcanic events over a three-week period.

The wireless sensor node used at Reventador is based on the Moteiv TMote Sky sensor mote, which includes a TI MSP430 processor and CC2420 radio. Sampling is performed by a custom sampling board that provides two or four channels of 24-bit analog-to-digital conversion based on the TI AD7710. Nodes are interfaced to either a single-axis seismometer (GeoSpace GS-11) or three seismometers in a triaxial configuration (GeoSpace GS-1). Both sensors are passive instruments; ground motion generates a voltage which is amplified and digitized by the sampling board. In addition, each node is attached to an omnidirectional microphone (Panasonic WM-034BY). Each node is equipped with an 8.5 dBi omnidirectional antenna mounted to 1.5 m of PVC pipe. This permits line-of-sight radio range of over 1 km without amplification; at Reventador, nodes were typically placed 200-400 m apart. Nodes are powered by two D-cell batteries with a lifetime of approximately 1 week. Each node is enclosed in a weatherproof Pelican case.

While our previous work was focused on data collection, pushing distributed processing into the network will greatly reduce radio bandwidth and power requirements, allowing us to increase the number of sensors at a volcano. Sensor nodes can perform collaborative data filtering and fusion to calculate energy release, determine seismic and acoustic wave arrival times, characterize and differentiate eruption earthquakes from sub-surface earthquakes, and timestamp phase arrivals for discrete events.

2 Earthquake localization

As an initial step in this direction, we are exploring approaches to real-time earthquake localization within the sensor network. Earthquake localization is a classic inverse problem in volcanology, which seeks to determine the source locations of seismic activity within the interior of the volcano [1]. Calculating the location of earthquake sources yields a deeper understanding of volcanic activity, magma movement, and gas expansion within the volcanic edifice. Source location can also assist in hazard mitigation, since swarms of earthquakes along the volcanic conduit may indicate an impending eruption.

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Our approach employs a multi-tiered sensor network consisting of multiple sensor patches deployed around the expected volcanic source region. Each patch is comprised of multiple (10 or more) seismoacoustic sensor nodes, a gateway node capable of performing a moderate amount of computation, a GPS receiver for time synchronization within the patch, and a long-distance radio modem providing connectivity to the volcano observatory. At the observatory, a base station laptop receives data from the gateway nodes and performs source localization following an earthquake. Sensor nodes within each patch form an adaptive multihop network for relaying data to the gateway. Gateways communicate directly with the base station via radio modem (although repeaters may be necessary based on topography). Accurate timing is essential for studying seismic signals, so each patch is time-synchronized using the FTSP protocol, and the network's global time is mapped to GPS time.

Each sensor node continuously samples seismic and acoustic channels at 100 Hz, storing data to local flash memory. The TMote Sky node has 1 MB of flash which can store approximately 20 minutes of sensor data. Each node also runs an earthquake detection algorithm triggering on significant seismic or acoustic signals. Upon detection of an earthquake, each node transmits a brief report to the gateway node within its patch. If the gateway receives enough reports within a short time window (e.g., 10 sec) it initiates a data transfer operation, downloading 60 sec of data from each sensor node. We have developed a reliable multihop data-transfer protocol, called *Fetch* [5], for this purpose.

After collecting data from each node, the gateway performs P-wave arrival time calculation [2] on each signal. This computation is fairly complex and requires computational resources not available on the individual sensor nodes. This results in a set of arrival times $T_p = \{t_1, t_2, \ldots t_n\}$ for each of the n sensor nodes in the patch p. Pushing the arrival time computation to the gateway node greatly reduces the amount of data that must be transmitted via the (extremely power hungry) radio modem link to the base station, thereby reducing power consumption.

Finally, the base station collects the arrival timesets T_p from each patch and uses this information to compute the earthquake location and origin time. For this we plan to use `lquake`, an existing tool which takes as input the P-wave arrivals from each station, the station locations, and a *velocity model* that captures the expected velocity of seismic waves at varying depths within the earth. It then computes the most probable source location based on the input data with potential accuracies in the tens of meters, depending on station location and timing accuracy.

3 Demonstration setup

Figure 1 shows a diagram of our proposed demo setup. The demo will consist of eight sensor nodes, each with an attached microphone and omnidirectional antenna mounted to 1 m of PVC pipe. Because ample station spacing is necessary to accurately localize event sources, sensors will be positioned around the periphery of the University of Colorado stadium. The gateway node is a low-power embedded PC based on the Soekris net4826 system board with a 233 MHz processor, 64 MB of RAM, and 64 MB of flash, running an embedded Linux distribution. The sensor nodes communicate with the gateway via a bridge mote attached to the gateway's serial port. The base station will be a laptop located at the conference demo site. To simplify the demo setup the gateway and base station communicate via 802.11, rather than over a Freewave radio modem.

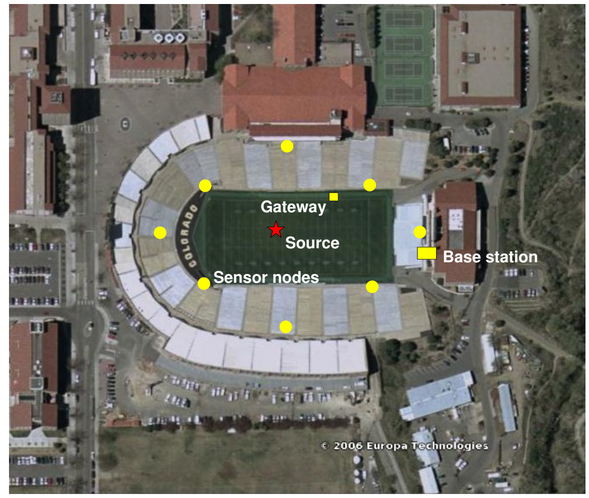

Figure 1. **Configuration of our proposed demo.**

Although in the field we will detect and locate earthquakes using seismic waves, for the purposes of our demo it is simpler to perform localization using infrasonic (low-frequency acoustic) waves. The use of an acoustic source also simplifies the velocity model used by the localization algorithm, since the speed of sound in air can be assumed constant. We will actuate the sensor array using a source of infrasonic energy, such as a gunshot (firing blanks into the air) or small explosion (small firework[1]). The network will detect the event, compute wavefront arrival times, relay the data to the base station where the location of the event will be calculated and displayed on a map of the stadium.

4 References

[1] B. Chouet. Volcano seismology. *Pure. appl. geophys.*, 160:739–788, 2003.

[2] R. Sleeman and T. van Eck. Robust automatic P-phase picking: an on-line implementation in the analysis of broadband seismogram recordings. *Physics of the Earth and Planetary Interiors*, 113:265–275, 1999.

[3] G. Werner-Allen, J. Johnson, M. Ruiz, J. Lees, and M. Welsh. Monitoring volcanic eruptions with a wireless sensor network. In *Proc. Second European Workshop on Wireless Sensor Networks (EWSN'05)*, January 2005.

[4] G. Werner-Allen, K. Lorincz, J. Johnson, J. Lees, and M. Welsh. Fidelity and yield in a volcano monitoring sensor network. In *Proc. 7th USENIX Symposium on Operating Systems Design and Implementation (OSDI 2006)*, Seattle, WA, November 2006.

[5] G. Werner-Allen, K. Lorincz, M. Ruiz, O. Marcillo, J. Johnson, J. Lees, and M. Welsh. Deploying a wireless sensor network on an active volcano. *IEEE Internet Computing, Special Issue on Data-Driven Applications in Sensor Networks*, March/April 2006.

[1] The sale and use of fireworks is legal in Colorado.