Crewe, A., Horseman, T., Dietz, M., Oddbjornsson, O., Dihoru, L., Kloukinas, P., ... Taylor, C. (2018). Development of a high channel count distributed data acquisition system for shaking table testing. In *Proceedings of the 16th European Conference on Earthquake Engineering* European Association for Earthquake Engineering (EAEE).

16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING THESSALONIKI
18 - 21 JUNE 2018

DEVELOPMENT OF A HIGH CHANNEL COUNT DISTRIBUTED DATA ACQUISITION SYSTEM FOR SHAKING TABLE TESTING

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ABSTRACT

Collecting data during shaking table tests is often challenging because the presence of the instrumentation and the associated cabling has the potential to affect the dynamic behaviour of the model. This is particularly true if the specimen being tested exhibits any form of rocking behaviour as any instrumentation cabling running between the rocking components has the potential to add significant undesirable stiffness across the joints. This issue has been encountered in some ongoing research at the University of Bristol investigating the seismic performance of Advanced Gas Cooled Nuclear Reactor Cores. To overcome the limitations associated with conventional systems, a distributed acquisition system has been developed. The new system is comprised of high sample rate, 32 channel simultaneous-sample-and-hold acquisition units (µDAQs) that are small enough to be embedded inside the model components. These µDAQs are then daisy-chained together with miniature flexible ribbon cable that provides power, synchronisation and network communication signals. Data are collected on the micro SD cards integral to each µDAQ and from which they can be uploaded once a test is complete. This paper gives an overview of the design of the µDAQ system followed by a demonstration of its capability. Theoretically, the maximum channel count of the µDAQ system is circa 14,000 (i.e. 63 strings each of 7 µDAQs each acquiring 32 channels of data) with a rate of 5,000 samples per second. It has the potential for use in other experimental programmes where high channel count, high speed, simultaneous-sample-and-hold, and minimal-wiring data acquisition is required.

Keywords: Shaking table; data acquisition; sensors

1. INTRODUCTION

Data collection during shaking table tests of specimens can be challenging for several reasons. In many cases a significant amount of instrumentation is necessary to capture the complete behaviour of the specimen. The data from this instrumentation then needs to be collected and this is usually done with some form of acquisition system placed remotely from the shaking table. Each sensor then requires a cable to supply power and return the signal to this acquisition system. For tests where the specimen is very stiff relative to the stiffness of the cables or sensors, the additional stiffness of the cables or sensors has an insignificant influence on the response of the specimen. However, where the specimen is sensitive to any changes in stiffness this type of instrumentation system is less appropriate. This is particularly true if the specimen being tested exhibits any form of rocking behaviour, as any cabling running between the rocking components has the potential to add significant undesirable stiffness across the joint, potentially changing the dynamics of the whole system.

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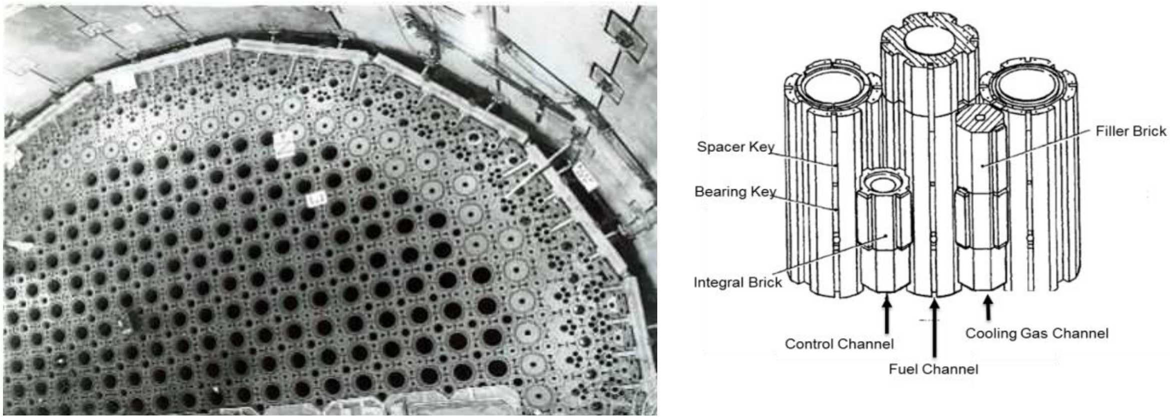


(a) (b)

Figure 1. Plan view of the actual graphite core (a) and the keying system between the components (b)

