REMOTE CONDITION MONITORING AND VALIDATION OF RAILWAY POINTS

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1. Introduction

After several recent railway tragedies in the UK, the condition of the railway infrastructure has become a matter of rising concern, for the railway industry, government and the general public. This has led to an increasing focus on railway safety and the optimal management of railway maintenance. Recent developments in microelectronics and information technology make possible the application of low-cost, high-quality condition monitoring to trackside equipment, in order to reduce the likelihood of breakdown and to enhance railway service quality. Based on a partnership between the University of Oxford and Westinghouse Signals in the UK and Australia, research has been carried out into the development of an on-line conditioning monitoring system for railway points ("WestWatch"), using some of the techniques developed at Oxford for validating industrial instrumentation [1]. This paper describes the background to the project and the condition monitoring system. Data has been analysed and evaluated from a test site in Chippenham, and on main-line railways at Melbourne, Sydney and Brisbane in Australia. Initial results suggest that condition monitoring may offer valuable information, particularly by measuring the impact of each train as it passes over the points. To conclude, consideration is given to implementation issues and how such a system might be used to enhance railway maintenance practice.

2. Railway point machines

Point machines, which switch the track between two alternative routes, have always been an essential component of railway networks. Their reliability directly affects the quality and safety of the rail service. Fig. 1 shows a simplified diagram of a typical electrically-driven point machine and its linkages [2]. To move the switch rails from one side to the other, the motor torque is first transferred to the clutch, then to the belt and ballscrew which converts the rotating torque to a force in the axial direction. Via the crank, the force direction is rotated through 90° to drive the switch rails. The rails have two movement directions, either to the normal position ("Normal" movement) or to the opposite "Reverse" lie ("Reverse" movement). When the switch rails have moved across, the lock blade is used to secure them in place, preventing slippage. A set of electrical contacts operated by the detect blade is used to indicate to the signalling control system (or interlocking) that the switch blades have been successfully locked into position.

Variants on the lock and detect mechanism have been used globally for decades as the basic points safety system. The railway signal associated with the set of points will not permit a train to proceed until lock and detection are completed. In the UK, for example, it is a legal requirement that detection should succeed for a gap of 3mm or less between the switch rail and stock rail on the closed side, and that detection should fail if this gap exceeds 5mm. Normally, a 'points failure' entails the inability to make detection after the points machine has operated to switch the rails, or the loss of detection due to some mechanical movement of the system. As this in turn leads to a block in the signalling system, it is classed as a signalling failure. This may cause train delays and passenger inconvenience, but minimises the risk of a train passing over faulty points. Tragedies such as Potters Bar, where a catastrophic mechanical failure occurred during a train transit, are consequently extremely rare.

The Railway Safety Report 2001 states that the number of signalling failures leading to train delays was broadly comparable to the previous year, but the duration of delay associated with each incident increased significantly over the year. Railtrack, the UK railway operator, owning 32,000 km of track and 2,500 stations, reports that the number of signalling failures causing delay during 1999-2000 was over 25,000, while the delays incurred add up to 760,000 minutes [3] [4]. The economic consequences of such delays are high, both directly in terms of financial penalties,

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and indirectly in terms of network traffic throughput and customer dissatisfaction. Points are known to be responsible for a high proportion of signalling failures.

The detection mechanism in a points machine is discrete: from a signalling perspective a detection failure is usually sudden, with little prior warning (however there is anecdotal evidence of temporary losses of detection, particularly during train transits). Currently, the only tool available to avoid points failure is maintenance, which is routinely undertaken at fixed intervals, e.g. every 4, 13, or 52 weeks; the level of scheduled work varies from basic inspection to full servicing [5]. During servicing, the alignment of the points, including the lock and detect mechanisms, may be tested, and adjusted mechanically. Although the servicing intervals have been established as a result of statistical analysis of failure events by manufacturers and railway service companies, the failure statistics cited above imply that scheduled maintenance alone is currently not providing a satisfactory level of reliability. The aim of the work described in this paper is to use continuous, automated monitoring of the condition of the points machine and its point-work in order to enhance current maintenance practice.

An underlying assumption is that, given the mechanical nature of the system, many faults are likely to be incremental in nature, and that there exist physical parameters which, if monitored, might offer evidence of the fault condition before a failure takes place. Catastrophic failures occurring without prior indication are clearly not amenable to advanced warning, and complete fault coverage is not possible (although even here condition monitoring can provide data so that the failure mechanism can subsequently be studied in depth): the intention must be to reduce, not eliminate, unforeseen points failures. With these caveats stated, the motivation is clear for the development of a points condition monitoring system:

- To use an array of sensors to monitor all relevant parameters, in order to provide advanced warning of degradation prior to points failure;
- To provide, in the event of a catastrophic failure, the immediate past history to identify the cause;
- To provide continuous monitoring, as a supplement to scheduled examinations by maintenance personnel;
- To provide on-line accurate measurement, e.g. of position and load force data, to support maintenance action (e.g. adjusting mechanical alignment);
- To provide an automated archival record from which broad trends can be extracted from the entire railway asset base.

3. Failure analysis and measurement selection

A failure analysis has been carried out to determine the most significant fault modes and to identify which parameters should be measured in the condition monitoring system. A typical electrically-operated points machine (Style 63), manufactured by Westinghouse Signals and widely used within the UK, was selected for analysis, on the basis that the manufacturer's expert knowledge was available. Failure statistics were obtained from Railtrack maintenance records for a thirteen mile stretch of track in south-east England, which incorporates 170 Style 63 points machines. From January 1, 1994 to December 21, 1998 there were 937 faults recorded. These have been classified into 3 major fault categories, as shown in Table 1, as being related to the points proper (i.e. the track), the points machine itself, or other causes (including no fault found).

Two observations resulting from this categorisation concur very well with the experience of Oxford validating instrumentation for the process industry:

- The most common and important faults occur not within the device itself (i.e. the points machine), which is relatively self-contained and protected, but rather with its interface to the larger system (i.e. the track associated with the points). 56% of the faults are found in the points, but in addition it may be argued that at least some of the lock and detection out of adjustment faults are also mechanical interface problems, and so the proportion may be as high as 65%. Condition monitoring which is restricted to points machine components may not be able to track and anticipate most fault modes directly.
- In over 11% of cases, maintenance personnel were unable to find a problem at the points to which they had been called. One possible reason is the presence of an intermittent fault, which might be diagnosed by a constantly active monitoring system; this in turn could result in improved maintenance efficiency.

In order to identify suitable signals to detect and anticipate failure, a useful distinction is drawn between the *cause* of a failure and its *functional effect*. The *cause* of the failure is typically what a maintenance engineer will report, based upon the required corrective action. By contrast the *functional effect* of the failure describes the mechanism by which the cause induces failure (e.g. obstruction, looseness, detection or lock failure, failure to move). It is readily seen from maintenance records that there are far more causes then functional effects. It is unlikely that all possible causes of faults can be identified using automated condition monitoring. For example, the maintenance engineer may record various types of obstruction (e.g. bolts, ballast, dead animals), but it is not feasible to distinguish between them in a condition monitoring system. The strategy adopted here is to monitor signals which verify the proper functional operation of the points machine and associated track, rather than focussing on the development of specialised mechanisms for detecting quite specific causes of failure, each of which may reoccur with extremely low probability. This strategy rejects the pursuit of the negative assertion that none of a particular set of faults has been found, in favour of the more positive assertion that there is a good relationship between a comprehensive set of monitored signals. For example, the mechanical components are in good alignment, the switching operation is behaving nominally, and rattles and shifts during train transits are within tolerances. In other words, fault detection is superseded by active validation of the proper functioning of the points. While there can be no guarantee that all faults will be anticipated, it is at least possible that an unforeseen fault category (e.g. missing fastners) will manifest itself by its impact on the parameters that are monitored (e.g. changes in the signature of the switching operation, increasing rattle during train transit).

Based on a detailed analysis of the fault data provided, measurements were selected as shown in Fig. 2. Most monitor positions: those of each of the stock rails, the moving rails, the lock and detector blades and the position of the points machine itself, all relative to a fixed reference beam. The assumption is that if all of these measurements maintain an acceptable relationship with one another, then any form of mechanical misalignment of the points is unlikely. Note that all of these measurements are in the horizontal plane only; additional measurements of movement in the vertical plane, especially during train transits, might provide useful additional data on the integrity of the ballast packing. In addition the motor voltage and current and load force are measured which, together with the dynamic switch rail position, provide comprehensive data on the points machine movement. The temperatures of both the points machine and rail are monitored to allow thermal expansion and contraction to be considered when measuring changes. Discrete signals are provided to monitor case opening and closing as well as hand-crank insertion and removal. These can be used to provide automated records of maintenance action for management, and for field support for maintenance engineers.

There are two basic modes of operation for which data must be collected, while a third emerged during field trials:

- Points machine movement (a ‘movement event’). When the points machine is activated, data must be collected at high speed to capture the features of the movement. Currently, the motor current and voltage, load force and switch rail positions are monitored during a points machine movement.
- Background data. All of the sensors (excluding the motor current and voltage which by definition should be nominally zero) provide useful data on the behaviour of the points machine in stasis.
- Passage of a train over the points (a ‘train event’). Specialised procedures have been developed to detect and record train events, as evidence suggests they are important in explaining points behaviour.

Separate data records are kept for the two switch rail positions, or in the case of a movement event, which direction the switch rail is travelling. The terms ‘Normal’ and ‘Reverse’ are used to denote the different static states, while a ‘Normal’ movement moves to the Normal state.

One criticism of the approach adopted here is that the large number of sensors reduces the reliability of the condition monitoring system. However, as will be shown later, the redundancy between sensor data can be used to validate individual sensor readings and to provide graceful degradation of diagnostic function when sensor failure occurs. Reliability and complexity are discussed further at the end of the paper.

4. System Architecture

Having identified a set of signals to monitor, the next step is to design and implement a system capable of collecting and processing raw data, implementing condition monitoring algorithms, and generating diagnostics and alarms. The WestWatch architecture is shown in Fig. 3.

Signal conditioning is kept to the bare minimum (buffering, scaling) so that raw data is transferred to the digital domain as early as possible. 7 Analog-to-Digital Converters (ADCs) are used in parallel to monitor all the measurement channels. The devices used, Analog Devices 7731 sigma-delta (ΣΔ) ADCs, provide multiplexing on up to three input channels, good noise rejection (essential for the railway environment), and a high degree of configurability (e.g. programmable gains, trade-off between sampling rate and precision).

The role of the FPGA and processor are described in the following subsections.

