Design and development of a low-cost, high-performance, strong-motion accelerograph

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ABSTRACT: This paper outlines the conception, design and development of the CUSP accelerograph system. The CUSP accelerograph provides a cheap strong-motion specific instrument that fulfils the requirements of the earthquake engineering community without the high cost penalty associated with purchasing the unwanted resolution of a sensitive seismograph.

1 INTRODUCTION

Since our knowledge of the historic activity of the Alpine Fault was refined in the late 1990s, the Engineering Seismology Group at the University of Canterbury has worked towards setting up a dense regional network of about 80 strong-motion instruments in the central South Island of New Zealand, in anticipation of a large earthquake on the Fault. The aim of this paper is to give the background to the project, the Canterbury University Seismograph Project (CUSP), and especially to describe the strong-motion accelerograph that has resulted from it.

Before the work of Yetton (2000) in dating recent earthquakes on the Alpine Fault, it had been thought that the average recurrence interval for large events on the Fault was about 500 years. Yetton found convincing evidence for a recurrence interval of about 250 years, with characteristic earthquakes of around M8, and with the last event dated precisely at 1717; that is, about 290 years ago. This result, together with clear evidence of a seismic gap several decades long in the central South Island, suggests that a great earthquake is likely on the Fault within the next few decades, providing an excellent and rare opportunity to record the shaking, both near and far-field, from such an event. The region is already served by a backbone of instruments, generally 18-bit accelerographs, in the national network operated by GeoNet. The University group sought to add about 80 instruments, the “Canterbury Network”, in three sub groups, as follows:

1. A dense array near the Alpine Fault, designed to follow the progress of rupture on that or nearby faults. This would comprise about 20 instruments.
2. A group of about 20 instruments at selected sites in the city of Christchurch, to record site effects on the highly variable fluvial and estuarine soils beneath the city.
3. About 30-40 instruments spread over the Canterbury Plains and the coastal plains of the Buller and West Coast regions, to record regional attenuation of strong ground motion.

At the time of instigation of the project, the range of available instruments was limited. The traditional manufacturers were focusing on high dynamic range instruments with consequent high development and construction costs and thus high selling prices. This left the earthquake engineering community little choice in the performance they could select, with instrumentation budgets being spent on fewer, higher specification instruments. This is unfortunate, as typical earthquake engineering applications require high spatial resolution, not high amplitude resolution (Trifunac and Todorovska, 2001).
A further problem with most commercial systems is the high dependence on proprietary systems for both operating and communicating with the instruments. This leads to high costs in modifying the system to make use of newer and cheaper communications systems as well as high design and maintenance costs. Clearly a well thought out and specified purpose designed low cost strong motion accelerograph was required.

Therefore, the Engineering Seismology Group enlisted the help of the Electrical and Electronic Engineering Department at the University of Canterbury to design a simple, low-cost, low-maintenance accelerograph, in the 12 to 13 bit range. The result is the CUSP-3A accelerograph, which is described below and illustrated in Figure 1.

![CUSP-3A accelerograph](image)

**Figure 1** CUSP-3A accelerograph.

In parallel with development of the instrument, work also progressed on various aspects of the fault-rupture array, including the following (François et al., 2002):

1. The improved coding of the MUSIC algorithm (Goldstein and Archuleta, 1991) for use both in designing the array itself, and in inverting data obtained from it.
2. The selection of potential sites.
3. Finding the optimal array configuration at the selected sites.

2 DESIGN OBJECTIVES FOR THE ACCELEROGRAPH

There were three main design objectives: The first was to keep the initial cost of the instrument low, the second, to minimise maintenance costs, and the third was to protect against component obsolescence. Of the first two, the latter is more important in the overall cost of running a network. The Geomechanics Group at the University of Canterbury has had experience in operating a small network of 9 film-recording strong-motion instruments in the South Island since the late 1970s. The main cost in operating the network was in the routine maintenance of the instruments, with most of that cost in travel to the dispersed sites. Thus, in designing the CUSP instrument much effort was given to minimising the need for site visits by remote monitoring of instrument status and remote down loading of records via the Internet. The construction cost was kept down by the use of micro
machined (i.e. MEMs device) accelerometers, originally developed for the automotive industry to trigger car air bags, but subsequently made available with characteristics more suitable for seismology. Much of the design effort went into extracting better performance from these mass-produced devices by extensive calibration and data processing. Because strong-motion accelerographs have a long working life, a further design objective was to minimise vulnerability to obsolescence.