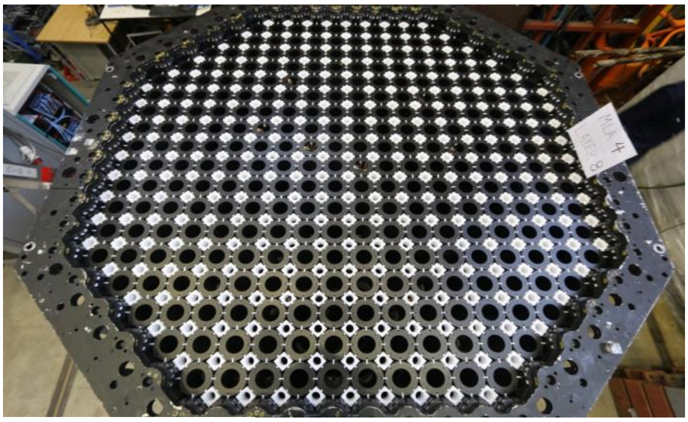
While wireless sensors (Rakicevic et al 2015) might be considered as a solution to this problem, having been used successfully for structural health monitoring, their use in a laboratory environment is more restricted. Reasons for this include the size of the resulting sensor package (which must include Wi-Fi hardware) and the need for a power supply to the sensor (requiring either a battery or connecting cabling). This means that wireless sensors are appropriate for shaking table use only when the geometry of the sensor and the specimen allow.

The challenge of instrumenting many rocking interfaces in the confines of a complex model has been faced in some ongoing research at the University of Bristol that addresses the seismic performance of Advanced Gas Cooled Nuclear Reactor (AGR) Cores (Dihoru et al 2011). In such cores, columnar stacks of precision-machined graphite components are used to sustain the nuclear reaction by moderating unbound neutrons. The geometry and mechanical properties of the graphite components change under prolonged exposure to neutron irradiation. To help understand the seismic response of degraded cores, a physical model has been created to enable measurement of the kinematics of multitudinous embedded components.

1.1 Physical model of an AGR core

The UK's AGR nuclear power stations have cores that consist of thousands of graphite moderator bricks interconnected through a graphite keying system (Figure 1a). The bricks are stacked in vertical columns so their bores can provide channels for the passage of fuel assemblies (within 'lattice' columns) and control rods (within 'interstitial' columns) along with coolant flow. The bores must remain vertical within tight tolerances so that the control rods and the fuel stringers have a secure and unimpeded travel. The vertical faces between neighbouring bricks are separated slightly to allow for thermal expansion during reactor operation. A radial keying system allows free radial movement of the bricks during thermal expansion and contraction of the surrounding steel structures, and acts to resist relative motion between bricks by providing reaction forces to lateral movement once the clearances between the keys and the keyways have been taken up (Figure 1b).

As AGR cores age it becomes necessary to consider ever-higher levels of graphite degradation. The capacities of the existing numerical models, GCORE (Kralj et al 2005) and SOLFEC (Bicanic & Koziara 2008), therefore needed to be extended to capture the behaviour of AGR cores with higher degrees of damaged graphite components. To validate the computer models and to enhance the understanding of core dynamics it was also recognized that seismic testing was needed, especially where components may behave in ways not adequately accounted for by the computational analyses. To this end a quarter-scale physical model of an AGR constructed from Acetal was developed by the University of Bristol to provide a facility for monitoring the kinematics of embedded components under a variety of degradation scenarios during seismic excitation (Dihoru et al 2017).

(a) (b)

Figure 2. View of the quarter-scale AGR model (a) and detail of the quarter-scale Acetal model components (b).

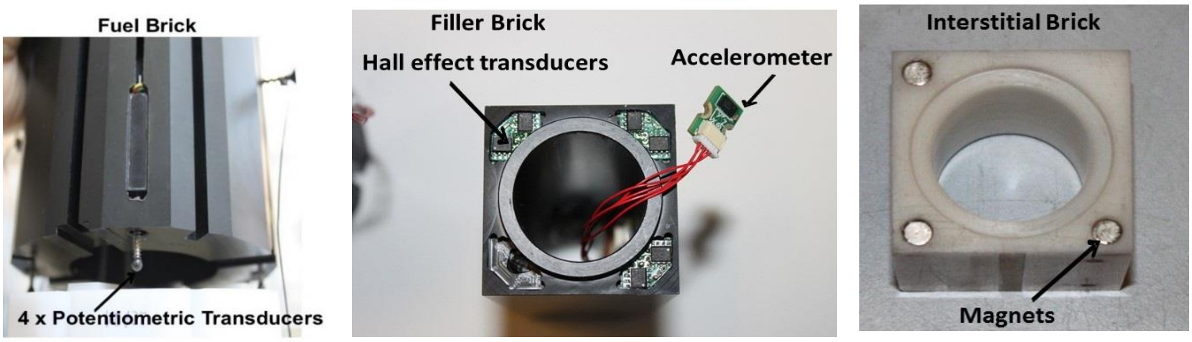
An overview and some detail of the of the quarter-scale model and constituent components can be seen in Figure 2. The contrasting scales of the physical model, epitomised by circa 440,000 components of which approaching 200 are instrumented and a 2.75m diameter with a minimum bore size of just 31.7mm, combined with a requirement to record circa 3,200 channels of sensor data highlights the scale of the challenge to experimental design.

