Linux for low cost eddy current detectors
Finds nails in your walls and cracks in your aircraft

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Abstract

This handy little unit attaches to your notebook or PDA computer. Placed against a wall, it detects nails and other structures inside. Requires linux running on a device with duplex stereo sound, a few electronic parts and a bit of soldering assembly.

The underlying CANDETECT software combines the Open Sound System with some signal processing to measure inductive coupling parameters for non-destructive test. Originally intended for aircraft aluminium structures, it characterizes the proximity and characteristics of conductive materials. `http://candetect.sf.net/`

In addition to being a fun toy and occasionally useful tool, it demonstrates why Linux intrinsically accelerates prototyping and development of new products. The talk will discuss the acquisition software, review the performance data it achieved under laboratory testing and demonstrate the unit.

Keywords: audio band, eddy current, electromagnetic inspection, NDE, through wall detection, TWD

1 INTRODUCTION

The CANDETECT project[1] at SourceForge enables low cost eddy current inspection by eliminating the expense of specialized computers, external amplifiers, modulators and power supplies. Our solution consists of software that can run on any Linux-supported platform and an inspection probe that is designed to be plugged directly into the connectors for `/dev/dsp`.

This paper reviews a few applications that the project seeks to address and summarizes the design of our probe. It describes some of the computer platform issues, explains the software being used and and discusses why Linux is the best approach to building a practical solution. The paper also examines some of the outstanding challenges and concludes with plans for future work.

2 SITUATIONS

Over 5000 repair stations in the USA employ 36000 experienced aviation repairmen to manufacture, modify and maintain high quality General Aviation aircraft parts. Over 340000 (yes, a third of a million) mechanics (or "Aviation Maintenance Technicians" AMTs), located at airports nationwide, install, replace and inspect those parts on the 163000 registered small aircraft. There are more mechanics than aircraft because many of them work part-time, or seasonally, or only maintain specific models. As a result, they cannot justify buying expensive computer systems that will only be used a few times each year for non-destructive inspection.

Corrosion often occurs inside the lower surface of a structure, where it is inaccessible to normal inspection methods. Water that enters the structure tends to drain downwards and multilayer joints offer nooks and corners where surface tension can retain the water and discourage drying. This corrosion encourages crack growth around the fasteners that hold the multilayer structure together. Figure 1 is a prior result[2] where this software detects a short crack through a $2.5\,cm$ thick layer of Aluminium.

In earthquake prone areas, such as California, construction using bricks would be unsafe. Instead, a strong yet lightweight frame consisting of wood or aluminium vertical beams (on a $\approx\ 40\,cm$ spacing) is covered by a thin flat layer of particle board, plaster or similar with only enough strength to support itself. During an earthquake, such a wall would push adjacent furniture over unless the top of each item has been securely fastened to the wall. When attaching furniture or cabinets to framed walls, it is important to align the screws with the stronger internal structure that can bear a load. Walls also contain pipes and electrical wiring, which are usually best avoided when driving long screws through the wall.

Non-contact location measurement often uses magnetic mutual inductance. The simplest implementation drives an alternating current into one moving coil and measures

