Embedded LINUX in a Soft Real-Time Task: The Canadian Geological Survey Internet Seismometer

9-01

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1 Summary

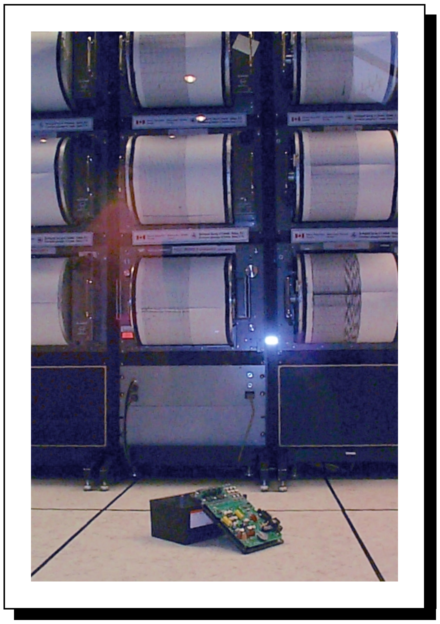
Arescon ltd. developed the real-time software and an embedded operating system for a new type of three-component accelerometer for the Canadian government. The accelerometer is a prototype instrument for the proposed Canadian Urban Seismology Project (CUSP).

Several hundred of these instruments are to be deployed in urban centers throughout the Canadian high-seismic-hazard regions.

The instrument incorporates an Internet data server and an automatic event parameter reporting system. Aside from strong-motion and engineering seismic research, the dense network of instruments will provide real-time data for disaster response services during and immediately after a substantial earthquake.

2 Background

Seismology as a science is traditionally focused on the question how earthquakes occur, what their sources are and if there is any way to predict where and when an earthquake will occur, as well as it is now possible to predict the weather over the next days, weeks or even month.



While our understanding of the sources of earthquakes and the dynamic processes in the earth's crust has taking large steps over the last century, advances in earthquake prediction, in the sense of forecasting their onset, have been rather disappointing.

On the other hand, techniques to assess the *potential* risk that a particular building, a house, a hydro-dam or a bridge may be damaged during an earthquake provide a valuable bases to prepare for the aftermath of a large earthquake. Insurance companies use those risk assessments to calculate their earthquake insurance premiums and engineers need the same kind of information to design buildings which can withstand the shaking of the largest earthquake which can *probably* occur in a particular location.

In simple terms, earthquake hazard and risk assessment tells you what the chances are that you are struck by an earthquake of a certain magnitude and what the worst case scenario you should prepare for, may look like.

Earthquake hazard assessments are largely based on a good knowledge of the sources and defining tectonic structures in the region as well as on statistical analysis of historic data. Here the general idea is, that the likelihood that a particular place will be affected by an earthquake is based on the sequence of quakes that have affected that particular place in the past. Since our instrumental record of past earthquakes is rather short in comparison to the times over which tectonic features evolve, the statistical assessment alone is often difficult and unreliable.

Additionally scientists and engineers started to realize more recently, that hazard assessment which is focused only on the earthquake sources, does not tell the whole story. The actual earthquake damage sustained by structures in a larger city for example showed a rather complex pattern and the effects of earthquakes of even moderate magnitudes would actually vary widely over the distance of a few city-blocks [7].

Traditional earthquake hazard maps do not have that kind of resolution since local effects which can actually amplify (or attenuate) ground motion triggered by an earthquake, could only be accounted for in a limited way.

These local effects are in general related to the geological structure of the immediate subsurface and the topography of an affected area. While geo-technical models exist which can explain amplification and attenuation of seismic waves depending on the local subsurface, it was soon recognized, that those effects should actually be directly measured.

A good (and rare) example of a highly detailed earthquake hazard map for the greater Victoria Area (British Columbia, Canada) can be found under
“http://www.em.gov.bc.ca/Mining/Geolsurv/Surficial/hazards/default.htm”.

Amplification effects appear to be non linearly dependent on the amplitude of the original excitation and actual measurements are very much needed to fine-tune prediction models.

A further complication and a directly related problem is the prediction of the actual damage the local shaking my cause to a particular building [5], since this “is a complex function of amplitude, frequency, and duration, and varies with the structure or component being considered” [9].

While a world-wide network of only a few hundred, highly sensitive instruments is sufficient, to detect, record and localize almost any significant earthquake on earth, it is quite obvious, that in order to study the highly localized *effects* of an earthquake on densely populated areas, a very dense network of instruments would be required.

Additionally, those instruments would, rather than being extremely sensitive, have to be able to record very strong and violent ground motion and survive an actual earthquake themselves.

Instruments of this kind, are called *strong motion* seismometers and a variety of them is commercially available. For a dense station network of several hundred instruments, however, current strong motion seismometers are not ideally suited. They lack built-in communication capabilities which would allow data to be retrieved remotely.