1.2 Instrumentation Requirements

A key aspect of the validation of the numerical models of the AGR cores is the ability to assess the dynamic profiles of the lattice and interstitial channels during a seismic event. To achieve this, one must monitor the kinematics of the bricks inside the array. Assuming the bricks themselves to behave as rigid rocking bodies, the problem reduces to the measurement of the relative motions between vertically-adjacent bricks. A variety of instrumentation was designed to monitor the internal behaviour of the array (Dihoru et al 2015). Figure 3(a) shows the typical potentiometric transducers installed within a lattice brick. The lattice columns of the quarter-scale AGR model contains eight such bricks requiring a total of 32 sensors to measure the global behaviour. In addition to these sensors each lattice brick contains two triaxial MEMS (micro-electro-mechanical-systems) accelerometers, giving a total of 14 accelerometers installed in each lattice column. Figure 3(b and c) show prototypes of the two brick types that alternate to form the interstitial column. These bricks are smaller than the lattice bricks, a total of 14 bricks are needed to form a complete interstitial column in the quarter-scale model. Because full 6DOF (six degree of freedom) motion is possible between adjacent bricks it was necessary to employ a complex arrangement of 12 non-contact Hall sensors to measure the relative motions. Each interstitial column therefore requires a total of 156 such sensors to capture the global response. In addition to these sensors a total of 13 MEMS accelerometers are employed within interstitial brick motions. More details about the instrumentation in the model can be found in (Dihoru et al 2014).

Traditionally, sensor outputs would feed out of the specimen to remote signal conditioning and data acquisition systems. However, the bore diameters are simply too small to contain the volume of cabling that would be required to service such high numbers of sensors. Moreover, the stiffness of any such cables would also affect the dynamics of the model by modifying the global and local behaviour of the bricks which naturally exhibit a strong rocking behaviour. A better solution is for acquisition to occur locally to the sensors, with minimal cabling.

An additional requirement was the synchronization of the data acquisition system with other instrumentation installed outside the model reactor core such as traditional accelerometers to monitor the shaking table motion, an infrared camera system to record the displacements of infrared reflective markers on some of the bricks on the top layer of the array and a high resolution video camera recording images of the whole of the top of the array. The two camera systems can be seen in Figure 4.



(a) (b) (c)

Figure 3. Instrumentation in lattice brick (a), filler brick (b), and associated magnets in interstitial bricks (c)

1.3 Micro Data Acquisition System Design Requirements

To monitor even a relatively small number of columns in the reactor core model required a very high channel count data acquisition system that could be integrated into the components of the model reactor core. A bespoke Micro Data Acquisition System (µDAQ) was created to perform data acquisition inside the quarter-scale model. The main requirements in the design brief were:

- µDAQs must fit inside the smallest bore of the model (i.e. that of a filler brick - 31.7mm diameter, 149mm long).
- Bricks to be arranged in approximately 20 columns of 7 or 8 bricks, simultaneous acquisition across every brick and column.
- Digitise, simultaneously, approximately 30 analogue signals in each brick.
- Acquire at 5000 samples/s (5kSPS) with as great a resolution as possible and provide low-pass anti-alias filtering.
- Store the data to non-volatile memory, to prevent data loss in case of power supply interruptions.
- Connect to the outside world via the bottom of the column (so as not to inhibit operation of the camera systems).