4.1. Field-Programmable Gate Array (FPGA)

FPGAs are silicon chips consisting of regular arrays of small logic blocks; the function of each block, as well as the interconnections between blocks, are programmable. For dedicated I/O tasks, an FPGA has many benefits over a conventional processor. In the WestWatch system, the 7 ADCs are programmed and monitored in true parallel by the FPGA on a continuous basis. The FPGA also controls a 256K x 16bit RAM; this is used to store data (for example the complete data set from a points machine movement). This relieves the processor from the burden of providing rapid, real-time responses to point machine events. All real-time I/O requirements, as listed below, are dealt with by the FPGA.

- Each of the 7 ADCs has three input channels; at present 16 of these channels are in use.
- For static, background data, updates on each of these channels are required by the processor at 1Hz maximum.
- Points machine movements are detected by a sudden rise in supplied current and voltage. These must be detected as quickly as possible so that the new channel scanning pattern can be established.
- During an event each ADC monitors a single channel continuously. Currently 5 of these channels are recorded.

These requirements are achieved as follows. In background mode the FPGA continuously reprograms the ADCs to poll each input in turn. A complete scan of all 21 channels is completed within 7ms, corresponding to a sampling rate of 140Hz. As long as no movement event occurs, the data on each channel is averaged within the FPGA. On request from the processor (typically once per second) the accumulated average is reported and a new averaging process is begun. If the beginning of an event is detected by the FPGA, via thresholding levels on the motor current and voltage, then the FPGA immediately switches data acquisition to movement event mode, where each ADC scans a single channel only at 2500Hz. The switch to event mode occurs within 7ms of the motor current and voltage rising above the selected threshold level. The event data is stored in local RAM. The processor is informed of the start and completion of the event, after which the event data is read back to the processor on request.

4.2. Processor

The processor is a Pentium 166MHz on a PC-104 form factor, running the condition monitoring application under the real-time operating system VxWorks. A local (silicon) hard drive is used to store programs and data. The tasks of the processor are as follows:

- Poll the FPGA once per second for its status. If the FPGA is in background mode, collect background data and update records; if it is in movement event mode, wait until the event is complete and then retrieve event data from FPGA.
- Process event data to generate event record files and to calculate parameter values based upon event data.
- Update the object-oriented database, which stores the values of all key parameters at different time scales.
- Use the database to update the status of all diagnostics and alarms.
- Alert maintenance staff to any significant change (e.g. via e-mail, or SMS message).
- Record background data and comment files for incorporation into archival reports, e.g. case open/closed, crank engaged, user comment submitted from console, diagnostics.
- Detect train events on-line and generate train event record files and reports.
- Generate ASCII logfile giving time-stamped messages of all activities.
- Provide http, ftp and telnet services for local or remote access, with full security features enabled (e.g. two levels of password protection).

5. Diagnostics and Alarms
The railway environment provides particular challenges for a condition monitoring system:

- The cost of site access is high, both for installation and for subsequent modifications;
- Site access involves a degree of risk to personel due to trains;
- There is little data available to model the behaviour of the points layout, particularly during train transits and in faulty conditions.

A carefully structured program is thus required for developing diagnostics, in which data is collected and analysed, and consultation takes place between developers and users, before algorithms are finalised. It is quite straightforward to develop algorithms and set alarm thresholds that seem reasonable based on relatively limited experience; it is far harder to regain credibility once a system has a reputation for generating false alarms and generating unnecessary work for engineers and management.

One important issue is to ensure that the condition monitoring system is flexible and can be configured remotely, thus minimising the need for site access. Remote software services such as http, ftp and telnet provide effective management tools for both software and data, allowing for example the Australian sites to be monitored and upgraded from Oxford.

Two complementary mechanisms are provided to allow incremental improvements in alarms and diagnostics:

- Simple alarms are provided based on high or low values on any of the monitored parameters (or parameters calculated from movement or train events). This allows simple, 'shallow' reasoning to detect undesirable conditions. For example, if the stock rail has moved from its calibrated zero by more than 2mm (say), then this is inherently undesirable and an alarm can be raised. Here the effect of the fault is detected – a shift in the stock rail - even though the underlying cause is uncertain.
- Based on experiment and field experience, 'deep' knowledge is being developed to diagnose specific important fault types (e.g. high slide chair friction) based on the behaviour of several parameters. For example, figs. 4 and 5 show points machine reverse movement data for Chippenham and Melbourne respectively. Signal processing of the data sets provide various parameters values (e.g. peak force, peak current, duration of applied current, start of switch rail movement, switch rail movement duration). Values and trends are combined with expert knowledge to derive diagnostics.

Both approaches are currently implemented. Several diagnostic algorithms have been developed and are now being field tested for robustness. As discussed at the end of the paper, thresholds, particularly for simple alarms, must be chosen based on as wide field experience as possible and, ideally, in consultation with maintenance staff.

When an alarm limit has been exceeded, a number of strategies can be used for informing higher level systems and/or maintenance staff that action is required. For example, WestWatch can send e-mails or SMS text messages to maintenance personnel. Trials have demonstrated that a mobile phone can receive a text message within 20 seconds of a fault condition occurring. Higher level monitoring software can take similar action if contact is lost with any WestWatch module (e.g. due to loss of power or communications).

Later sections of the paper provide examples of the types of data collected, alarm limits, and diagnostics.

6. Web Interface and Archival Records
The WestWatch system provides a Java-based Web interface to control and monitor its functionality. Remote or local users can access data and adjust configuration settings via a standard Web browser. The top and bottom sections of the display provide the status bar, message window, and menu bar. The main screen can be selected using the buttons provided, for example:

- The User screen (Fig 6) provides a high-level summary of the status of the points. Red/yellow/green lights indicate components requiring maintenance attention; the hand-crank and casing lights flag on-going maintenance activity.
- The Measurement page (Fig. 7) shows the current values of all monitored parameters.

- The History screen (Fig 8) provides extended time windows of past performance of individual parameters,
- Various Configuration screen allow system settings and alarm limits to be modified.

A key function of the WestWatch system is to provide a record of the behaviour of the points. The same database can be viewed in different ways according to the needs of the user. For the maintenance engineer, the most recent and current data is of greatest importance, and so the Web interface provides access to the most recent values of all parameters on a number of different timescales (e.g. Fig. 8), and to the last five points movements and train events on each side (e.g. Fig 9).

For the purposes of maintenance management, different views of the same database are provided. Higher level monitoring software downloads data from each site on a daily basis and carries out off-line analysis to generate a permanent, archival record. The resulting trends may be produced on several time-scales, e.g. day, week and month, and include alarm limits and time-stamped records of significant events (e.g. case opened/closed, alarm limit exceeded). A daily summary may be sent to relevant staff (e.g. maintenance managers) via email. Fig. 10 shows an example of a trending diagram for the peak driving force during reverse movements at Melbourne over a 24 hour period.

7. Train events

It is a well-established principal of validation that faults are more readily observed when the system under scrutiny is undergoing stimulation, rather than when it rests in stasis. The most obvious example of system stimulation is when the points are thrown, and naturally all points condition monitoring systems are active when this happens. However, it must surely be the case that the passage of a train, with the corresponding huge injection of mechanical energy into the system, provides the greatest opportunity for testing the fastness of mechanical alignment.

Figures 11, 12, and 13 show typical train event data for Melbourne, Sydney and Brisbane, respectively. In each case the train event is clearly visible in most if not all of displayed signals, these being the position sensors (on the closed side, where applicable), and the load force sensor. The use of multiple sensors ensures that a train event can be correctly identified, reducing the risk of spurious noise on one sensor leading to the recording of a false train event. Two basic properties that can be monitored for each parameter during a train event are the degree of variation (for example its standard deviation), and the permanent, static shift in value that takes place as a result of the train transit. The examples given show the diverse nature of the train events that have been recorded.

Figure 11 is from Melbourne. All measurements show the disturbance caused by the train, but the only significant shifts in value are for the detection rod and the switch rail, both of which move by about 0.2mm. The Brisbane data (fig. 12) shows a much longer train event of some 120s duration. Here the stock rail exhibits the largest shift, again by 0.2mm. The example from Sydney (fig. 13) shows much more significant shifts – a loss of load force of 15%, and movements in stock rail, lock and detection of 0.8mm, 0.5mm, and 2mm respectively. A 2mm shift caused by a single train transit might indeed be considered significant from a maintenance point of view, if detection failures are to be avoided.

The examples typify the variations observed in the points machine and its associated track during a train passage, which appear to depend upon the condition of the points machine and track, as well as the nature of the traffic (e.g. high/low speed, light electric passenger train, heavy goods diesel, etc). Train events can thus provide valuable extra information on how securely the mechanical system is fixed. It is a straightforward matter to provide alarms on the extent of such shifts, or the standard deviation (‘extent of rattle’) of the signals during a train transit. Trending may also be deployed to see how such parameters vary with time. The selection of threshold values, however, must be undertaken with care, as discussed below.

Figure 14 illustrates the extent to which train events can be a significant factor in explaining points behaviour. It shows the position of the detector rod in the reverse position over a 24 hour period at Melbourne, which experiences a series of jumps. It has been confirmed, using the train detection algorithm, that each jump corresponds to a train event. It is evident that during peak traffic, there is a cumulative increase in position towards 2mm; later in the day with fewer trains the average position moves back towards 1mm. Of course, non-emergency maintenance action often takes place at periods of low train activity, such as at night. An examination of the detection rod alignment may reveal nothing amiss, only for a detection failure to occur during heavy traffic.

Conversely, after a points failure, if there is any significant delay before maintenance occurs, then with further train events prevented, examination may result in a No Fault Found verdict.

The train transit data shown thus far is collected and analysed at 1Hz; this appears adequate for diagnosing conditions on the points machine and layout. However, higher speed data acquisition (140Hz) has also been used to provide more detailed information on the train impact, as illustrated in Figure 15, at the cost of much larger data files. Once again the sensor readings show strong correlation, in particular with regard to the timing of signal peaks and troughs, which correspond to the individual wheel axles of the passing train. More detailed analysis may yield the train speed and acceleration, and possibly the axle condition (e.g. the large spike seen on several sensors after 30s might be attributable to a flat wheel). This could considerably enhance the utility of the WestWatch system.

Train detection is a further demonstration of the flexibility of the WestWatch system. At the time of installation, no consideration had been given to using train events to provide diagnostic information. As its importance became clear from the field data, detection algorithms have been developed at Oxford and downloaded to the Australian sites. Clearly, password protection and version control systems are needed to ensure such procedures are secure and effective.

