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Terra-Scope - a MEMS-based vertical seismic array

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Abstract. The Terra-Scope system is an affordable 4-D down-hole seismic monitoring system based on independent, microprocessor-controlled sensor Pods. The Pods are nominally 50 mm in diameter, and about 120 mm long. They are expected to cost approximately $6000 each. An internal 16-bit, extremely low power MCU controls all aspects of instrumentation, eight programmable gain amplifiers, and local signal storage. Each Pod measures 3-D acceleration, tilt, azimuth, temperature, and other parametric variables such as pore water pressure and pH. Each Pod communicates over a standard digital bus (RS-485) through a completely web-based GUI interface, and has a power consumption of less than 400 mW. Three-dimensional acceleration is measured by pure digital force-balance MEMS-based accelerometers. These accelerometers have a dynamic range of more than 115 dB and a frequency response from DC to 1000 Hz with a noise floor of less than 30 $ng_{rms}/\sqrt{Hz}$. Accelerations above 0.2 g are measured by a second set of MEMS-based accelerometers, giving a full 160 dB dynamic range. This paper describes the system design and the cooperative shared-time scheduler implemented for this project. Restraints accounted for include multiple data streams, integration of multiple free agents, interaction with the asynchronous world, and hardened time stamping of accelerometer data. The prototype of the device is currently undergoing evaluation. The first array will be installed in the spring of 2006.

Keywords: vertical seismic array; MEMS-based sensor; and real-time system.

1. Introduction

The increasing availability of vertical seismic array data from around the world has broadened our ability to analyze wave propagation and site response in the near surface. With accelerometers at depth, we can trace the actual effects of the near surface materials on the propagating seismic waves. So-called vertical arrays have come online in several sites in California, Taiwan, and Japan. By comparing multiple downhole recordings and a related surface recording, one can observe how the waves change as they progress through the ground, encountering the materials in the soil profile. We are installing two prototype vertical seismic arrays directly on either side of the Hayward Fault on the UC Berkeley campus. The arrays consist of eight Pods spaced over the 35 m embedment depth, and will be unique in the world for its proximity to a major active fault, its integration into a local and regional seismic system, and its low installation cost due to the use of currently unfolding micro-electronics and computer science devices and methodologies.

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Our array uses a powerful yet inexpensive and easy to install down-hole seismic tool called Terra-Scope. Each station of the array consists of three-component accelerometer units, tilt sensor, magnetometer, and pore pressure sensor. The sensors will be incorporated into an intelligent networked sensor Pod that includes upwards of two Mbytes of non-volatile memory, a sixteen-bit micro-controller, sixty-two channels of digital interfaces, eight analog channels, an Ethernet client, power controller, and backup batteries. Since each station is a digital entity, all communications along the array can take place on a bi-directional backbone. The terminus of the array, at the top of each bore hole, will be a powerful Local Gateway that will serve as data aggregator, GPS-based timer and locator, power source, Ethernet server, and wireless data link. We estimate that each Pod will cost is about $6000 using present-day costs.

The system uses a simple software solution based on a custom event-driven scheduler to multiplex the concurrent flows of information across each gateway, which is connected to a transceiver, a secondary storage device, a sensor oriented I/O system, and a power management subsystem. Compared with traditional data logging systems, networked sensors offer two major advantages: they can be retasked in the field and they can easily communicate with the rest of the system.

2. Vertical arrays

A down hole seismographic array is a sequence of instruments installed at various depths in the ground to record the ground motion (generally in terms of velocity or acceleration) at multiple depths and at the surface of a site during an earthquake. As the authors and others (e.g. Elgamal, *et al.* 1996, Stiedl, *et al.* 1996) have pointed out over the years, vertical array data provides a direct way to quantify the accuracy of ground motion predictions, the models used to make such predictions, and the applicability of our estimates of in situ soil properties.