How important these communication capabilities are, becomes apparent if these instruments are also to be used as real-time sensors in an actual major earthquake in order to provide a basis of reconnaissance for the emergency response teams. In order to respond to a major earthquake disaster the limited resources of fire fighters, ambulances and other disaster relief crews have to be prioritized.

A dense network of strong motion seismometers in an urban area could provide the data for the generation of a shake map which could, within minutes after the event, direct disaster response teams to the most affected areas within a city and save extremely valuable time, which would otherwise be needed to first assess the situation. The Taiwan Central Weather Bureau's Seismic Network [10] [11] and the Southern California TriNet [3] have successfully implemented the generation of shake-maps based on strong-motion instrument networks. Japan operates the Kyoshin strong motion network[6] with about 1000 seismic stations since 1996.

With the perspective to an application as a system for instant damage estimation it is evident, that a seismic station within such a network has to be completely self contained, robust, and be able to establish data communication with a central facility in (almost) real time.

Practical considerations also mandate, that each individual instrument can be monitored and serviced remotely. If up to 300 instruments are deployed in a city like Vancouver alone, it is practically impossible to attend to each individual instrument on site in order to change parameters of the acquisition or to download data from a seismic event.

3 The GSC-PGC embedded LINUX Accelerometer

In perspective, the Geological Survey of Canada plans to deploy a great number of strong-motion seismometers in the urban areas of Canada's seismic risk areas [2] were at the same time a well developed Internet infrastructure is already in place.

In order to take advantage of this communications infrastructure a digital strong motion seismometer was designed at the Pacific Geoscience Center and was mated with an Internet data server so that data from an instrument can be retrieved via standard Internet protocols.

Arescon ltd. in Sidney, B. C., Canada was contracted to design the data acquisition software and the communications and data server package.

Normally the instrument acquires continuous acceleration data from the three orthogonal sensors and stores five minute blocks in a file system which is accessible over the Internet. This file system can hold data from about two and a half days and is permanently updated.

Additionally, velocity, displacement [4] and certain spectral properties [5] are continuously calculated as well. As soon as the instrument detects a seismic signal, parametric data, such as peak ground acceleration, velocity and displacement together with spectral intensity data are reported in a message send to central computer.

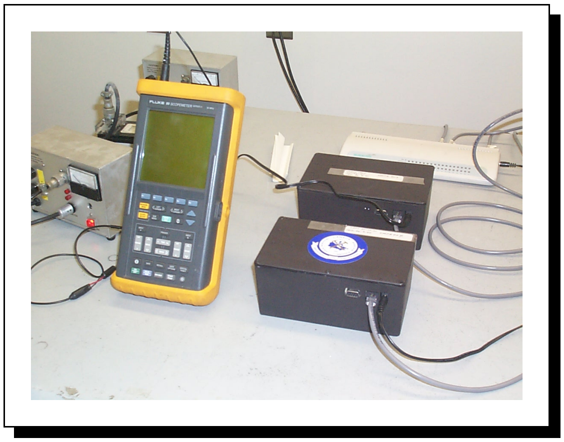


Figure 1: Two Internet Accelerometers in the Lab

In the hardware design, the distinction between data acquisition system and data server is somewhat artificial. An embedded computer, in the current design the Intel compatible JUMPtech ETX/MGX single board computer, is used to perform part of a digital signal-processing chain for the data from the accelerometers as well as to provide data storage and access to data by the standard File Transfer Protocol (FTP). The computer runs under the free Open-Source operating system LINUX in a small and very specialized (embedded) version which also was designed by **arescon ltd.** from several different sources (see 8).

4 Acceleration Sensors

Most existing strong motion seismometers use electromechanical "force feedback" sensors to measure ground acceleration. While these instruments have very desirable characteristics like the coupled pendulum instrument developed by [8] for example, they are expensive due to the complex manufacturing of the electro-mechanical sensors in rather small production numbers.

With current technology it is possible to manufacture micro-machined solid-state acceleration sensors in larger quantities and a study by the U.S. Geological Survey has shown [1], that rather sensitive seismometers can be built using these sensors.

The accelerometer hardware, which was designed by Ken Berverley at the Pacific Geoscience Center (PGC) in Sidney, British Columbia, also employs micro machined acceleration sensors. While the sensors used here are less sensitive than the ones studied by [1], they are in turn produced in very large quantities as parts of airbag triggering devices for the car industry. They are consequently relatively cheap.

The instrument is designed to measure acceleration in three orthogonal directions. For each of the sensing directions four accelerometer chips are operated in parallel to improve overall noise performance. The current design exhibits a sensitivity of $0.5\ mg$ (with g the earth' gravitational acceleration). For comparison: The average person senses ground acceleration from an earthquake when it reaches about $15\ mg$.