8. Implementation Issues

A successful condition monitoring system may be characterised by the following attributes:

- It uses appropriate technology, properly implemented, to provide diagnostic information about the asset that was not previously available.
- When maintenance action is informed by the condition monitoring system, the overall availability of the asset increases.
- The condition monitoring system is accepted as beneficial and trustworthy by both maintenance engineers and management.

There is ample data to suggest that, in principle, the WestWatch system can provide valuable additional diagnostic information on the condition of railway points. However, important caveats remain in the three areas of safety, functional robustness, and maintenance practice, which form the focus of current research and development work.

Not only is the railway environment exceptionally harsh (e.g. mechanically and electrically), the equipment is also safety-critical. Even though a condition monitoring system may be viewed as advisory, and hence non safety-critical, it is essential that it does not interfere with the safety-critical functions of the points machine and track. Furthermore components, particularly the sensors, field wiring, connectors and mountings, must be highly reliable if the condition monitoring system is to save more maintenance work that it generates. Field experience thus far suggests that there is a need to identify more robust field components.

The system must also prove to be functionally robust, particularly regarding diagnostics. The relatively high number of sensors provides more comprehensive coverage of points function, but also adds to the complexity of the system. Further work is needed to improve the sophistication of sensor validation, exploiting the redundancy between readings, and thus to extend the reliability of the system in the face of a sensor failure. A separate issue is the robustness of diagnostic algorithms under different track conditions, which leads on to the interaction between condition monitoring and maintenance practice.

This paper has suggested several ways in which WestWatch could enhance current maintenance procedures:

- The provision of continuous, high precision measurement of all relevant parameters, with archiving.
- The ability to automate requests for maintenance through diagnostic algorithms and alarms.
- The ability to upgrade diagnostic algorithms and alarms remotely.
- Maintenance support e.g. expert engineers remotely accessing points data to advise maintainers in the field.

It is no trivial task, however, to augment maintenance practice to make use of the data provided. For example, at what level should thresholds be set? Is a shift of 2mm in the detection rod during a train event (fig. 13) sufficiently serious to require maintenance action? Should the speed or traffic type have any bearing on threshold values? If a

2mm shift is deemed to be excessive, must maintenance work be immediate, within a week, within a month? As much of the data provided is new (for example, engineers are currently not able to accurately measure points movements during the passage of a train), there will at first be limited experience to draw on when selecting threshold levels, which will hence need refining in the light of further experience. Further trial sites and partners are currently being sought to extend field experience and thus to begin developing suitable maintenance strategies to best exploit the capabilities of a points condition monitoring system.

Any widespread implementation of condition monitoring must be justified in terms of a cost-benefit analysis. It has been argued by some that a better use of resources is simply to replace aging equipment rather than attempt to prolong its life through monitoring. The data in this paper demonstrates that there is value in continuous monitoring of the overall infrastructure, and specifically the points layout, especially during train transits, as this provides fundamentally new data that is not available under existing maintenance practice. It is certainly the case that validation is more effective when integrated within new products rather than retrofitted to existing devices. For example, the Oxford research group has developed a new flow meter with in-built validation based on ten years of previous research, and Westinghouse and other railway suppliers are developing new points machine products with integrated condition monitoring. Clearly however, it will be many years such devices become widely used, and in the interim, the retrofitting of condition monitoring has much to offer in improving rail network reliability.

Acknowledgements
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References

1. Henry, M., Clarke, D. "The self-validation sensor: rationale, definitions and examples", *Control Eng. Practice*, 1993,1, (4), pp.585-610
2. Westinghouse Signals Ltd. "Style 63 point machine installation and maintenance", Instruction book M3402, 2nd Edition.
3. Railtrack, "2001 Network Management Statement Part 1".
4. Railtrack, "Railtrack corporate sustainability report".
5. Goodwin, M., "Recent methods and trends in determining point maintenance frequencies", *Proc. Instn Civ. Engs Transp.*, 1998, 129 May, pp102-105.

Category	Number of faults	%	Faults in Individual Component (% of total)
Points (external to the machine, such as Slide chairs, Fixing, Stretchers, etc)	521	55.61	Slide Chairs (21.1%), Fittings (10.5%), Supplementary Drives (5%), Obstruction (10.1%), Stretchers/Drive (6.1%), Misuse (2.8%)
Point machine	216	23.05	Point Lock Out Of Adjustment (OOA) (5.9%), Detection OOA (3.2%), Clutch (4.5%), Circuit Controller (4.5%), Motor (1.3%), Hand Crank (0.8%), Machine Case Fixings (2.1%), Fuses & Wiring (0.8%)
Other	200	21.34	Tested-OK (11.3%), Hand Crank-Cut-Out (3.1%), Blown Fuse (2.6%), Relay/Location Faults (1.4%), Supplementary Detector (2.9%)
Total	937	100	