Downhole recordings of ground motion give us a glimpse of how waves are traveling near the surface of the earth. By comparing multiple downhole recordings and a related surface recording, one can observe how the waves change as they progress through the ground, encountering the materials in the soil profile. Several vertical arrays have come on-line in several sites in California (Baise and Glaser, 2000, de Alba and Faris 1996, Archuleta, *et al.* 1992), Taiwan (Tang, *et al.* 1989), and Japan (Katayama, *et al.* 1990). Part of the reason for placing the instruments below the surface is to reduce the effect of surface noise caused by cars, wind, and people. Another benefit of placing the instruments underground is to record the ground motion at additional points along the path of propagation. These arrays are changing the way we understand seismic ground motion by allowing the 3-D evaluation of seismic wave propagation (Baise and Glaser 2000, Stidham, *et al.* 1999, Elgamal, *et al.* 1996, Abrahamson, *et al.* 1991).

Vertical arrays have traditionally been very expensive to install and maintain (Steidl and Nigbor 2001), being much like traditional structural seismic instrumentation. They suffer from a limited functionality, high cost of instrumentation and size. Some vertical arrays utilize a separate borehole for each instrument (e.g. Bennett, *et al.* 1984), others install multiple instruments into one hole (Anderson and Tang 1989), but require more complex ancillary systems, which increase the total cost tremendously. Also, for these systems, the data collection and management is inconvenient. The data are collected locally in the field, so it is inconvenient to expand the network, and the data can not be made available to the public as the events occur. One of the primary goals of our research is to facilitate the free and rapid public access to vertical array data, rather then the current multi-year wait, if and when a researcher does get permission to access the data.

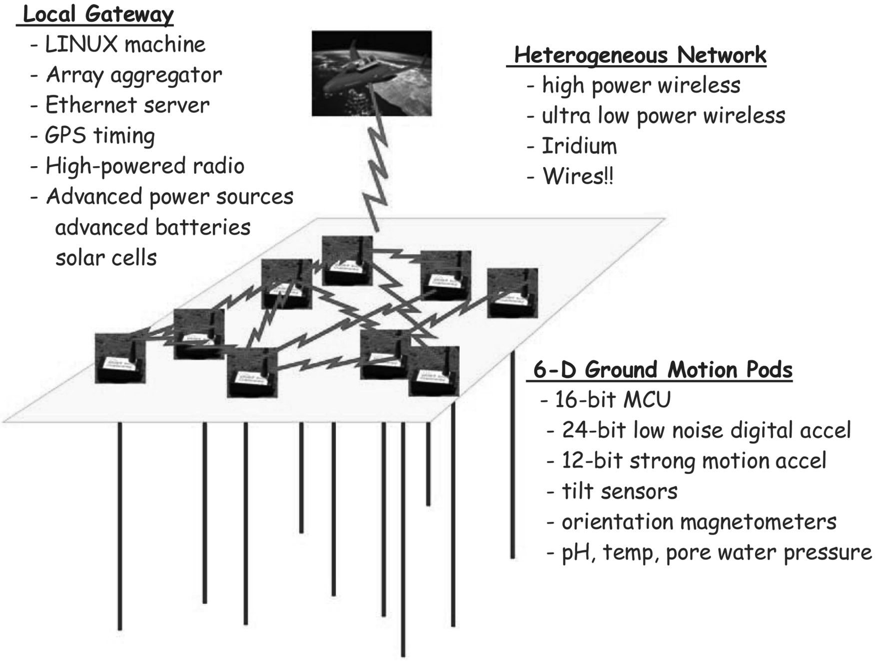

Fig. 1 Cartoon of the vertical seismic array and Terra-Scope instrumentation

We envision a field-deployable array that can be installed in a variety of manners. Initially the arrays will be installed into uncased (or cased) boreholes. By the end of the project, the arrays will be inserted into the ground by ubiquitous cone penetrometer equipment, and the array elements being commercial available to the entire community. A cartoon of the scope of the system is shown in Fig. 1.