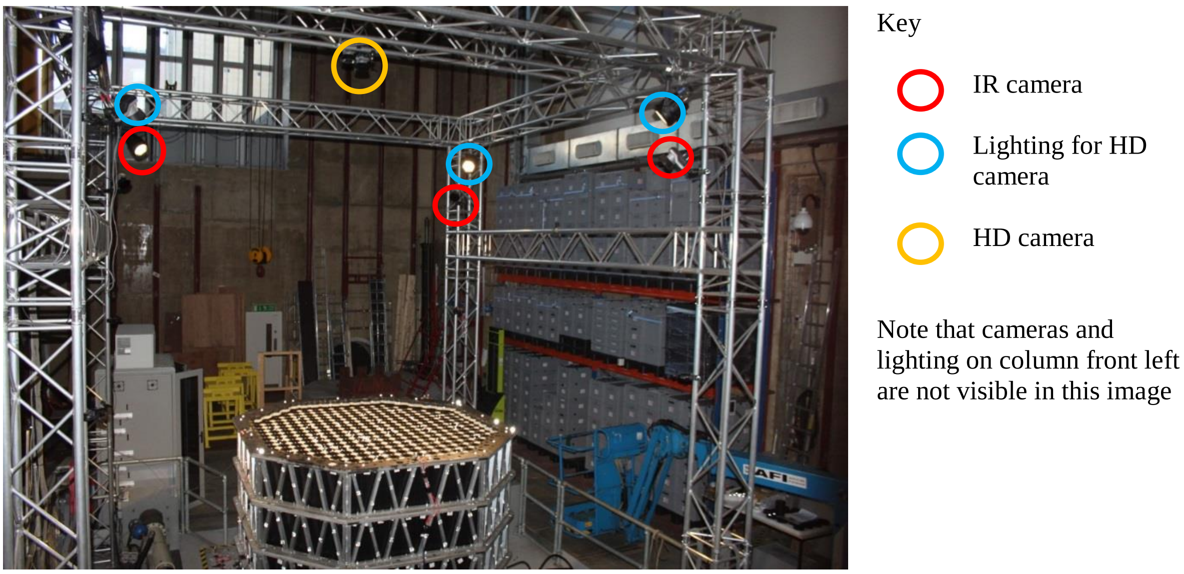


Figure 4. The quarter-scale AGR core on the shaking table surrounded by a gantry which supports the IR (infrared) and HD (high definition) camera systems

- Utilise cable of sufficient flexibility that it doesn’t significantly affect the dynamics of the experiment. Cable to provide power, control and communications.
- Be able to upload the stored data without physical intervention (bricks inside the array are not accessible during testing – only during build and dismantling).
- Provide power to the sensors in the brick – up to 20mA * 16 sensors at 5V.
- Be able to separate the bulk of the electronics from the brick for repair/upgrade.

Some of the key design decisions that followed on from this brief are:

- A small interface PCB was required to fit in the brick, containing the components for the power supplies for the sensors and a breakout area for connecting the cables from the sensors. The only connector that could be identified to join the µDAQ to the brick was a 36way PCIE end-launch, which required this brick PCB to include an edge connector.
- Micro SD cards are the only viable non-volatile memory option. Use of SD card is vastly simplified if a microprocessor/microcontroller is employed.
- A stack of multiple PCBs would be required, to provide sufficient area for (in particular) the smallest suitable low pass filters & multi-channel ADCs that could be found, and for the power supplies, (micro-) SD card and microprocessor required.
- Only the smallest of connectors would fit into the tiny space available.
- The power drawn by seven µDAQs coupled with the miniature connectors and cables necessary to fit within the space constraints required that a high voltage supply is employed with local efficient conversion to 5V/3.3V.
- CANbus was the only viable communications bus identified. Ethernet would be far preferable, but the bus topology required (multipoint to multipoint) made the use of Ethernet very challenging. RS485 would be adequate technically, but its lack of protocol could cause significant difficulty when transmitting large quantities of data.
- An FPGA was needed to interface the ADCs to the microprocessor, along with a buffer memory to account for the variable response time of the SD memory.

Based on the above a miniaturised 32 channel simultaneous sample and hold data acquisition unit was designed. A number of these units, one shown in Figure 5, can then be daisy chained using very small flexible ribbon cables (Figure 6) to form a very high channel count data acquisition system. While these units were designed specifically for the quarter-scale AGR testing they can also be used as a distributed data acquisition system for other types of dynamic tests.