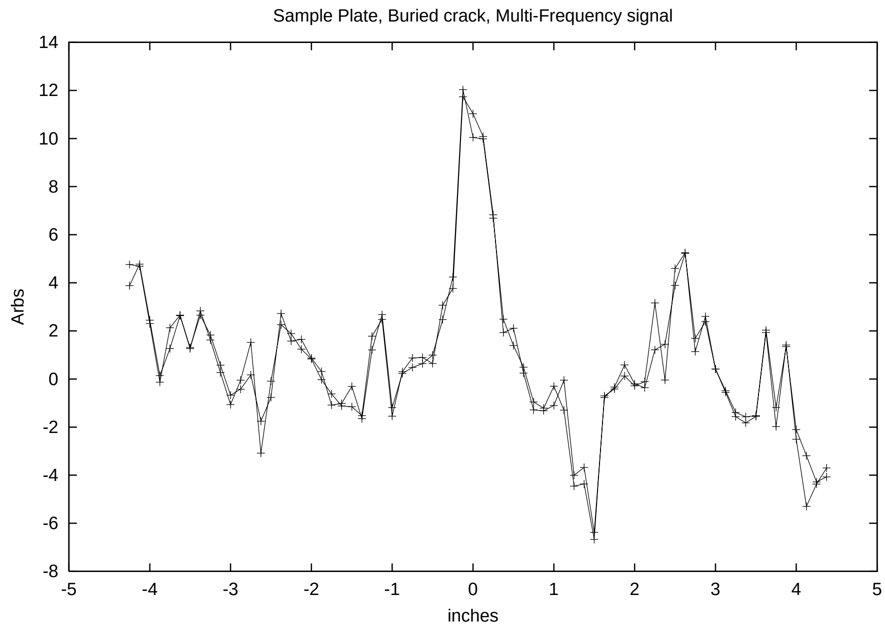

Figure 1: Prostar notebook, $2.5\,cm$ thick Aluminium sample plate, buried crack $0.25\,mm$ wide and $9.5\,mm$ long, depth of $1.9\,cm$ to the other side, multi-frequency measurement shows crack at the zero position. This previously-reported[2] result has limited signal to noise ratio, giving rise to the smaller peaks.

the relative strength of the detected signals in two fixed coils that are mounted at either end of the moving coil. Since our CanDetect software can generate two independent drive currents and monitor two independent signals, this Linux-based implementation can also provide real time two dimensional tracking and excellent precision.

It is often convenient to construct a probe that incorporates a one dimensional version of that location measurement and also one of the corrosion or wall inspection techniques described above. Suitable software can then inspect the structure and immediately plot the results in their absolute positions in real time. The integrated probe is beyond the scope of this paper, but only doubles the complexity of the mechanical construction.

3 COMPUTER PLATFORMS

The project aims to keep the cost to the user as low as possible. In part, this is achieved by eliminating the need for a dedicated computer, whether embedded or a normal desktop system. Although the mechanic or user could take advantage of an old computer, thereby eliminating the purchase cost of the unit, such systems tend to have lower reliability and the associated maintenance labor reduces the number of billable hours working for the customer.

An existing computer can usually only be used for the CANDETECT project if there is no risk to the current software and data contents. This is reliably achieved in a commercial workshop environment by running Linux in a diskless mode, preferably with the associated device drivers omitted. If the user does not already have a suitable computer system, perhaps the cheapest option is the CD-booting *New Internet Computer* (NIC)[3]. It has a retail price of $US\$200$ and includes everything except the monitor.

In order to simultaneously output and input a waveform, the sound card must be capable of full duplex operation. Many older cards, and also more recent notebook computers, are unable to achieve full duplex without reducing the sample resolution and/or sample rate. The card needs to operate in 16 bit mode, whereby each voltage reading is nominally capable of resolving $16\,ppm$ of full scale.

Until recently, palmtop handheld computers did not offer such audio capabilities, either due to limitations of the chipset or because the connectors were not available inside the case. This seems likely to change with the units currently under development.

4 EDDY CURRENT PROBES

Magnetoresistive (MR) sensors have a useful frequency response from $1\,Hz$ through $5\,MHz$ without needing special techniques[4]. Inductive coil sensors can also cover that range of frequencies, but generally not in a single sensor. One inductive probe sensor can cover a range of one or two orders of magnitude, before a differently designed sensor would offer significantly

Figure 2: Inductive coil pair, optimized for $10\,kHz$ and $2\,cm$ depth.

improved performance. If the intended application (such as looking for wall supports) only addresses a narrow frequency range, an inductive probe such as the one in Figure 2 can be effective, replacing the $US\$10$ cost of the MR sensor in low volume with the effort of winding a coil.

Some applications such as aircraft inspection require accurate characterization of each feature that results in observable signals. Characterization generally requires a broad range of frequencies, suggesting the use of MR sensors.

Honeywell MR sensors electrically appear to be a resistive bridge, just under $1200\,\Omega$ per leg, achieving $1\,mV/V/G$ at $55\,^oC$ and better at lower temperatures. A four times transformer improves the match to most sound cards, which expect a load around $80\,\Omega$, so that $4\,V_{RMS}$ may be applied to the sensor. The resulting signal from the sensor is best amplified using another four times transformer to increase the sensor's source impedance of $600\,\Omega$ to $10\,k\Omega$ and convert the differential signal into the ground-referenced single ended high impedance voltage expected by the sound card. In conjunction with the $20\,dB$ gain that is usual for most microphone inputs, the system can measure $6\,G, 0.6\,mT$ signals (full scale) without external powered active components.