2.1. System identification

Vertical array recordings of ground motions provide an excellent source of information; however, there are some major issues with the data that need to be accounted for properly in any analysis (Steidl, *et al*. 1996). These issues include non-vertical wave propagation (Abrahamson, *et al*. 1991, Ellis and Cakmac 1991), existence of surface waves (basin effects), the frequency content of the data (Nyquist frequency), upgoing/downgoing waves, and the orientation of instruments. Another issue common to many deep soil sites results from the greater geologic structure. Many deep soil sites are located in large sedimentary basins which in terms of wave propagation may result in extensive surface waves and other basin effects which may impact the recorded ground motions and confuse the site response (Baise, *et al*. 2003).

2.2. Terra-Scope

The Terra-Scope system, as outlined in Fig. 1, is comprised of several interacting parts. The array itself is composed of a number of independent sensor Pods dispersed in a borehole, and linked by wire to a base station. The base station, while systemically independent form the local gateway, is housed

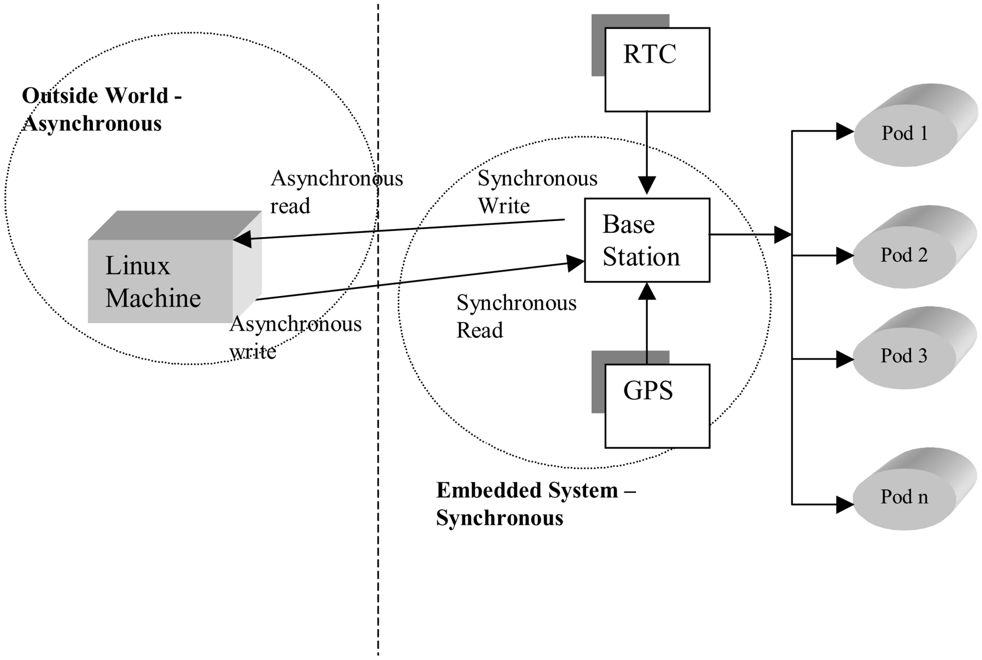

Fig. 2 Systems conception of the Terra-Scope

within the same inclosure as the gateway. The gateway is the path to the outside world for the system. The system is conceptualized in Fig. 2.

2.3. Networking gateway

At the head of each array sits a local gateway (LG), about a 75 mm cube. It serves as the host of the absolute time master clock (either from GPS or U.S. time standard WWV) as well as an Ethernet host to store and distribute data and information out to the world. The LG is based on a variable clocked RISC-based, low power (1.5 amp) LINUX machine (ARCOM Viper) with 64 Mb SDRAM and an embedded Ethernet server. The wide area network (WAN) connection is wireless (e.g. direct radio link, two-way satellite) or wired as is convenient. The LG will aggregate and process the multiple data streams from array stations, and either push the data onto the web or store it until queried by the main server. Included in the LG is a GPS which will provide exact timing for all the array stations, as well as providing accurate array location. Local batteries are charged by an attached solar array, and when possible a hard-wired powered Ethernet link will provide ample power for the entire array. The system architecture addresses the possibility of disconnection at every level. Each layer (Pods, gateways, base stations) has some persistent storage which protects against data loss in case of power outage. Each layer also provides data management services.

While many types of communication can be unreliable, when it comes to data collection, long latency is preferable to data loss.