Table 1. Points and points machine fault categories

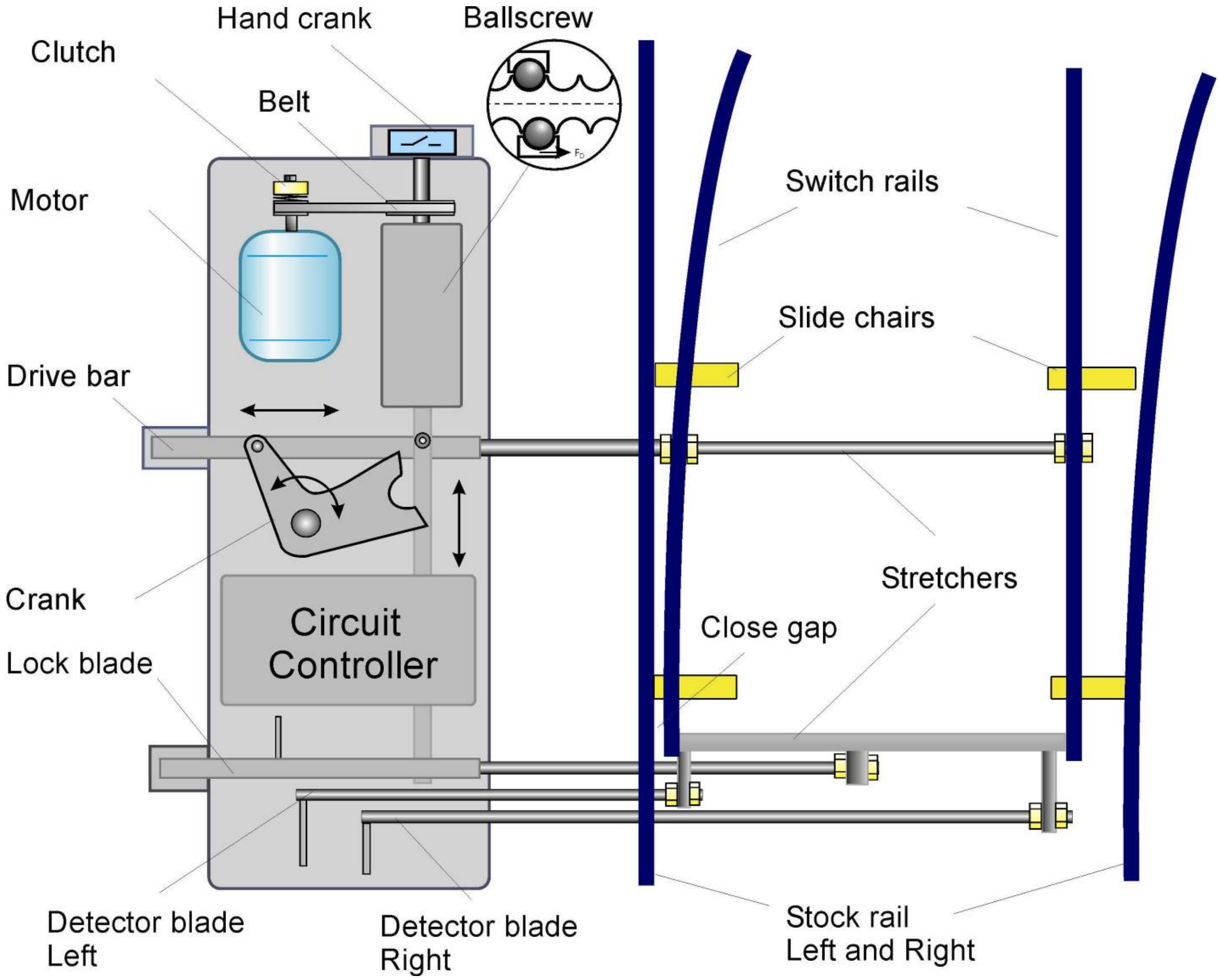

Figure 1. Electrically-driven points machine and track

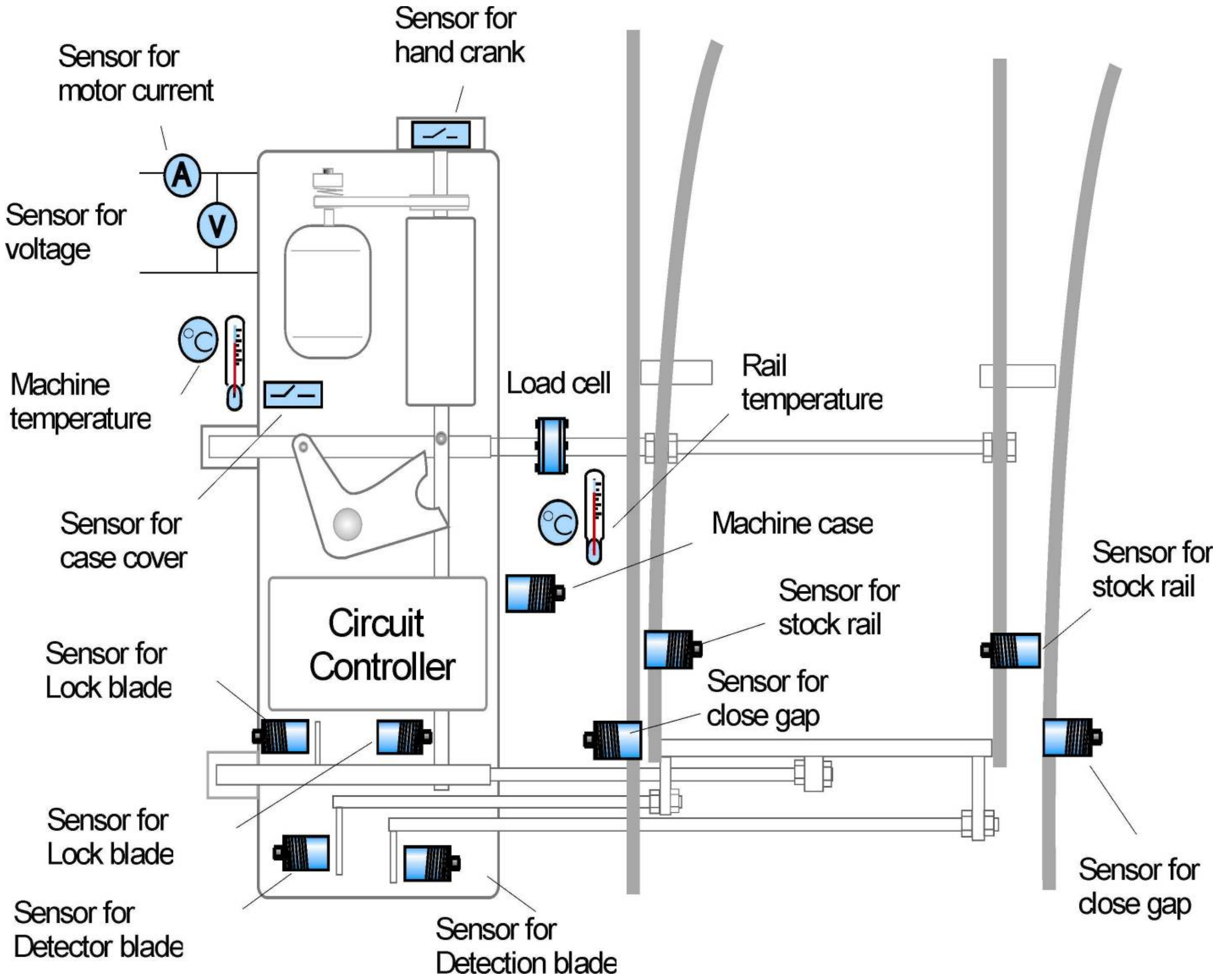

Figure 2. Sensors used in WestWatch condition monitoring system

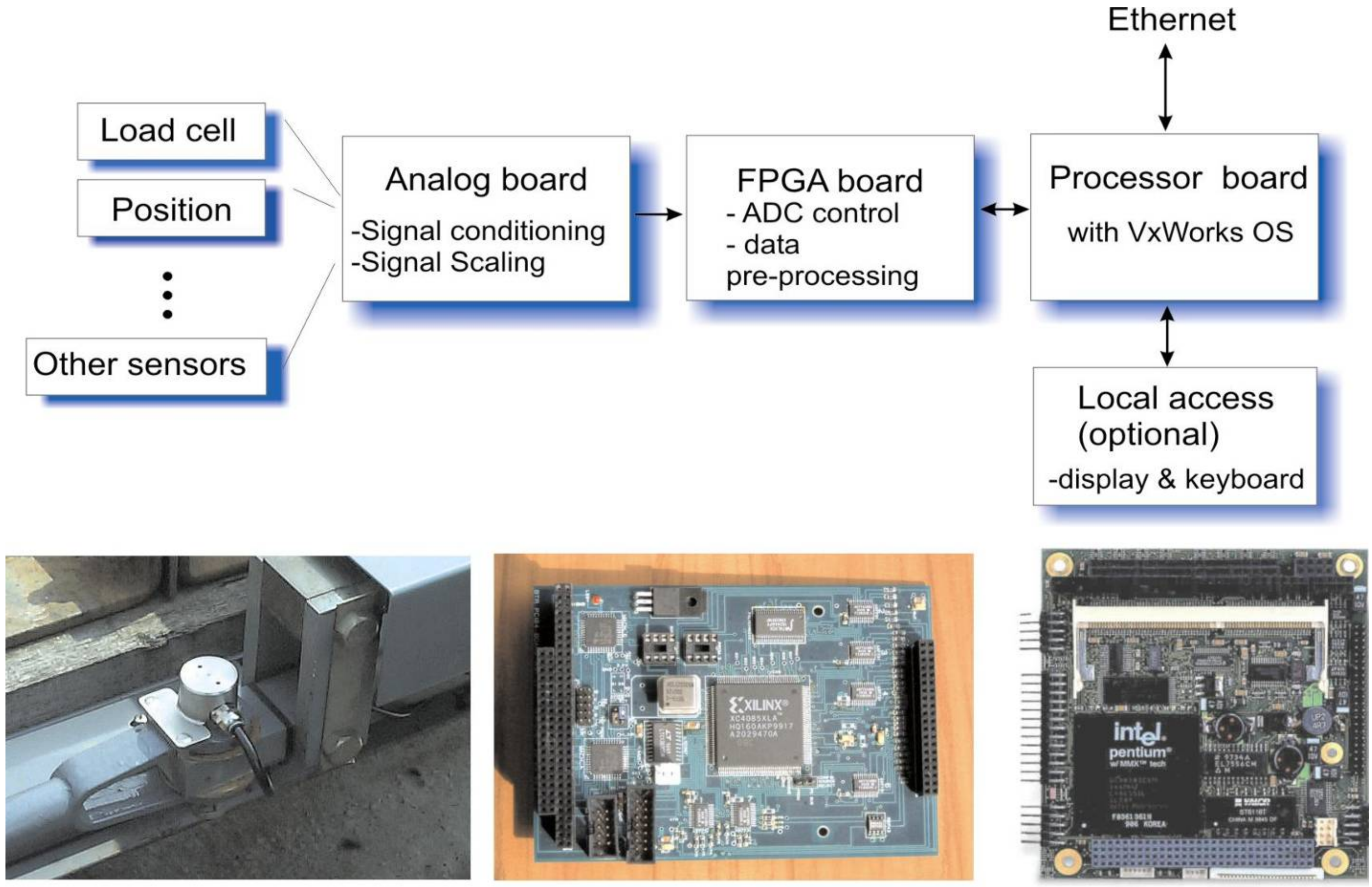

Figure 3. WestWatch system architecture

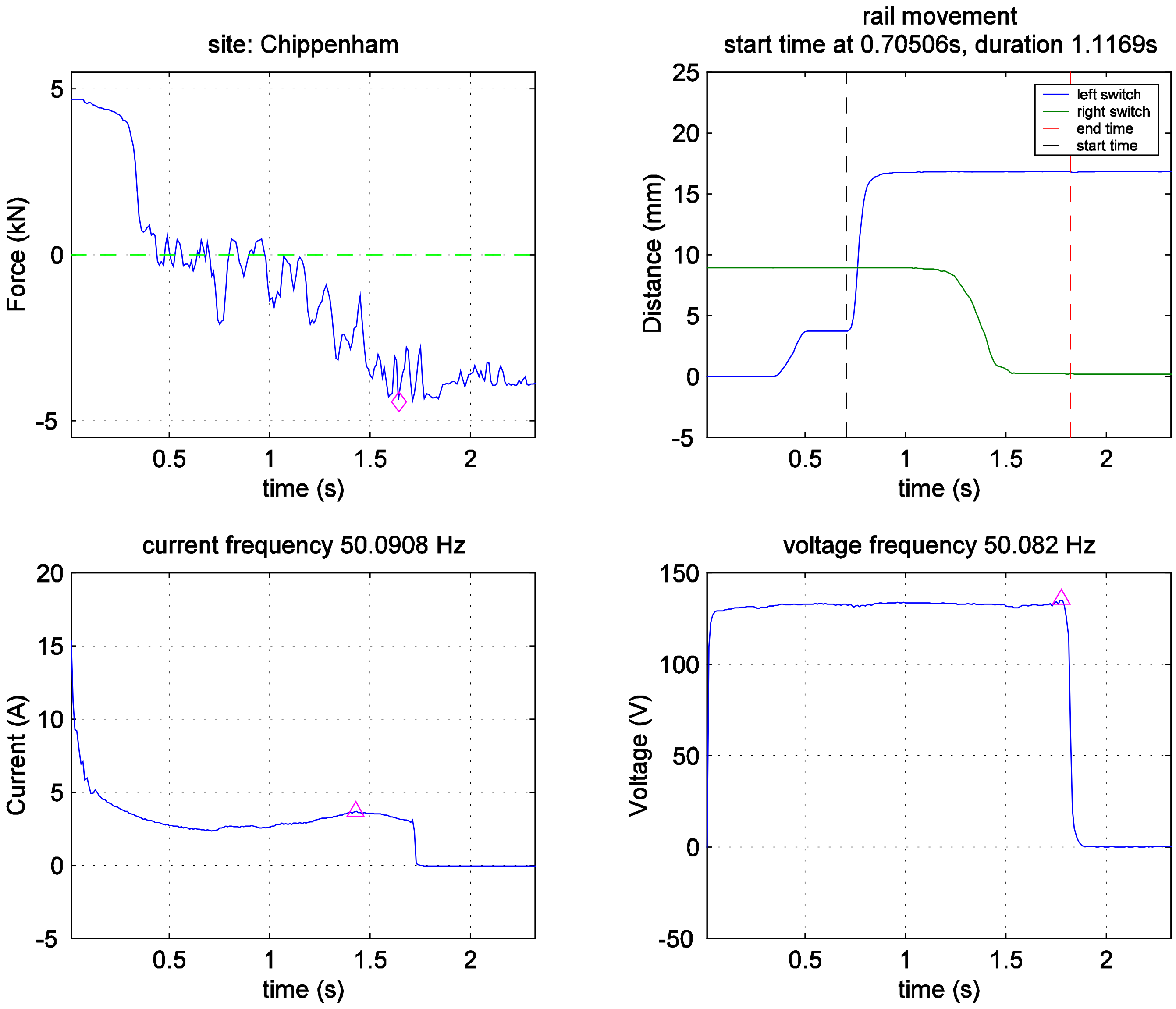