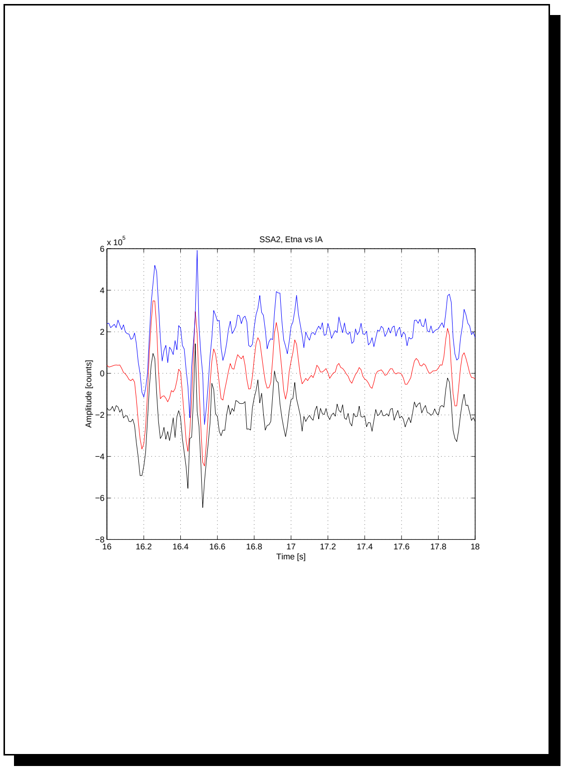


Figure 2: Comparing the Internet accelerometer (middle trace) with two different commercial instruments in a simulation of the 1992 Landers earthquake.

Recordings from a simulation of the Landers (California 1992) earthquake are shown in figure 1. We had mounted several Internet accelerometers and four commercial strong-motion seismometers (Kinemetrics Etna and SSA2) on a large shake-table when several brick wall elements were tested with respect to their earthquake resistance by the engineering group of Prof. Carlos Ventura (University of British Columbia, Dept. of Mechanical Engineering).The middle trace in figure 1 was recorded by one of the Internet accelerometers, upper and lower traces are from a Kinemetrics SSA2 and Etna strong motion seismometer respectively. The recordings compare well, differences at higher frequencies are due to the fact that the instruments could not be mounted all in the same location on the shake-table.

5 A network friendly, soft-real-time operating system

The output from the sensor packs is digitized by a 16-bit A/D converter and digitally filtered (decimated) in a first stage before it is passed on to the single board computer which is an integral part of the data acquisition system and also implements the data- and communications server for the instrument. The sensitivity of the digitization is ultimately equivalent to 18 bits due to oversampling and a two-stage decimation filter.

The single board computer runs a multi-threaded processing and acquisition software which also was devised by **arescon ltd.** under LINUX, an Open-Source, free operating system.

While LINUX was initially not designed to meet the challenge of a real-time operating system, it proved to be very well suited to provide the scheduling of processing and acquisition task with sufficient accuracy for this particular application. LINUX handles program tasks which – while running independently – still have to communicate with one another, very well since it implements much of the functionality of the POSIX standard, in particular a subset of the POSIX-Timers and POSIX-Threads system libraries.

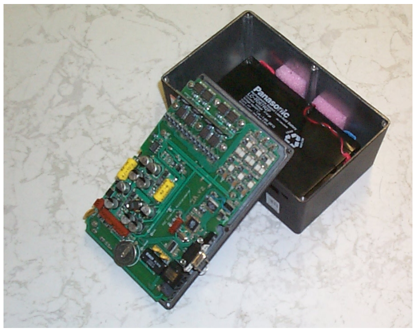


Figure 3: Power-supply, the accelerometer (upper left corner of the circuit board) and the computer fit on two sandwiched circuit boards. Most of the space is taken up by the emergency battery.

Since, for the purpose of limiting manufacturing costs and design complexity, an individual instrument does not have an accurate clock, synchronization is maintained over the Internet by means of the Network Time Protocol (NTP). The instrument becomes a client to several Internet timeservers and the sophisticated algorithms of the NTP protocol suite then keep the normal system clock in tune with the high precision GPS or Cesium clocks of remote timeservers. The ultimate timing accuracy is in the order of 10 milli-seconds, which happens to be the final sampling interval, with which the seismic signals are digitally recorded. Thus the instrument will be typically not deviate more than one sample interval from true time.

For maintenance purposes, to perform firm-ware up-dates or to change the acquisition parameters, the embedded LINUX system features secure shell access (OpenSSH2), which grants full command of the system with all the security of authentication and encryption to prevent the system from being abused in cracking attempts. A full suite of system and acquisition log-files can be monitored with a Secure-Shell connection if troubleshooting is required.