Within the LG also resides the gateway, which serves as the downhole array bus-master. The gateway is a custom designed “mother Pod” operated by the same TI MSP430 microcontroller (MCU) with a 64 Mb SRAM buffer to facilitate rapid uploading of Pod event data arrays. The gateway also owns a real-time clock unit (RTU) and a GPS to insure the accuracy of the RTU.

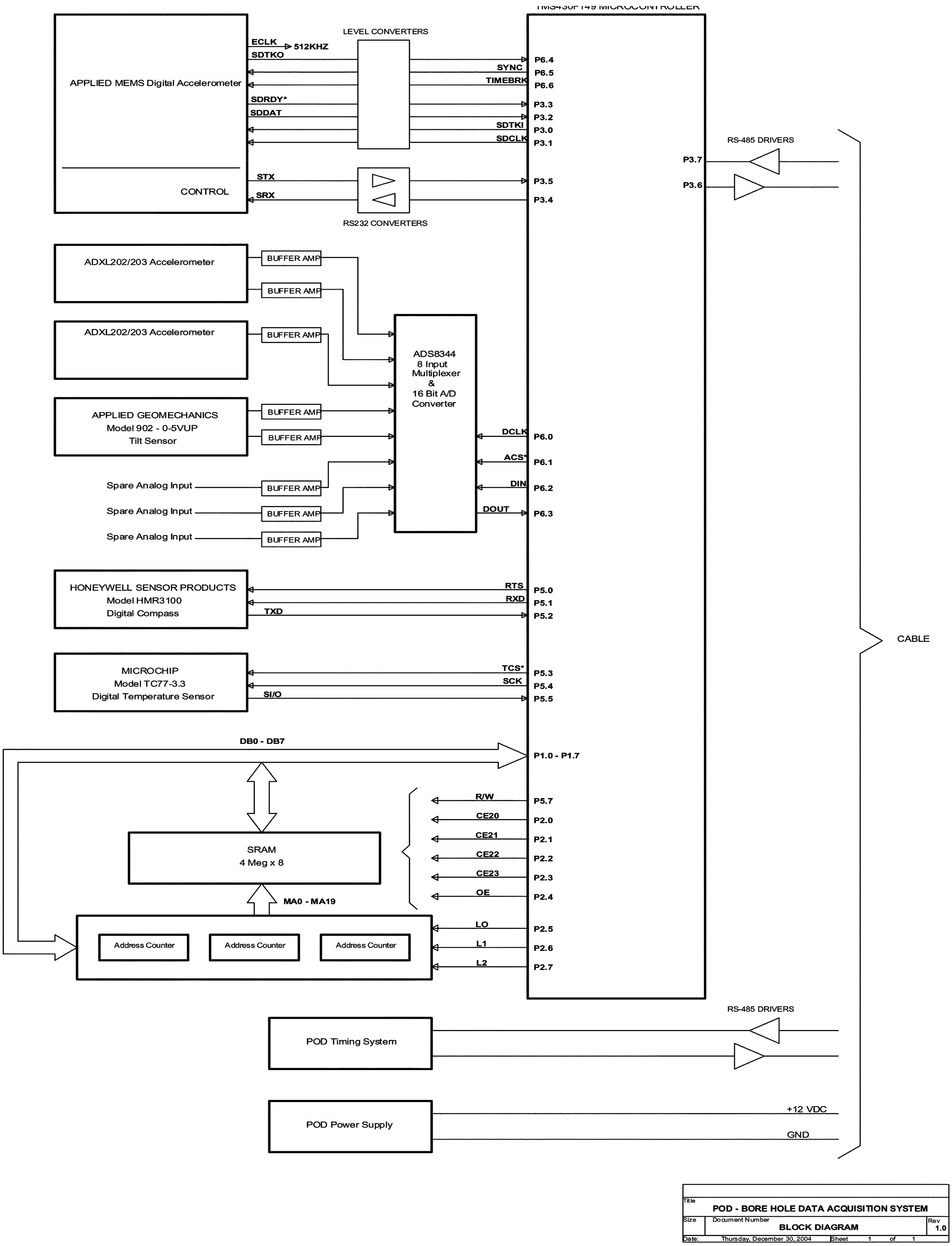

Fig. 3 Block diagram of the Pod

2.4. The Pod

The Pod is the active independent down-hole measuring device that is the heart of Terra-Scope, shown as a block diagram in Fig. 3. Each Pod is an independent, MCU-controlled agent with two or more Mb of non-volatile memory. The Pods are nominally 50 mm in diameter, and about 120 mm long. They are expected to cost approximately $6000 each. The system is designed to implement the following:

- Integration of advanced technology AppliedMEMS accelerometers (30 ng_{rms} √Hz noise floor, 24-bit direct digital); second set of accelerometers extends dynamic range to 1.7 g;
- Tilt (pitch and roll) with 0.003 degree repeatability;
- Azimuth ~ 0.1 degree repeatability;
- Real-time clock within 0.5 ms;
- Parametric measurands include temperature, pH, pore water pressure, etc.;
- Recording all of dynamic variables at a digitization rate of 250 Hz for at least one minute before trigger and two minutes after;
- Fully dynamic networking, real-time reprogramming and peer-to-peer sensor fusion.

These sensors are integrated into the real-time system by the local Texas Instruments MSC 430 microprocessor (MCU) and static random access memory (SRAM) banks. All sensors but the tilt sensor are micro-electro mechanical systems (MEMS)-based devices, allowing for small packaging and low power consumption.

2.5. Application specific embedded system

We are basing our device on the concept of an instrumentation processor - an “open source” solution, if you will, to embedded networked sensing. This intelligent platform will accept any sensor (analog or digital) as an input signal, process and buffer the signals, and interface with any commercial-off-the-shelf (COTS) radio module, embedded system, or computer. The main driver for development of this technology are the many problems that researchers have had in using the Mote devices available from vendors such as Crossbow Inc., and Dust Networks. These devices are in practice sole-source packages, and the user is beholden to the manufacturer to make them work properly. Experience using the Motes by relatively competent users (e.g. Berkeley, LBNL, UCSD, LANL, MIT, Senera Inc., Shinkawa Sensor Technologies etc.) has shown that the devices most often do not work as advertised. Engineers will make much greater use of wireless instrumentation if they do not have to earn a Computer Science Ph.D. in order to do so. What is readily available in COTS form, with many varieties and alternatives are MEMS-based sensors and radio frequency (rf) data transmission links. The user will select a wired or wireless link that best serves their need, at a price they can afford. In fact, advanced processing of complex sensor data is the space from which commercial developers are moving away from.

3. System design

The system under consideration will be used to measure seismic signals traveling through soil and rock. Given that these are very dispersive materials, the frequencies of interest are very low, up to about fifty Hz at the most. To cover any eventualities such as structural monitoring, and to facilitate improvement is signal to noise ratio through oversampling, the design criteria is to allow digitization rates of up to 250 samples per second, or a Δt of four ms. For a digital system running at eight MHz, this data rate can be