Figure 4. Points machine reverse movement data from Chippenham test site

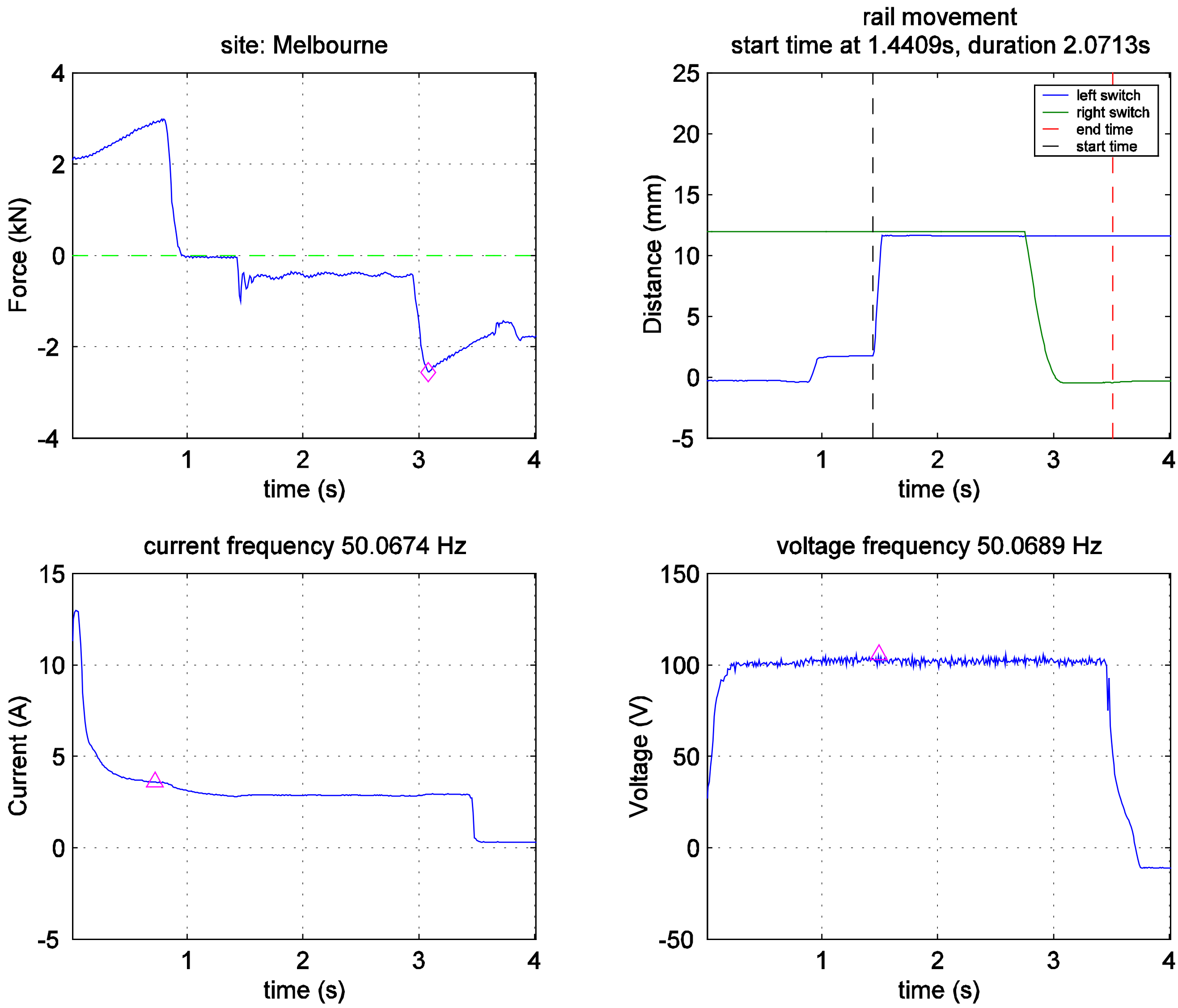

Figure 5. Points machine reverse movement data from Flinders Street Station, Melbourne

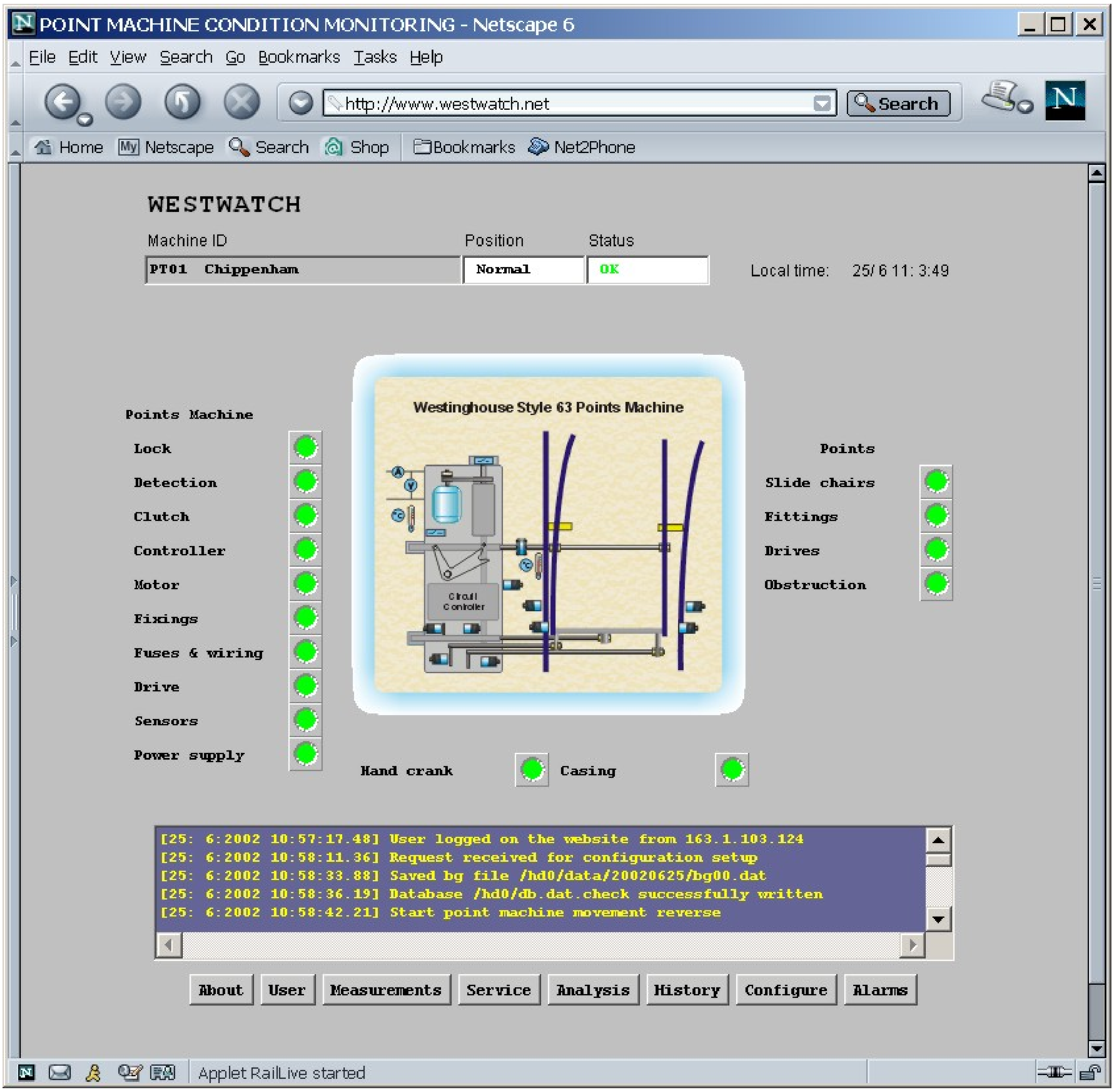

Figure 6. WestWatch Web Interface User Screen.

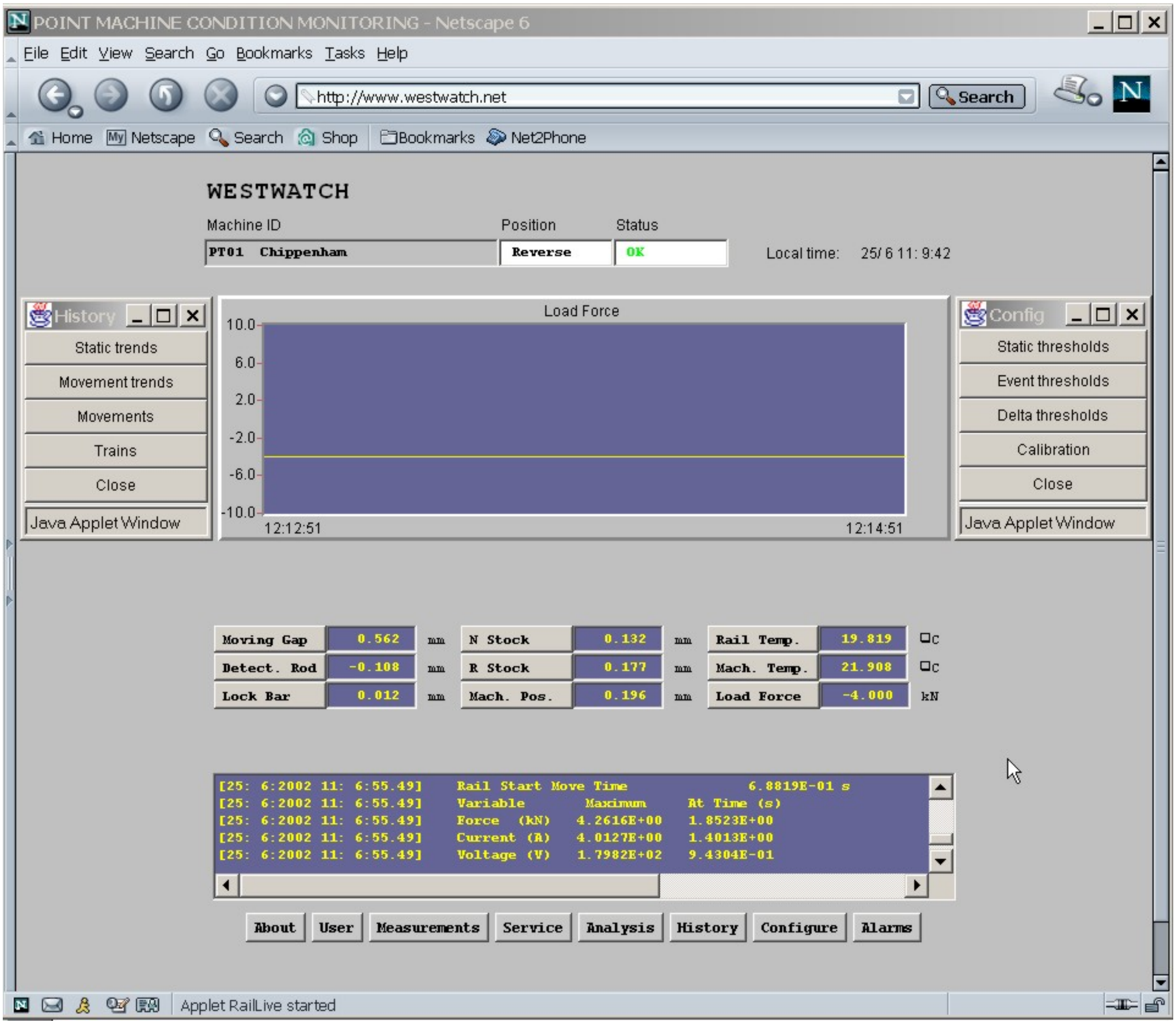

Figure 7. WestWatch Web Interface Measurement Screen.