Conventionally, the sensor bridge has a constant voltage applied across it, such that the output signal is proportional to the magnetic field. The electrical noise associated with low frequency operation impairs performance, so a higher signal to noise ratio can be attained by modulating the magnetic signal into the optimal performance band of the sound card input amplifier. The actual frequency to be used is different for each sound card and needs to be measured during initial system configuration, taking into account the performance of the two transformers. Once the frequency is determined, the appropriate sound card channel is instructed to generate that waveform continuously.

The magnetic excitation field that illuminates the sample is generated by the second output on the sound card. Since this field must be generated at the desired measurement frequency, transformers cannot be used to match the impedance. Depending on the probe design, the available field strength will differ; a conventional current sheet probe, for example, can readily achieve $0.1\,G_{RMS}$ on most sound cards.

No other electronics are needed to operate the probe, so it is unpowered and can readily be used in conjunction with a notebook computer (or a suitable handheld PDA) that is mobile and running on batteries.

5 SOFTWARE APPROACH

We currently use **AudNet**, which was developed for this project, to operate the soundcard and a patched version of *xoscope* to plot the streaming results as shown in Figure 3.

5.1 AudNet Library

The library operates the sound card, ensuring that there is always something to be played and retrieving the signals that were recorded. Clients submit requests for measurements, which are performed as soon as possible, then collect the responses from a queue. Many different kinds of measurement request can be submitted at any

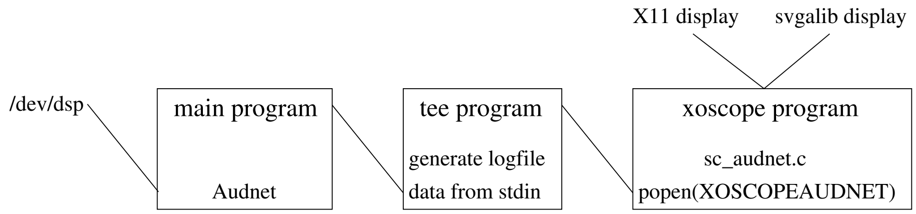

Figure 3: Block diagram showing interconnection of program elements.

time, the library simply works through the to-do queue until it gets to the end (if it ever does). When the request queue becomes empty, the most recent request is simply repeated until a new one shows up.

Each request consists of one waveform for every electrical output channel available, normally two for most sound cards, together with the number of times that the waveform should be repeated. All the incoming signal during those repeats is collected into a single response for the client. Since many electromagnetic systems are slightly resonant, the request also specifies how many times the waveform must be performed until the probe and sample have reached a predictable state for reliable measurement. These skipped cycles are only performed when the library switches from one request to a different request definition; they are not needed when a request repeats.

Each response consists of one waveform for every electrical input channel available, normally two for most sound cards. All input and output values are scaled so that full scale is $-1 \ldots + 1$ in the waveforms.

Since playback data has to be placed into the sound queue a second or more before it is played, and recorded data appears in the sound queue a short time after it is recorded, the library keeps track of how much data is in those sound queues. Often, the request being sent out is a different one from the one whose data is being collected into a response.

5.2 main - AudNet Sample Program

This program expects the first command line parameter to be a frequency in Hz and the second command line parameter to be the phase adjustment of the output in degrees. It requests the library generate a clean sinewave on one speaker channel and a clean cosinewave on the other channel with a frequency that is as close as possible to the requested one. The library delivers measurement responses about ten times per second.

Whenever a new result is generated, the program writes a line to the standard output and flushes the file to ensure that the recipient receives the result. The line has three numbers, corresponding to the actual frequency, the measured signal at the desired phase and the signal in quadrature to that phase. The line also contains two sections, enclosed in braces, which provide a simple text representation of each value at multiple sensitivity scales. This is generally ignored, but extremely useful for diagnosing problems without the necessity of starting the full X environment to view data.

This is much simpler than modern approaches, but many eddy current systems in industry do exactly this.

5.3 xoscope - Graph Plotting

The original **xoscope** application is intended for use as an oscilloscope, whereby a hardware driver monitors a signal source for a specified trigger condition and hands a waveform fragment back to the main application. The user interface allows the trigger and plotting parameters to be specified, rather like an oscilloscope, and periodically asks the driver to try to find a new trigger event.