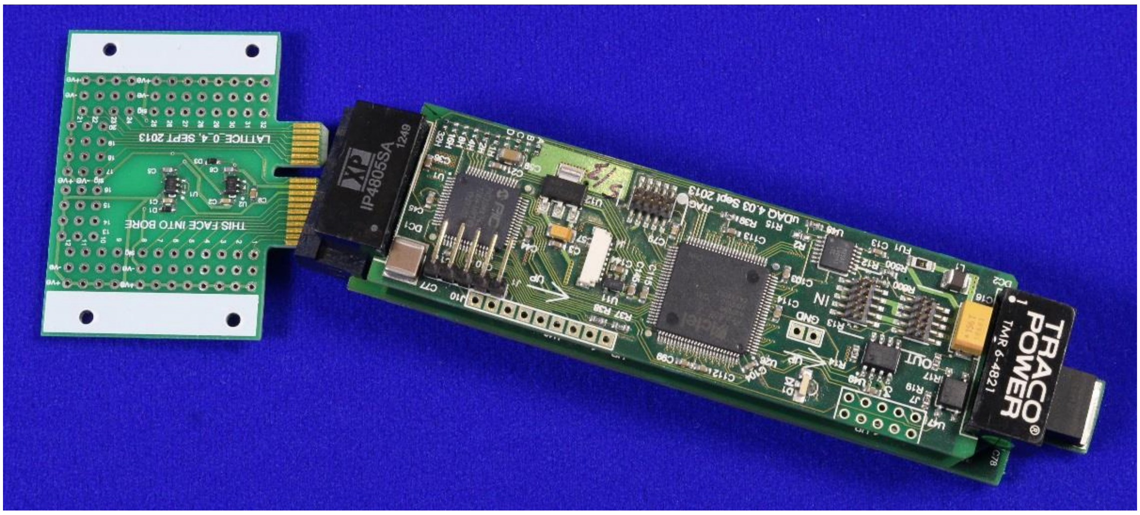


Figure 5. Miniaturized 32 channel simultaneous sample and hold data acquisition unit

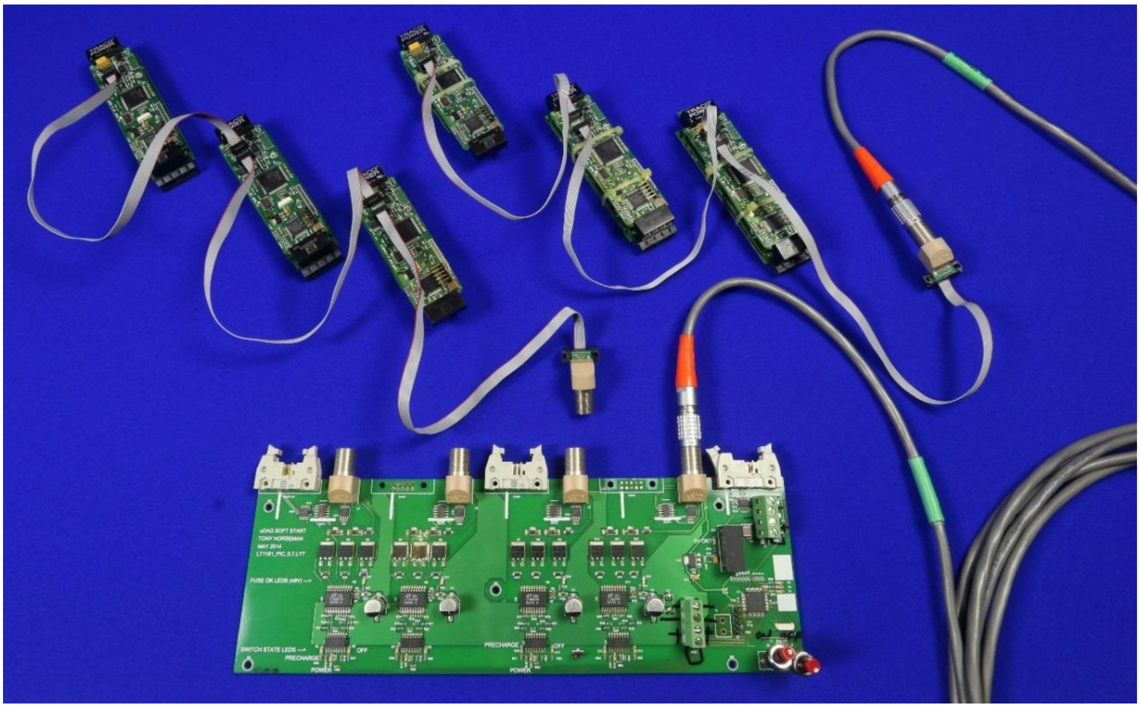
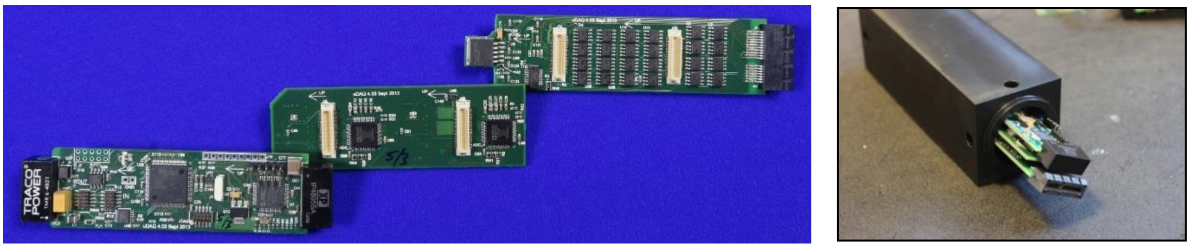