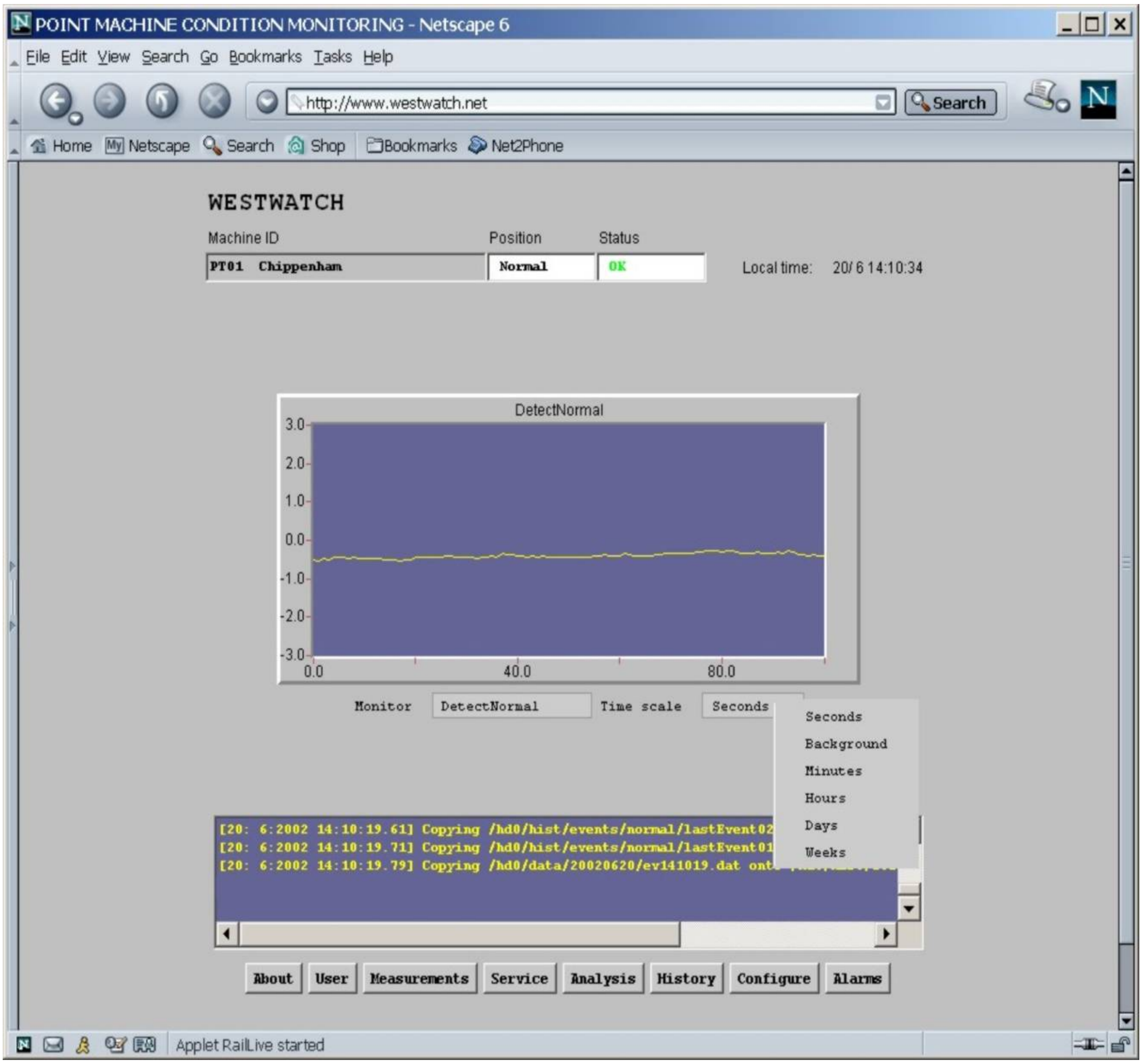

Figure 8. WestWatch Web Interface History Screen.

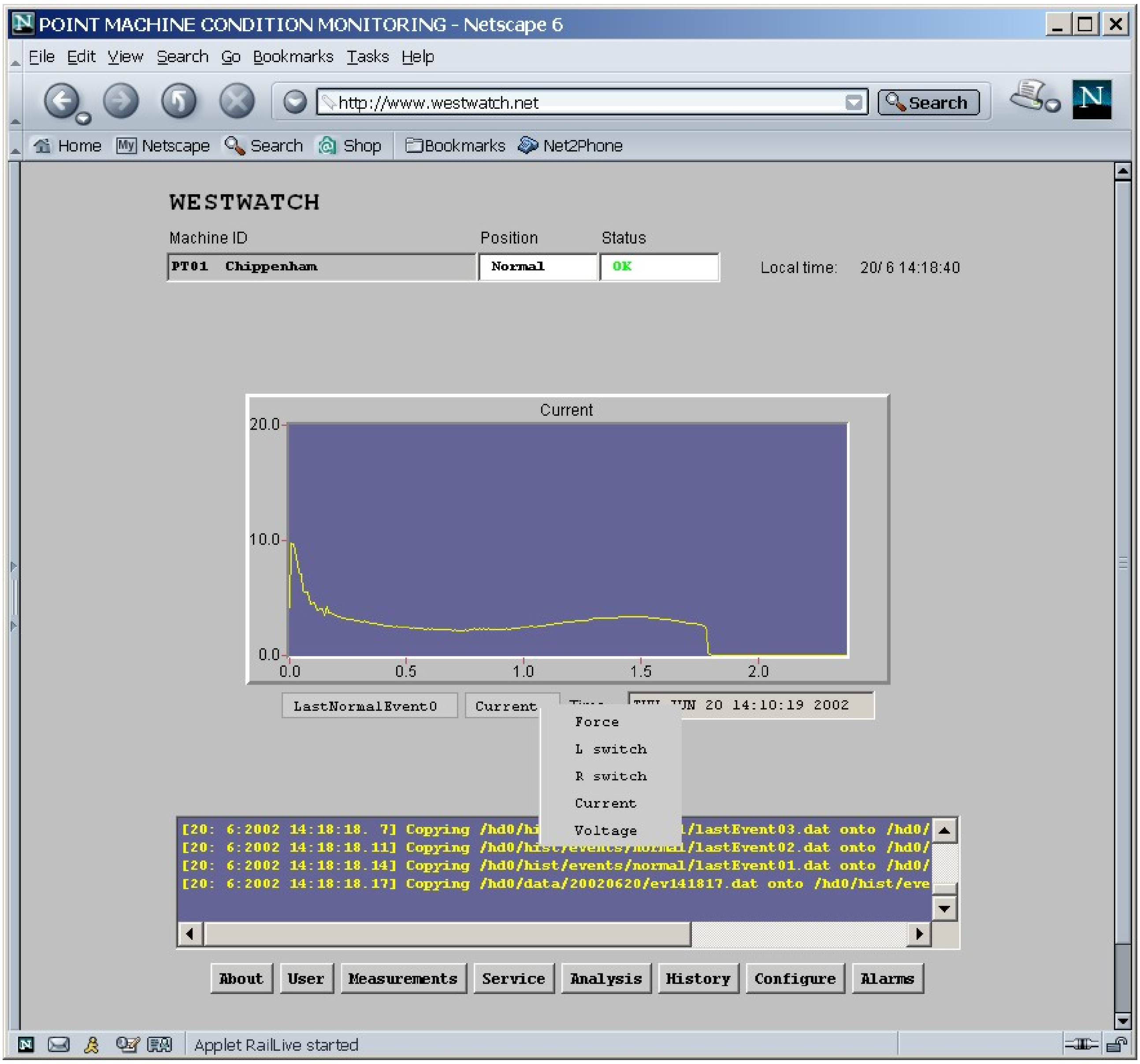

Figure 9. WestWatch Web Interface History Screen –recent points movement.