The trouble with this approach, for CanDetect's purposes, is that a real oscilloscope will discard input signal whenever it is too busy to draw to the screen and the software version does the same thing. This is fine when the goal is to monitor a high speed transient waveform, but problematic for viewing a slowly changing signal over many seconds. Initially, the linux-soundcard driver was replaced with an audnet-based one. However, when running on the NIC, the user interface often would not call the hardware driver for many seconds while some disk access or screen refresh was in progress. The maximum value of this interruption determines the necessary length of the soundcard buffer, yet a five second delay is not acceptable for a simple interactive device.

A new version of the hardware driver for xoscope was created, which reads an environment variable *XOSCOPEAUDNET* for a command line which is expected to provide suitable data with 10 Hz sample rate. This environment variable is initialized, before starting *xoscope*, to ensure that the *main* program above is invoked with desired settings. The floating point values are scaled so that one count of the oscilloscope waveform is $10\,ppm$ of the soundcard fullscale input, but in consequence signals in excess of 32% of fullscale are clipped due to

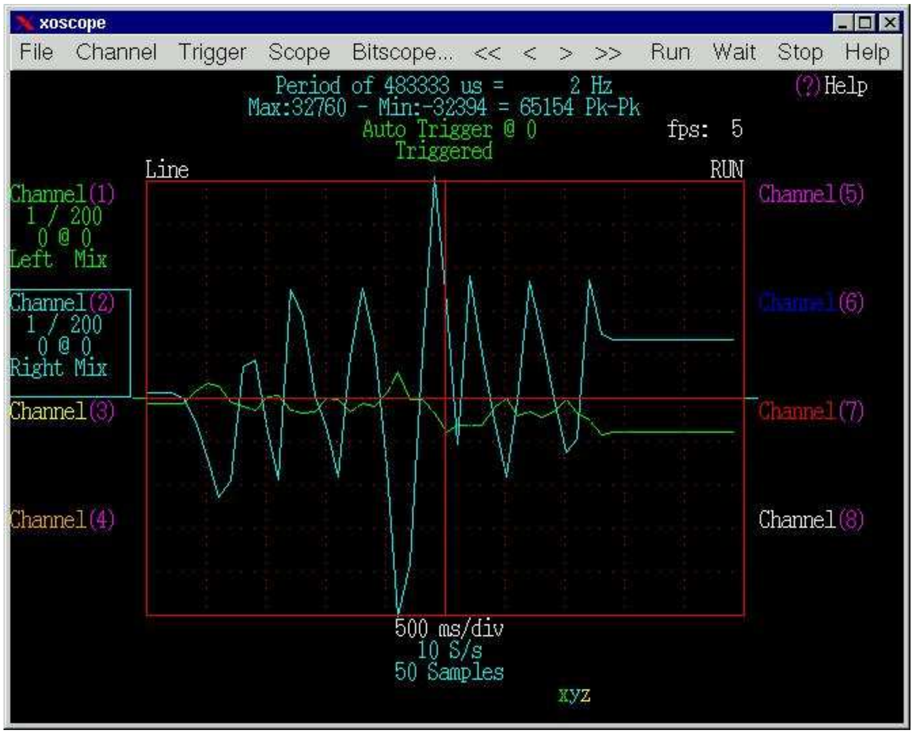

Figure 4: Snapshot of the `xoscope` window during data acquisition

the limited dynamic range of the application's internal storage buffers.

The necessary modifications to xoscope's CVS checkout version are also tracked in the `src` module of CanDetect's CVS `xoscope.patch` and should be applied before configuring the package. In addition to placing that new driver into the build sequence, it modifies some of the runtime defaults (and legal value ranges) to match the CanDetect data source expectations. It also modifies the configuration script to create a new option *–without-vga* that forces non-detection of the *svgalib* support and eliminates the associated code (and library searches) from the package. This is useful when building the binary application on a computer which has *svgalib* support installed and the binary will be used on a computer without the library installed (such as the NIC).

5.4 Building binaries

The easiest way to build everything in the CanDetect project, including the custom version of *xoscope*, the *main* program and the *candetect.raw* CD for NICs is to use the inter-module makefile. Perform a single checkout of the whole CVS archive, run *make* and wait for it to complete as shown in Figure 5. The CVS passwords are blank, as usual, and you will need to enter your system's root password to conduct specific operations (read each command line carefully). Note that this will create a directory called xoscope next to the one containing all the CanDetect modules (to avoid getting CVS confused).