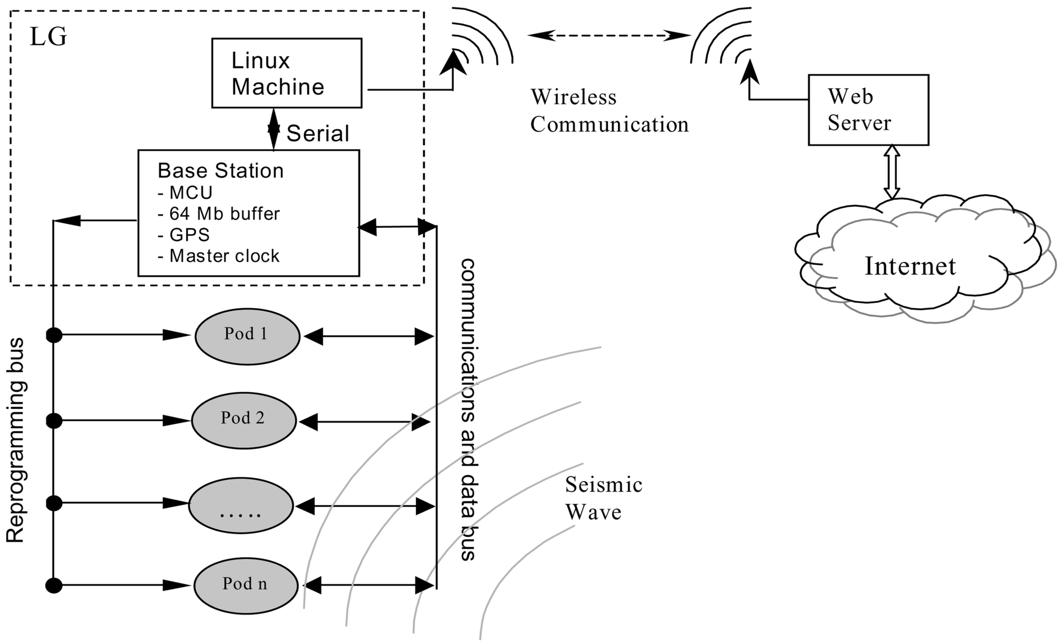

Fig. 4 System architecture

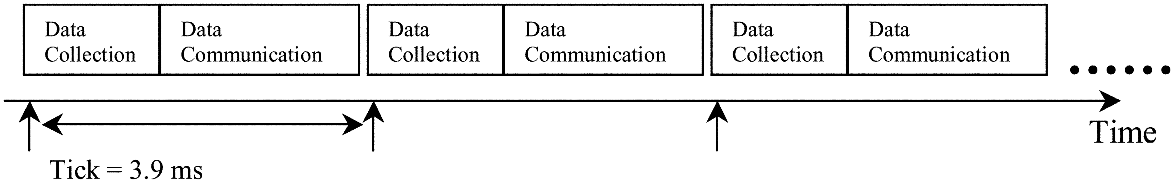

Fig. 5 System timing pattern

considered relatively slow and many tasks ordered and completed between sampling. Fig. 5 depicts the system architecture. The nominal one minute pre-trigger segment insures that motion occurring before strong shaking is captured. A nominal two-minute post-trigger recorded segment insures that all motions and aftershocks are recorded. The system is designed so that a second three-minute event can be recorded to a second bank of SRAM while the first segment downloads independent of system operation.

Each base station is the command center for an array; multiple hardware Pods are suspended on a bus cable at different levels, synchronized with the LG global timer, sample data, and communicate with the base station. A slim cable of three twisted conductor pairs provides both physical connection and communications channels between the Pods and the base station. For security, one pair of conductors is reserved for twelve volt power, one for bidirectional communications, and the third for dynamic reprogramming. The main responsibility of the base station is to (1) send the real time clock to the Pods, (2) connect the Pods to the outside world by sending and relaying commands from the embedded system to the Linux machine for data exchange through the RS232 serial port. The Linux machine is a single board computer running an embedded version of the Red Hat Linux operating system. It connects the users/operators and the system via a web server to allow remote and effortless interaction over the

Internet. This is accomplished by running two concurrent applications, one interacting with the base station embedded system and the other a GUI web interface to interact with the user.

Once a vertical array is buried in its borehole, it is unreasonable to retrieve it for repair or updating. The prime design consideration is the insurance of retrieving accurate time-stamped acceleration data. To this end we have incorporated a second digital bus to the MCU, which serves two purposes. Its main purpose is to allow dynamic reprogramming of each Pod. This allows for updates of firmware, as well as changes and extension of mission. This bus also serves as a "back door" to the Pod system to allow external downloading of memory in an emergency.