The data-server part implements two additional protocols for data retrieval: The Trivial-File-Transfer-Protocol (TFTP), which is well suited for non-interactive data downloads, and the regular FTP protocol (PureFTP) which provides authorized interactive access through a web-browser as well as a means to automatically download data periodically, for example with the *wget* program.

LINUX is booted out of a Compact-Flash memory and afterwards runs entirely in volatile RAM. One and a half days worth of data are stored on a RAM-Disk in ring-buffer fashion. After the storage limits are reached, the oldest data is overwritten.

When the instrument is initially deployed at a site it is configured by connecting a terminal (VT100) to its serial port. Thus, the network configuration and the station identifiers can be set for example, by simply connecting a Palm-Pilot to the instrument.

The currently implemented data-formats are the Canadian National Seismographic Network CA-format or as an option, the IRIS (Incorporated Research Institutions for Seismology) miniSEED format. A multicolumn ASCII format is also available.

6 Current developments

Efficient ways to integrate a large number of strong motion Internet accelerometers into the existing network of broad-band and short-period seismometers are currently being investigated.

PGC and **arescon ltd.** hope to deploy the first batch of about fifty instruments in the Vancouver area by summer 2002.

7 Instrument Specifications

Sensor: Each axis has four ADXL105 iMeMS accelerometer chips connected in parallel (to reduce noise and enhance linearity)

Full-scale: $\pm 4g$

Noise: $0.5mg$ RMS, DC to 42 Hz

Bandwidth: DC to 42 Hz (set by 151 coefficient FIR filter)

Sample Rate: 100 samples per second, optional 50, 60, 75, 150, 300.

Total instrument delay: $685ms$ due to a two-stage FIR filter implementation.
Nonlinearity: 0.2% of full scale.

Temperature Sensitivity: less than $\pm 0.5\%$ change over the operating temperature range.

Cross-Axis Sensitivity: $\pm 1\%$
Alignment Error: ± 1 degree

Zero-Adjust: none needed, provided the instrument is installed level.

Operating Temperature: -20 to $+50$ degrees C

Power Consumption: 8.1 W max at $+9$ V to $+18$ V DC, 5.7 W typical when the internal Battery is fully charged.

Built-in UPS: More than 6 h run time with internal 6 V lead-acid battery.

Computer: National Semiconductor Geode, 266 MHz, 128 Mb RAM, 16 Mb Flash disk. Optional 32 Mb up to 512 Mb Flash disk.

Operating System: Linux, Kernel 2.2.16

Data Format: Standard CNSN 5 minute CA data files, optional 5 minute miniSEED or ASCII data files.

Timing Accuracy: $\pm 10ms$, assuming reasonable access to NTP-servers.

Total Data Time Lag: 685 ms, due to FIR filter length.

Data Retrieval: Via FTP or TFTP, the 80 Mb RAM disk stores about 2.5 days of data.

Internet security: password protection for FTP access, secure shell access for maintenance.

Connectors: DB9-Female: Serial port to set up configuration parameters, RJ-45 10baseT Ethernet, 2.1 mm female for 12 V , 1.5 A regulated power supply.

Indicators: Heartbeat / diagnostic LED, Ethernet activity LED.

Physical: Hammond 1590EBK case, 7.4” x 4.7” x 3.1” high.

Mounting: Case should be cemented to the basement floor using “plaster of Paris” (recommended, since it makes leveling easier) or bolted down through a hole drilled in the case.

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8 Selected Links

8.1 Seismology

An example of an earthquake hazard map for the greater Victoria, B.C. (Canada) area can be found at:
http://www.em.gov.bc.ca/Mining/Geolsurv/Surficial/hazards/default.htm.

One of the most elaborate strong motion seismic networks is Kyoshin Net (K-Net) in Japan http://www.k-net.bosai.go.jp

The TriNet project http://www.trinet.org/shake/ has examples of actual shake-maps from recent earthquakes.

The IRIS consortium (Incorporated Research Institutions for Seismology) is at
http://www.iris.washington.edu.

The home page of the Pacific Geoscience Center is http://www.pgc.nrcan.gc.ca.

8.2 Embedded Systems and LINUX

General information about LINUX is at http://www.linux.org

A good overview over pre-cooked embedded LINUX systems as well as pointers to tools to “roll your own” is under http://linux-embedded.com.

An extremely useful software package which can be found in almost any small LINUX systems is the busybox http://www.busybox.net.

A good and pretty straight forward small LINUX system designed for network analysis and troubleshooting is:
http://trinux.sourceforge.net.
The Trinux boot and start-up scheme is built exclusively on shell scripts which can serve as an excellent tutorial on how to get things up and running.

The Open-Source secure shell project is at home under
http://www.openssh.com.

The home-page of Open-Source pureFTP project is
http://www.pureftp.org.