6 WALL SIGNALS

Inspecting the contents of a wall can generally be done with a narrow band of frequencies. Therefore, a purely inductive probe is acceptable for this application.

Our probe, as shown in Figure 2, consists of two coils, centers $62\,mm$ apart, glued to a piece of wood as shown in Figure 7. Each coil has a diameter of $56\,mm$, 80 turns of wire with a resistance of 6.2Ω and inductance of $0.8\,mH$ for an effective impedance of 50Ω at $10\,kHz$. The coils are connected in series, such that the current rotates in opposite directions, between the left and right signal out wires. The midpoint between the coils is connected to the mono microphone input and the grounds of the output and input are connected together as shown in Figure 6.

The plot in Figure 8 shows the measured sine wave amplitude, proportional to the voltage at the microphone connector, divided by the operating frequency. The voltage is proportional to the rate at which magnetic flux flows through the coil windings, so scaling this by the sine wave period converts the voltage into the total magnetic flux being measured by the coil. At audio frequencies, the skin depth is too deep to generate a good InPhase signal for such thin metal items as nails, so the red curve in the plot remains near the zero line. The magnetic loss, due to the hysteresis loop of the iron

```
$ mkdir candetect.sf.net
$ cd    candetect.sf.net
$ cvs -d :pserver:anonymous@cvs.candetect.sf.net:/cvsroot/candetect login
$ cvs -d :pserver:anonymous@cvs.candetect.sf.net:/cvsroot/candetect co .
$ make
```

Figure 5: Commands needed to build all the software for the NIC.

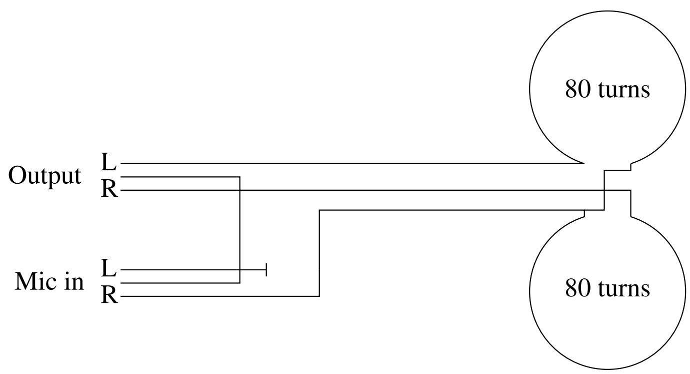

Figure 6: Schematic of the electrical connections for the probe shown in Figure 2 above.

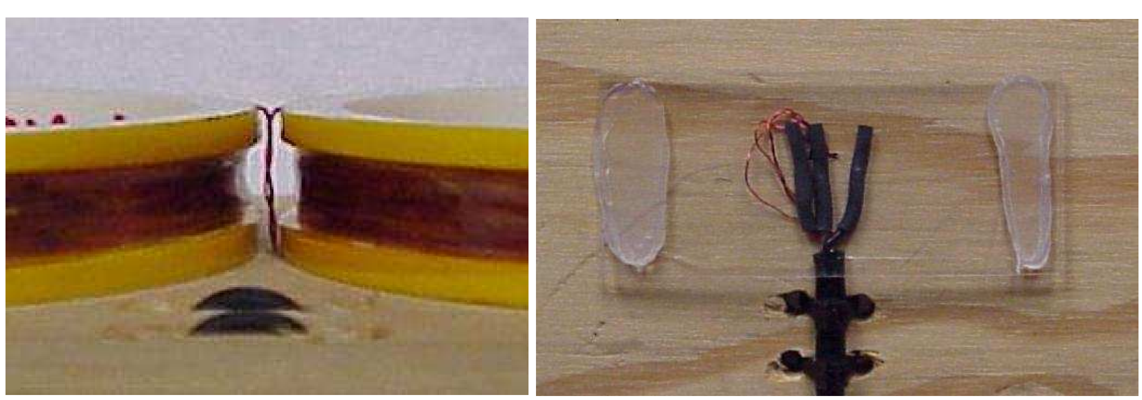

Figure 7: Construction details for the probe shown in Figure 2 above.