3.1. Real-time constraint

One of the most challenging demands for the system is monitoring the high-speed sampling rate which is up to 1000 samples/s for the digital accelerometer. In addition to simply sampling the incoming signals, our system also needs to meet communication and data processing demands. Careful software performance evaluation must be executed so that the time constraints can be met (LaPlant 2004). The Pods and base use the Texas Instrument MSP430 microcontroller, which has an eight MHz CPU clock. Based on its computing capability and system timing constraints, we chose 250 Hz as the main data sampling rate. This means that during every four ms interval, the Pods and base station must finish data collection, processing, and two way exchanges. In order to meet these design demands, we designed a custom scheduler (Liu and Layland 1973), similar to a multitasking operating system (Silberschatz, *et al*. 2004), to manage internal (Pod) and external (system) behavior in an orderly manner without the intellectual and monetary demands of a commercial embedded real-time operating system. The cooperative scheduler is a shared-clock scheduler (Pont 2001), which means Pods and base station share the same clock resource. As illustrated in Fig. 5, every 3.906 ms (256 times a second) the base station sends a clock tick to begin the scheduler cycle, each pod resets its timer for internal data collection (Phase I, 0.906 ms), then for management tasks and data transfer to the gateway (Phase II, 3 ms).

3.2. Time-division arbitration

The system uses a RS-485 shared bus for the communication between the base station and Pods. The RS-485 bus is a multipoint serial communication protocol for Master/Slave systems, which means it allows one sender and multiple receivers to operate at one time. Our communication protocols require the base station to arbitrate the communication token among Pods -- all Pods must get a token in order to communicate through the shared bus. We let the base station assign the token at its own manner without waiting for Pod acknowledgements.

The base station sends the token along with the clock ticks. It will first send the token to the Pod 1, then await the Pod's response. The Pod receiving the token can send notification of local command or upload data -- the rest of the Pods must keep silent. The base station arbitrates the token in the order of Pod number. Once the base station changes the token to the next Pod, all Pods will notice and update their communication status. With the time division mechanism, we can insure fair sharing. Figure 6 shows how will the Pods respond to notification.

If the ball shown in Fig. 6 represents the event occurrence, we see that each pod detects the seismic event at different times. Because the seismic wave propagates from depth upwards ground, usually the deepest pod triggers first. Since all the Pods have allocated time slot to talk to the base station, the first one who triggers and owns the token will send the notification to the base station. The base station will

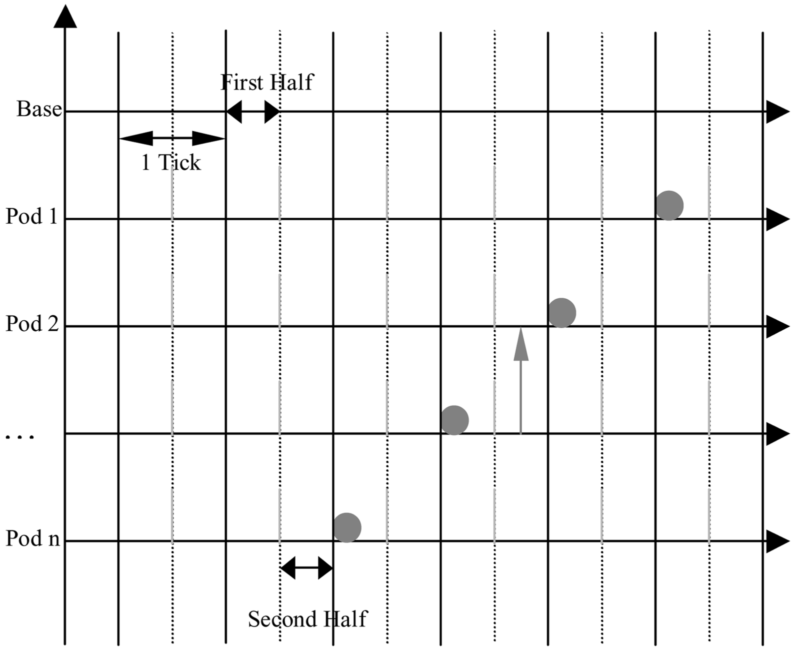

Fig. 6 Time division arbitration

ignore all other trigger notifications for the remainder of the event. In this diagram, the notification is shown as the horizontal arrow. For worst-case notification delay, it will be 4N ms (N is the number of Pods), which is much less than the three minutes event time.