Figure 6. An example of a two strings of three daisy-chained µDAQs (this system can acquire 192 channels of data)

2. MINIATURIZED DATA ACQUISITION (µDAQ)

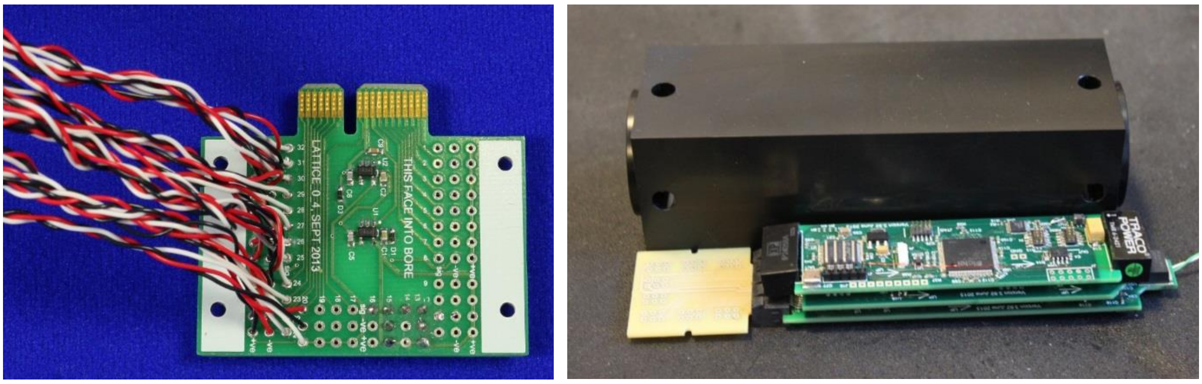
2.1 Physical design of the µDAQs

The biggest challenge faced in the design of the µDAQs for the AGR model tests was the very limited space available within the components in the specimen. The smallest component that would hold a µDAQ was a filler brick which had a cylindrical bore 31.7mm diameter and 149mm long. To provide sufficient PCB space for all required components a set of three PCBs (Figure 7a) were designed that stack together to form the µDAQ. The width of each of the boards was carefully designed so that the assembled µDAQ fits tightly within the bore of the filler brick (Figure 7b). This fit means that there is no chance of the boards coming apart during shaking. To connect the µDAQ to the sensors in the component the µDAQ is installed in, a sensor interface board is permanently installed in the component, with an edge connector to interface with the µDAQ. This interface board (Figure 8a) contains some limited circuitry to power the sensors, but mainly acts as a termination for the wires coming from the individual sensors in the component. The use of an edge connector connection between the interface board and the µDAQ (Figure 8b) means that the µDAQ can be removed from the component for software upgrades or for removal of the SD memory card for manual downloading of data, should the need arise.



(a) (b)

Figure 7. The three boards that form a single µDAQ (a) and µDAQ partially installed in a filler brick (b)



(a) (b)

Figure 8. A sensor interface board that will be attached to the brick (a) and a µDAQ and interface board beside a filler brick (b)

2.2 Overview of Implemented µDAQ Solution

The system developed comprises many small high speed 32 channel simultaneous sample and hold acquisition packages (µDAQs) which were embedded inside the model AGR components. These µDAQs were then daisy-chained together with small, and very flexible, ribbon cables that just provide power, synchronisation signals and network communication between the µDAQs. Each µDAQ collects data locally on an SD card and after one or more tests the data is downloaded from all the µDAQs for processing. The system has a theoretical maximum channel count of approximately 14,000 (i.e. 63x7x32) which would comprise 63 strings each of seven µDAQ boards (a total of 441 µDAQ systems) each acquiring 32 channels of data. For the current research project concerned with the performance of the AGR cores, a system comprising 138 µDAQ boards acquiring circa 3,200 channels of data has been deployed.