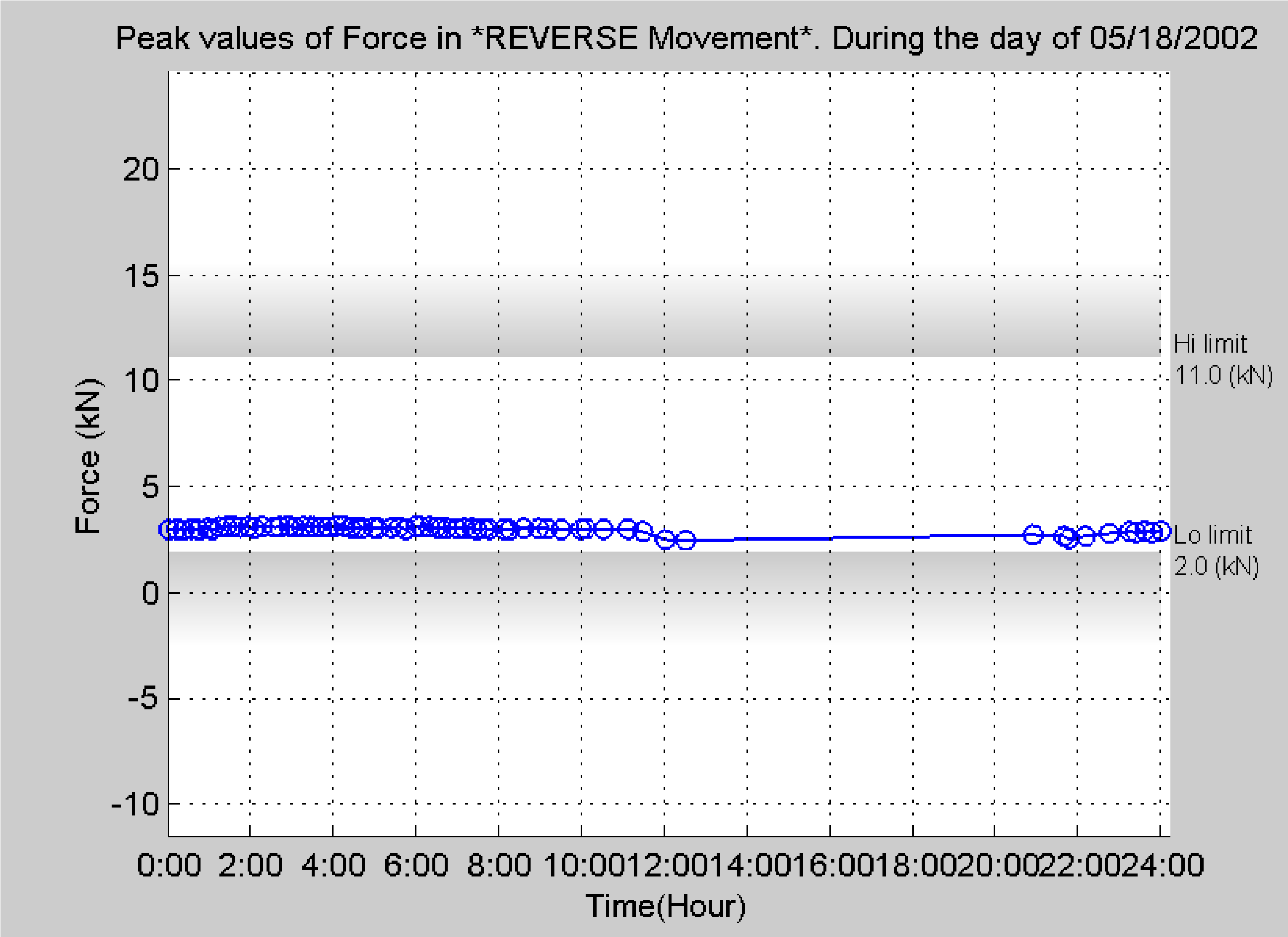

Figure 10. Trend diagram, showing the peak value of the load force during reverse movements over a 24 hour period, with alarm limits. Each circle represents a points machine movement at the Melbourne site. The time base is GMT; the period of night-time inactivity appears between 13:00 and 21:00 GMT.