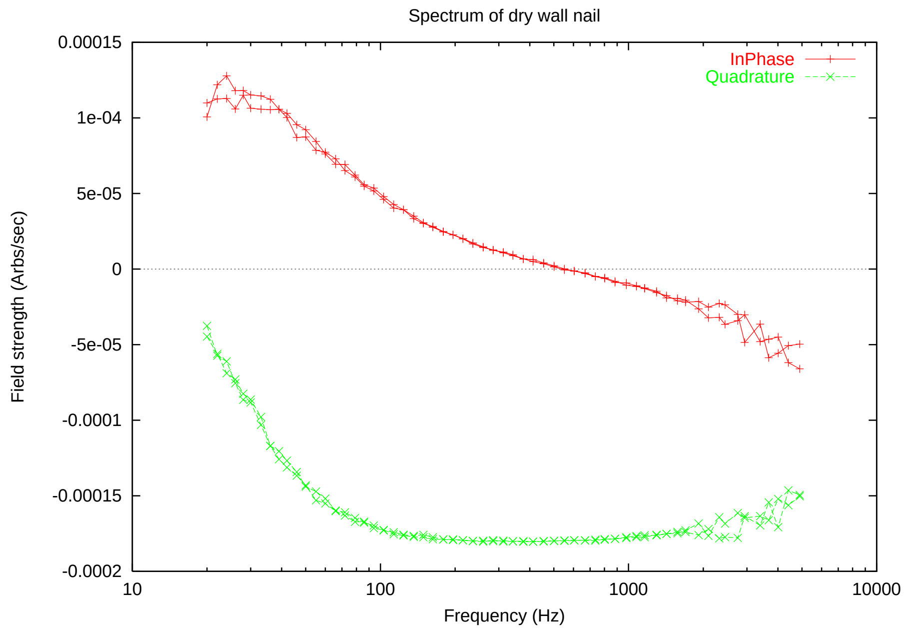

Figure 8: Prostar notebook, frequency response of a drywall nail. The nail is in the wall, invisible to the naked eye.

inside the nail, is essentially frequency independent and shows a useful Quadarature value for frequencies above $60\,Hz$. We chose the frequency to be $1\,kHz$, since this maximizes the wall area coverage rate for the user.

Scanning across a wall to find the invisible nails, the software will report a positive signal when the nail is inside the circle of one coil or a negative signal when the nail is inside the circle of the other coil. This is shown in Figure 9. When trying to examine a large area of wall, the coils can travel next to each other so that the sign of the signal indicates which coil encountered a nail. When trying to determine the exact position of a nail, the coils travel along the same path so that the central symmetry with no signal will indicate the location to within a few millimeters.

Power cables, as shown in Figure 10, or metal structural components will obviously have much larger signals.

7 LINUX BENEFITS / CHALLENGES

Under the Linux kernel, audio is accessed as a simple character device using file descriptors. Since network links can also be treated as file descriptors, these can be used by acquisition software to interact with a different computer containing the sound card. This greatly simplifies the comparison of different sound cards to determine which ones have beneficial electrical characteristics. Especially with respect to lightweight computer platforms, where screen size or processor resources would require adaptation of the software, these network-centric capabilities are valuable.

Linux offers several benefits when integrating the software into a simple device. It boots and shuts down rapidly, can be immune to being turned off by simply pulling the plug or batteries, is resource efficient and has a large base of knowledgeable developers.

Possibly the most time consuming part of developing non-destructive testing systems is their validation. This involves running the electronics and processing software against a broad range of samples in a variety of operating environments to demonstrate that the algorithms are robust. The Open Sound System, when integrated with the other Linux kernel functionality, provides a common execution environment for the software across a wide variety of computer hardware. This allows software validation results to be applicable since no source changes were made.

On most Linux-capable PDAs, sound hardware is either absent or the microphone is not available as a connector. If obviously-portable applications are demonstrated on notebook size computers, future PDA support is more likely.

The latency associated with kernel buffering limits the adaptability of the algorithms, thereby requiring the measurement of potentially-extraneous values and leading to a lower useful rate for the user. Ongoing kernel development is mitigating this inefficiency.