3 THE CUSP SYSTEM

It was sought to achieve these aims by producing an instrument utilising as many standard components as possible to reduce both initial costs in hardware and development expense. Installation and operational costs were also reduced by using standard communications facilities. Furthermore, the use of standard components significantly reduces the cost of maintenance, since off-the-shelf replacement components can be employed.

The core of the CUSP system is a commercial single board computer (SBC) running a real-time derivative of the reliable and efficient Linux operating system. Completing the CUSP system is a seismic acceleration transducer circuit, a GPS receiver and a power supply.

3.1 Single-Board Computer with Linux Operating System

This design choice has far ranging impacts on the construction, operation and long-term ability to upgrade as well as to maintain the CUSP system.

3.1.1 Construction

The use of commercial, off-the-shelf components with standard interfaces has immediate construction advantages, the most obvious being the range of supported hardware and software, allowing a standard operating system to be utilised (i.e. Linux), as well as standard communications interfaces (i.e. low cost modems etc), resulting in seamless component integration, fast development cycles and, ultimately, reduced development and component costs.

3.1.2 Operation

Standard components result in a high level of integration to standard communications, storage and operation systems. For example, it is possible to use proven and low-cost compact flash storage with a reliable journaling file system. Close integration to Internet protocols is possible, allowing standard Ethernet operation, including a web server style user interface for simple and intuitive configuration, interrogation, file transfer facilities, and secure encrypted data transfer/control using the SSL and SSH protocols.

3.1.3 Maintenance

A major concern when designing electronics instrumentation is the availability of individual components in even as little as six months after construction and is usually reflected in the instrument purchase price, where replacement part supplies are required to be held by the manufacturer. By utilising COTS equipment, this problem is placed back on the component manufacturer. Ultimately, if a component source is lost, it is a seamless and simple process to substitute one component for another, since Linux device drivers are available for almost every component.

3.1.4 Ongoing upgrades

As new technologies and techniques become available, the CUSP system can follow trends with minimal effort. For example, new communications protocols can be included at any stage with little effort, to add, say, networking for dense building arrays. The USB interface can be employed to add additional functionality as required, for example to monitor rainfall measuring devices. Obviously, it is a simple matter to upgrade the seismic acceleration transducer to higher performance units as micro-machined sensor technology advances.
3.2 The Seismic Acceleration Transducer Circuit

The seismic acceleration transducer circuit contains an orthogonal trio of the low-cost micro-machined accelerometers. Additional signal conditioning circuitry is required to both filter and convert the signal to a digital representation. A small microprocessor performs the coordination of this procedure and transmits the resulting data to the SBC. The micro-machined accelerometers present several undesirable characteristics that must be mitigated, and the correction is performed both in the dedicated circuit and in the SBC. This method has been chosen to reduce as much as possible the cost of the sensor system circuitry. The most serious of the undesirable characteristics is the drift of the quiescent zero point with temperature. The remaining problematic characteristics are the temperature dependence of the gain and the misalignment of the sensor axis relative to the instrument axes, due to both internal error and construction tolerances. These characteristics are all determined by a complex calibration process which effectively maps the characteristics of each sensor with temperature and removes the errors in software. The misalignment is corrected by applying a real-time correction matrix to the measured triaxial data. The resulting misalignment error rivals or betters that of the best available instruments.

The conversion circuitry results in a 16 bit digital representation sampled at 800Hz. This high sampling rate allows the adoption of extremely phase-linear analogue filters in the 0-100Hz band. Then a 4, 8 or 16x digital FIR decimation is performed by the SBC, efficiently reducing the sample rate to the required recording bandwidth.

The seismic acceleration transducer circuit is designed to be replaceable, allowing advances in the transducer technology to be capitalised on with minimal component upgrade costs. The remainder of the system is capable of recording up to 32 bits of signal resolution.

3.3 GPS Receiver

The GPS receiver is required to provide accurate time stamping of the recorded data. Additionally position is also measured and utilised for record identification by assigning a unique time and position for every record. Accurate timing is considered vital to a serious strong motion instrument and is thus a standard feature. The potential use of the instrument in buildings has resulted in a system whereby the GPS sensor can be remotely mounted and can communicate with the CUSP instrument via pre-existing Ethernet wiring in the building.

3.4 Power Supply

In order to provide reliable operation at sites with poor quality or unreliable power supplies, the CUSP system must be provided with a backup power supply. At most sites this would comprise a lead-acid battery and float charger. Significant design effort has been put into the CUSP power supply to provide battery protection. The system monitors the supply voltage and can be shut down automatically when a predetermined low voltage condition is detected, preventing over-discharge of the battery. The system can also be configured to automatically switch on when the supply voltage rises above a preset safe threshold to ensure continued operation. Over-voltage and under-voltage protection is provided in order to provide protection from fault conditions. Further to these features, the system temperature is also measured and, together with battery voltage, is available for remote monitoring to aid diagnostics. Several LED indicators are provided to indicate the system status (power on, operational, event in progress and GPS lock).