The interstitial and lattice columns in the core require strings of seven µDAQs connected to together to collect all the data. Each string is connected to an “end of column” circuit – this switches power on and off, distributes the sample clock (common across all strings) and routes the communications to a set of hardware from National Instruments. The µDAQs are controlled via messages issued from a bespoke user interface running on a PC which acts as the central hub.

The Graphical User Interface (GUI) is implemented and accessed through LabVIEW. The GUI acts through several NI Ethernet Expansion Chassis and 2-port CANbus modules to communicate with the µDAQ hardware. A rack of equipment provides power and power control to all the µDAQs, cable routing and sample clock generation and distribution. A schematic of the architecture can be seen in Figure 9.

2.3 Technical Details of the µDAQ Solution

One of the biggest challenges with the development of the system was the requirement to power all the sensors and the µDAQs through a small ribbon cable. To allow the use of a small cross sectional area cable, the main power input to the µDAQ is 48V. Locally, the 48V is used to generate the voltages required for the analogue and digital electronics, and the sensors. To cope with the heat generated by the µDAQ boards when deployed, forced air cooling was necessary during the experiments.

All the signals from the sensors need to be low pass filtered to avoid aliasing effects. Programmable hardware filters were specified for the project, 8^{th} order switched capacitor filters in 8-pin small outline packages were at the time found to be the best compromise of performance and size. The filters almost completely fill a circuit board of the maximum size that could be accommodated (Figure 7a, top). These are accompanied by four 16-bit, 8-channel ADCs.