The communication protocol also presents a fixed time for data uploading time. The three minutes of event data is stored in 1M Bytes of SRAM. Given the 2.9 ms real time constraint of Phase II, each pod can upload 256 bytes to the base station during one clock cycle. It will take 16 seconds to vacate a one Mb SRAM bank for the next event. Considering the TDMA protocol, it will take N periods for each pod to upload once, so the total time for vacating the RAM is 16N seconds. For a system with 10 Pods, it will only take 160 seconds to back up all the events data, so the RAM can be available for the next event. The time is very desirable when compared to general aftershock intervals.

3.3. Asynchronous communication

The pattern of real-time response of the system must be maintained in order to keep synchronization for all Pods. However, the Linux machine uses time slices of hundreds of milliseconds in length and can therefore only interact with the base station through independent asynchronous channels. So as to insure the time distribution of the base station not be disrupted by any request for data, we disable the interrupt on the serial communication channel of the base station and operate the link asynchronously. When the Pods transport the data to the base station, the Linux machine should not interrupt the base station, so internal buffers must be used in the link to hold commands until a free command cycle is reached. All the commands from the Linux engine will be loaded into the buffer, so the microcontroller can fetch the command when it sends a time tick.

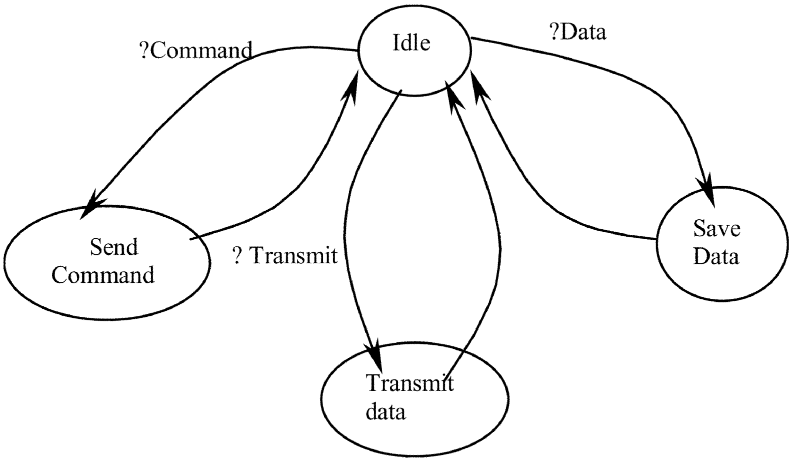

Fig. 7 State machine model of the Linux Machine

3.4. System administration

The Linux machine is the interface of the system to the outside world. There are three main tasks for the machine to perform:

1) Accept commands sent by the operator over the internet and transfer them to the base station;
2) Store and evaluate data sent by the system;
3) Transmit the data to the operator through the wireless radio module.

The Linux Machine is equipped with a Maxstream one Watt 2.4 GHz wireless module as the wireless connection to the web server or access point of the Internet. Due to the asynchronous communication with the outside world, we employ the interrupt mode so it can respond to external events in time. The state machine model (Lee and Varaiya 2003) is as shown in Fig. 7.

When the operator sends commands through the wireless module, the linux machine get interrupted by RS-232 COM 1, take the command, and forward it to base station. When the base station has data to upload, the LG is interrupted by the RS-32 COM 2, it extracts the event data, and stores locally for transmission or viewing.

4. Conclusions

The Terra-Scope system is an affordable 4-D down-hole seismic monitoring system based on independent, microprocessor-controlled sensor Pods. Each Pod measures 3-D acceleration, tilt, azimuth, temperature, and other parametric variables such as pore water pressure and pH and etc. A local gateway serves as a controller center for the communication between multiple Pods, it is also a data storage and gateway to the Internet. The down hole array monitoring requires a hard real time property for the embedded system. A microcontroller-based real time embedded system is carefully designed in order to meet the real time constraints. Different aspects of system, such as time synchronization, communication protocols and hardware design are all carefully examined in order to achieve the system safety and reliability. The prototype of the device is currently undergoing evaluation, and further experiments are expected. The first array will be installed in the spring of 2006.

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