4 OPERATION

The system can be connected to the Internet either via an Ethernet network or by a modem (cellular or telephone). Direct connection to a laptop computer is also possible and is used for the initial configuration of the instrument. Once the system has booted and normal operation has commenced (indicated by status indicators) the system can be interrogated via a standard personal computer over standard dial-up or direct Ethernet connection. A standard web browser serves as the main interface,
secured by operating under the SSL 128bit encryption system. Two user interfaces are provided: either an administrator logon or a general user logon. No unauthorised access is permitted.

The administrator has access to the following menu of operations, as shown in Figure 2:

- View, download and delete records – this allows direct visualisation of records presented as a jpeg image, download of records as a link and deletion of individual or multiple records.
- View and delete diagnostics information – including boot time, updates, errors etc.
- View access logs to the website – view who has logged on, what records have been viewed etc.
- Configure instrument automated outputs – configure whether alert emails are to be sent; how often reports are generated and to where they are FTP’d, whether or not records are automatically transferred to a remote FTP site etc.
- Configure instrument operational parameters – sample rate, trigger types, trigger levels, trigger filters etc.
- Configure instrument communications parameters – add/delete user accounts, turn on/off logging, IP numbers etc.
- View instrument status – battery levels and system temperatures (minimum and maximum included), GPS position and lock status, serial numbers, software versions, recording status and disk space remaining, reset triggers and position information etc.
- View a real-time stream of the current data – this is a java applet forming a real-time link to the incoming data and displaying the information in real-time as a triaxial stream.

Figure 2. Main menu, viewed by standard web browser.
General users have access to:

- View and download records, but have no delete access.
- View diagnostics information.
- View limited status information.
- View the real-time data stream.

The general user access provides a basic interface to view day-to-day useful information but does not allow any ‘unsafe’ operations to take place.

Further functionality, mainly limited to system administrators or the system developers, allows the connection to the Linux operating system via an SSH connection, which is a secure form of the popular Telnet interface. This allows the remote upgrading of software. The RSYNC function is provided, to give an advanced data retrieval interface, but it is anticipated that scripts interfacing with the web server will provide simpler functionality.

5 TESTING

The project was fortunate to have the University shaking table to use for instrument development and for final proving. Early shaking-table tests showed up a software error in internal timing and suggested other functional improvements. Long-term testing of the overall system was carried out by leaving an instrument on the shaking table for four months, while the table was used for about 30 routine shaking tests on structural models. In all cases, the instrument system and communications functioned correctly. Finally, beta prototypes were tested in the field at Ilam and at Wellington and again on the shaking table beside the table reference accelerometer and a well-established 18-bit commercial accelerograph. Fourier amplitude spectra from the CUSP instrument and the established machine were indistinguishable except over a small band about 40 Hz. This discrepancy caused considerable concern, since it was believed that the CUSP transducers behaved linearly until well above that frequency. It was a relief to learn later that it is known that the other instrument does not record correctly in that range.

The first real earthquake was recorded at Ilam in late September 2003 from a M4.9 earthquake at an epicentral distance of 40 km, in Pegasus Bay. The low peak acceleration, of 0.015g, provided a strong test of the triggering system, which was set to 0.006g. The record, whose N-S component is shown in Figure 3, barely rises above the noise level, which has an r.m.s value of 0.001g.

6 FUTURE ENHANCEMENTS

Due to the use of modular and standard components, the CUSP system is configured to capitalise on future technologies. Currently in development is a multi-channel system allowing up to an estimated 8 three-channel transducer circuits to be controlled from a single CUSP instrument, thus allowing buildings, bridges and other structures to be cheaply and comprehensively instrumented. Furthermore, support is to be added allowing unlimited numbers of multi-channel instruments to be chained together to form a synchronised network. Ethernet wiring based sensors are also currently in design allowing rapid and cost-effective structure sensor deployment.
CONCLUSIONS

The CUSP instrument presented fulfils the requirements of a cheap, basic strong motion accelerograph. Much additional functionality has been included that rivals or outperforms the best currently available instruments at minimal increased instrument costs.

With the addition of better (and more expensive) sensors, the instrument can compete directly with the best broadband seismographs but does not bind the system developer to the associated high costs.

The use of off-the-shelf technology combined with a reliable and maintained operating system results in a high performance, high reliability, low cost and obsolescence resistant platform ideally suited for long term strong motion monitoring networks.

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