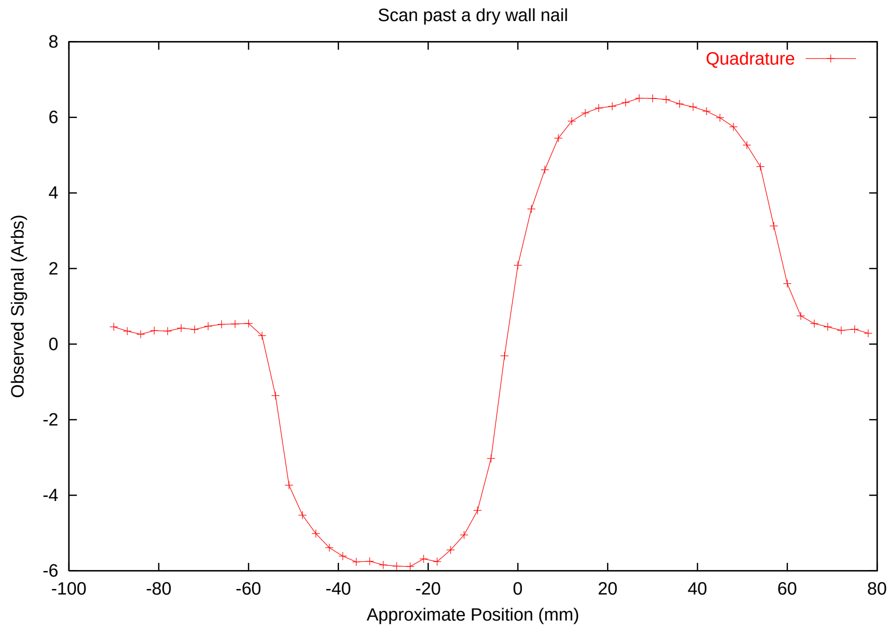

Figure 9: Prostar notebook 1 kHz, linear scan of an invisible dry wall nail.

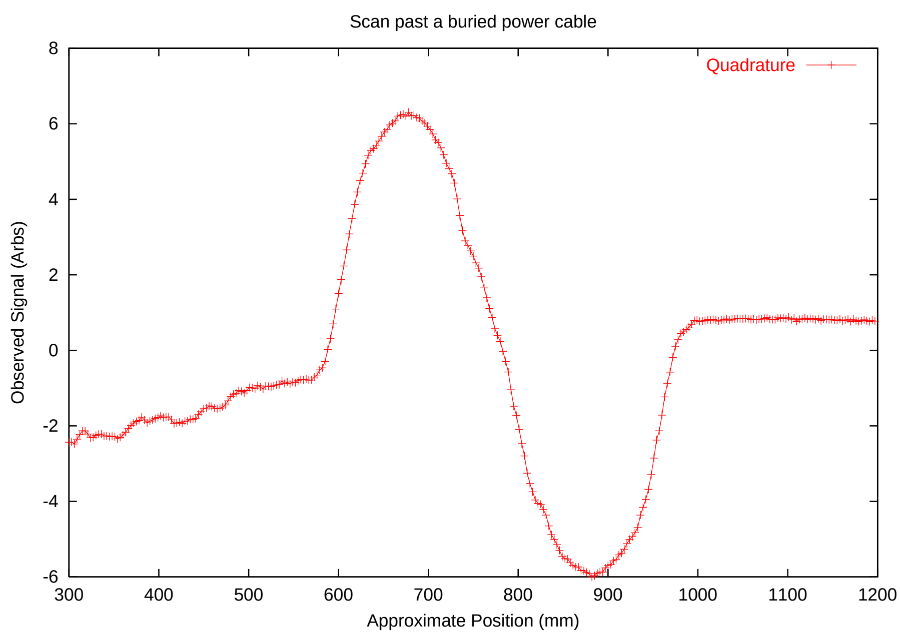

Figure 10: Prostar notebook 1 kHz, linear scan of an invisible 110 V power cable.

8 CONCLUSION

CANDETECT takes advantage of the simplicity and portability of Linux. It allows the same applications to run in many different settings while still providing a consistent performance and high measurement quality.

9 ACKNOWLEDGEMENTS

The NIC unit was donated to the project when selected as a finalist for the Embedded Linux Journal competition in 2001. More information about our winning entry can be found in the May/June issue[5] and on our website[1]. The inductive probe, after assembly by Brian Whitecotton, was photographed by Keith Ostrom.

References

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