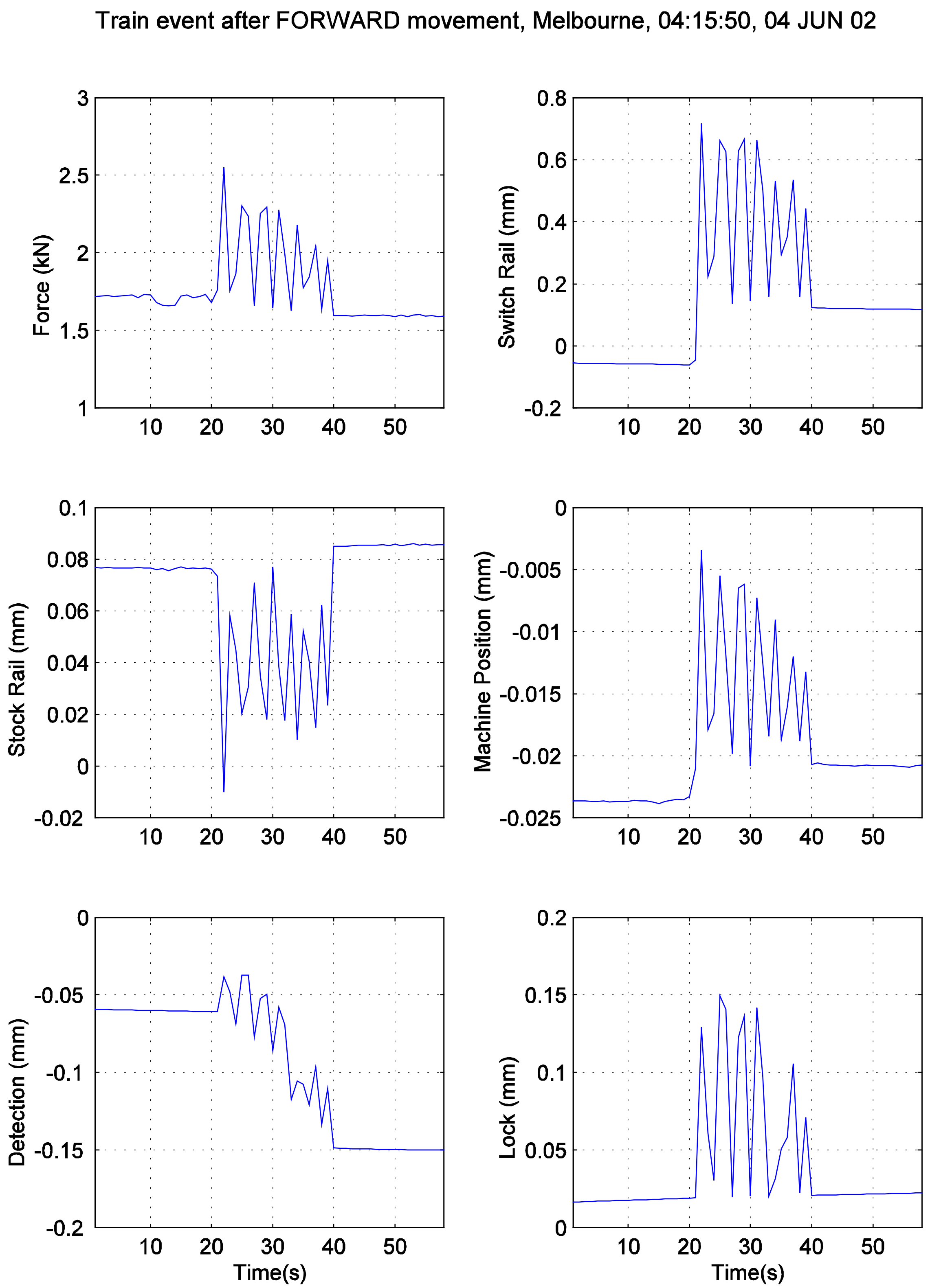

Figure 11. Train Event Data from Melbourne

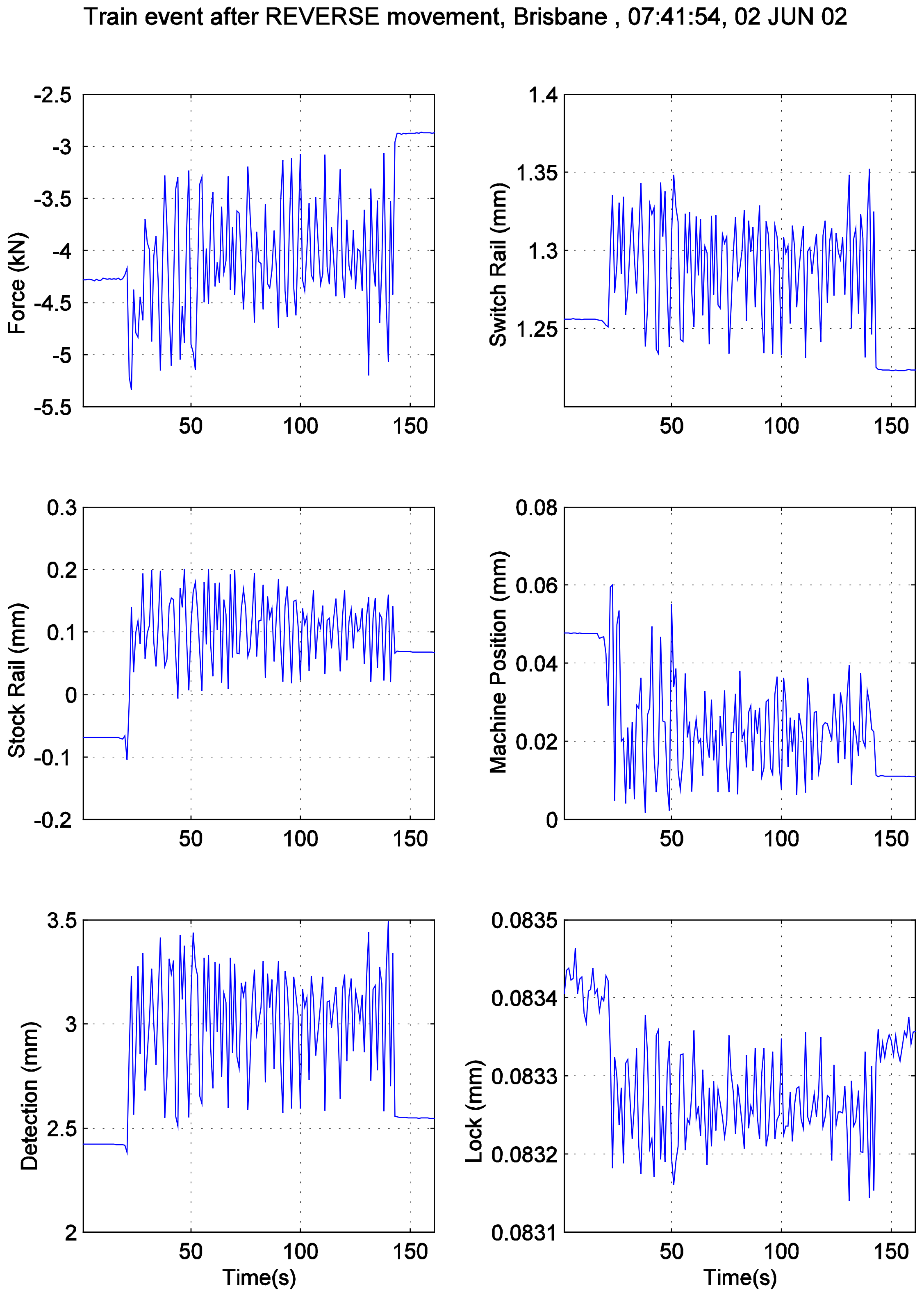

Figure 12. Train Event Data from Brisbane

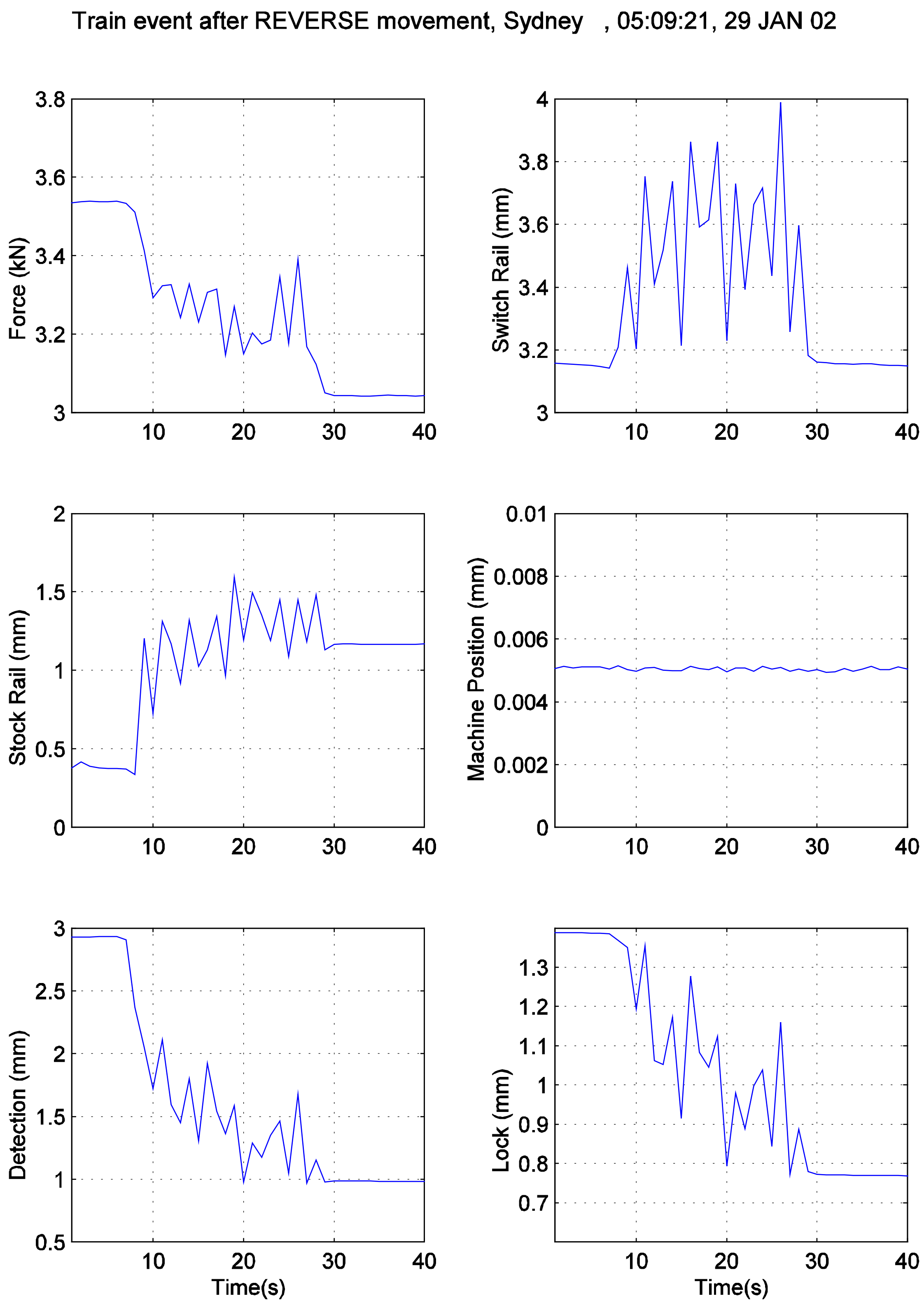

Figure 13. Train Event Data from Sydney

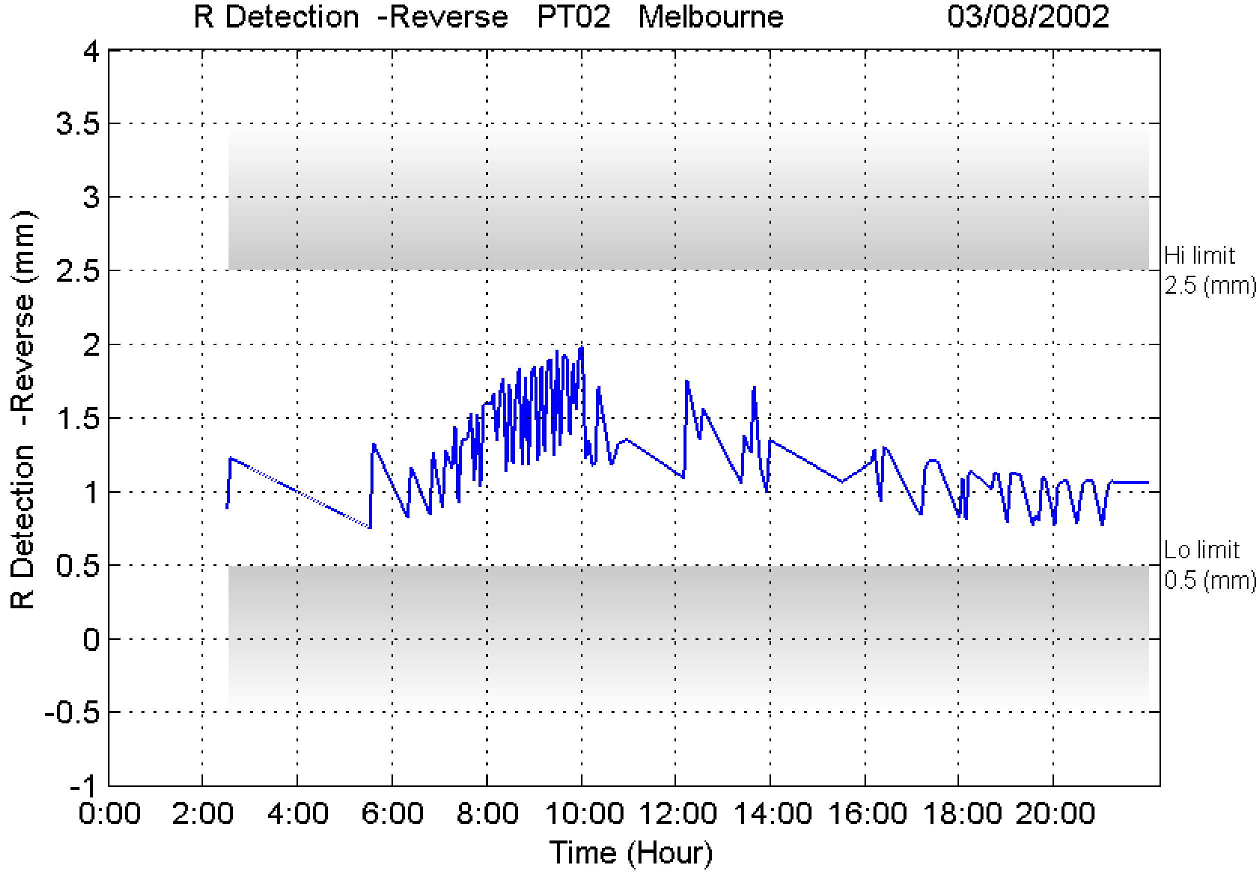

Figure 14. Position of Detection Rod over 24 hours at Melbourne

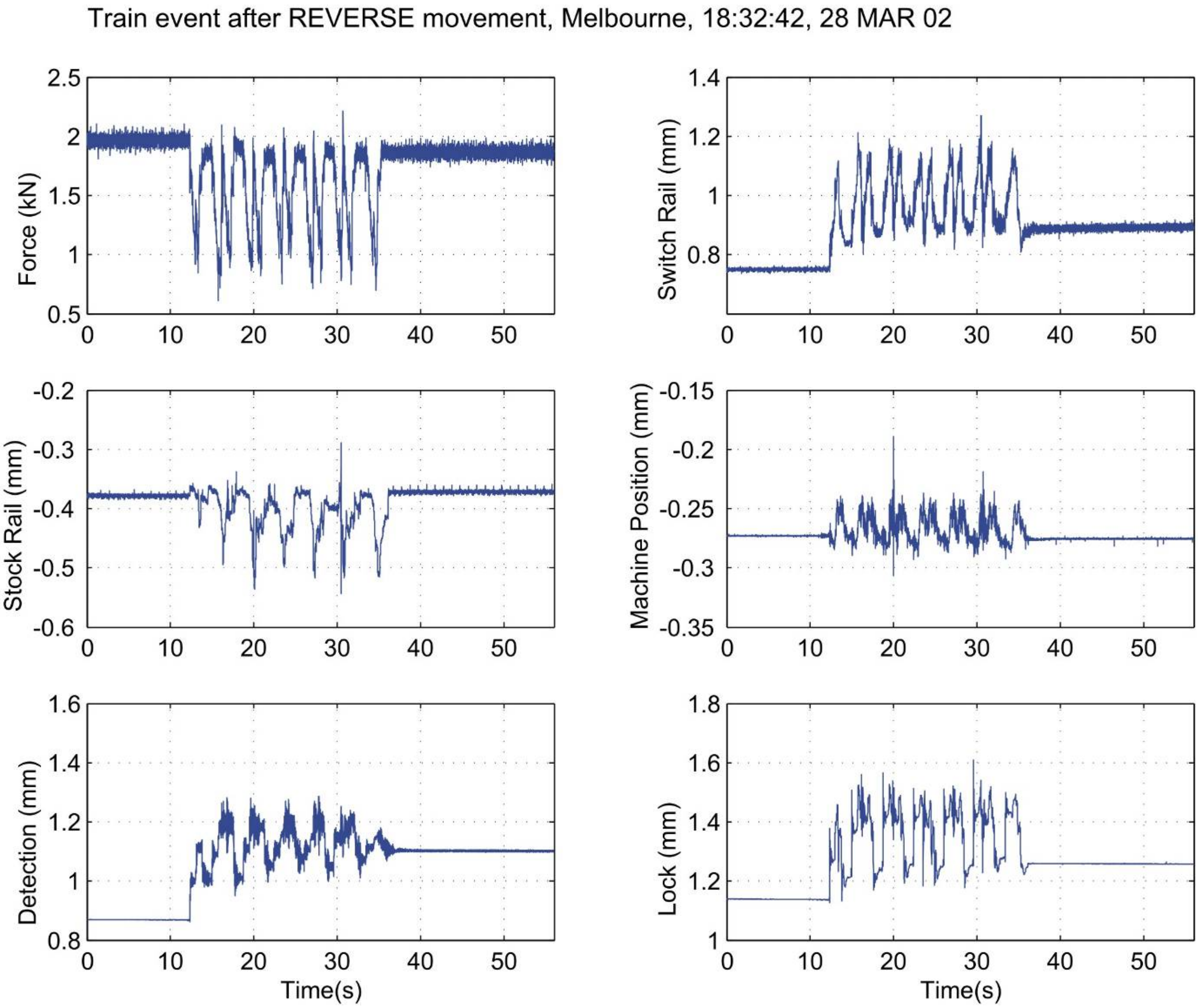

Figure 15. Train event sampled at higher speed (140Hz).