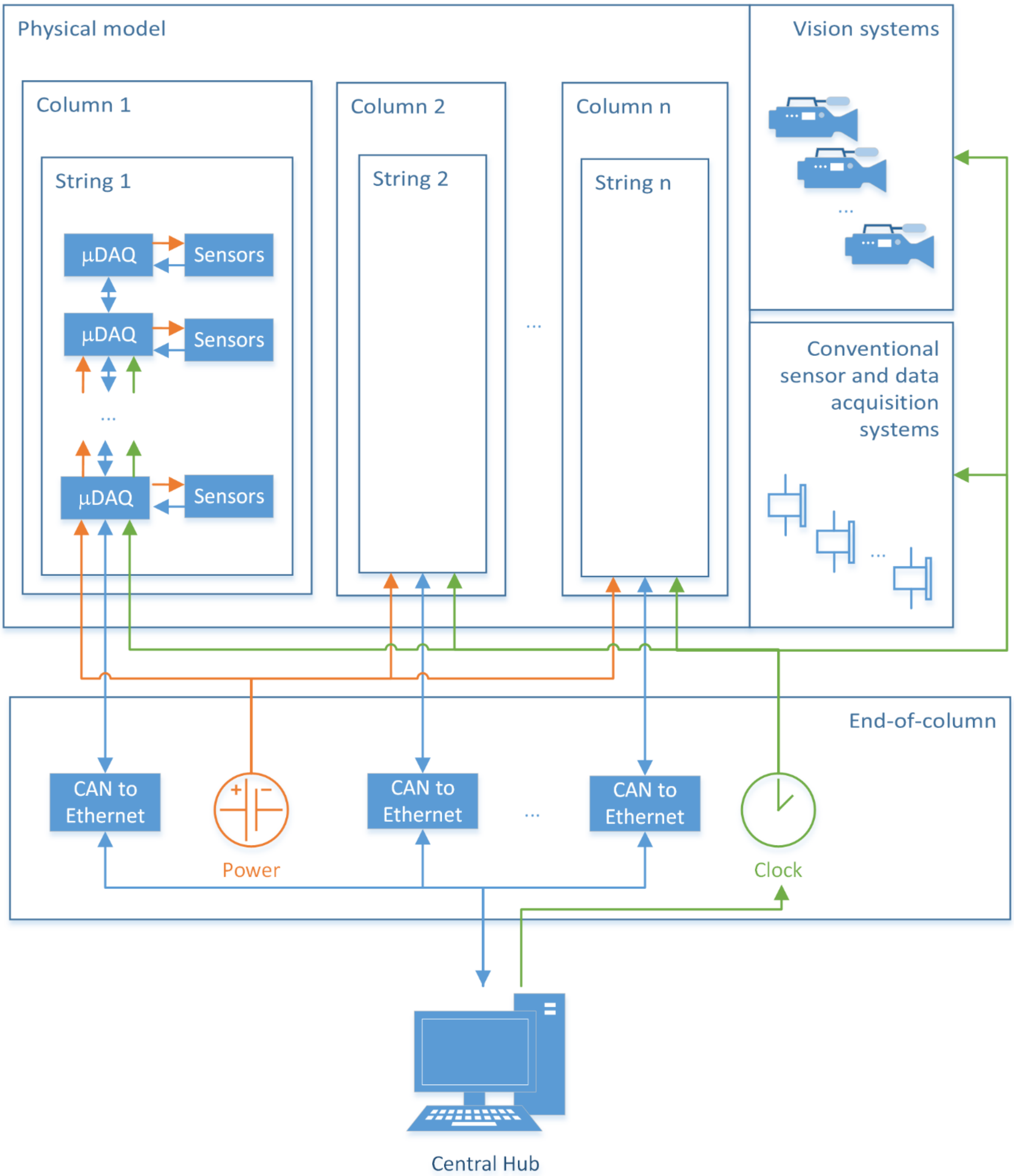


Figure 9. µDAQ system architecture

As the reading of the ADC is time critical, and to simplify the software in the microprocessor, a field programmable gate array (FPGA) is used to read the ADCs when the data is available, and buffer this data until the microprocessor and flash memory are ready to accept it.

Both control of the µDAQs and data upload is accomplished using the CANbus. A central hardware hub sends messages as determined by the GUI, to acquire data, upload, delete stored files etc. The µDAQs send data from the SD cards over the CANbus and this is reconstituted by the GUI into files on the PC hard disk drive.

Figure 10. End of column hardware that distributes power and timing signals to the strings of

Adjacent to the shaking table, on the solid floor of the laboratory, is a rack of hardware constructed to interface with the µDAQs (Figure 10). The enclosures contain power supplies to power the all µDAQs, the clock generator, and the National Instruments chassis/modules. User power controls are located on the front panels, and high quality Lemo connectors allowing high quality screened cable to be used for the first five metres before a transition to miniature ribbon cable at the bottom of each column in the experiment.

3. USER INTERFACE

The LabVIEW environment coupled with the National Instruments hardware offered a low-risk solution to the challenge of implementing a Graphical User Interface (GUI) to operate the µDAQs. An array of possible connected units offers the users control over which are included in the current operation, and the colour of that element of the array conveys the state of the µDAQ in question (idle, acquiring, uploading and so on). Behind the GUI is a substantial quantity of code to carry out the user's instructions and to format the received data as it is uploaded from the µDAQs. The same GUI also controls the clock generator, to select the run-time of the next experiment and to start the acquisition clock. For simplicity of structure, the clock is also controlled over CANbus.

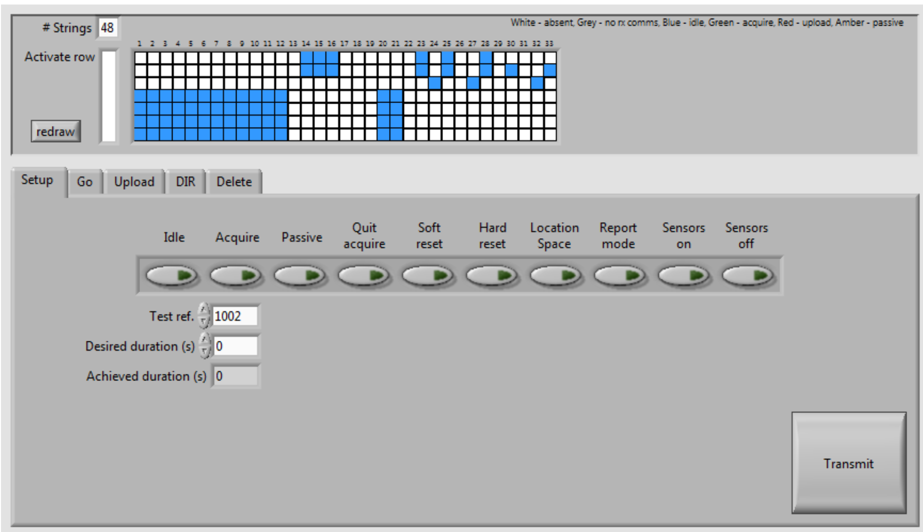


Figure 11. Graphical User interface

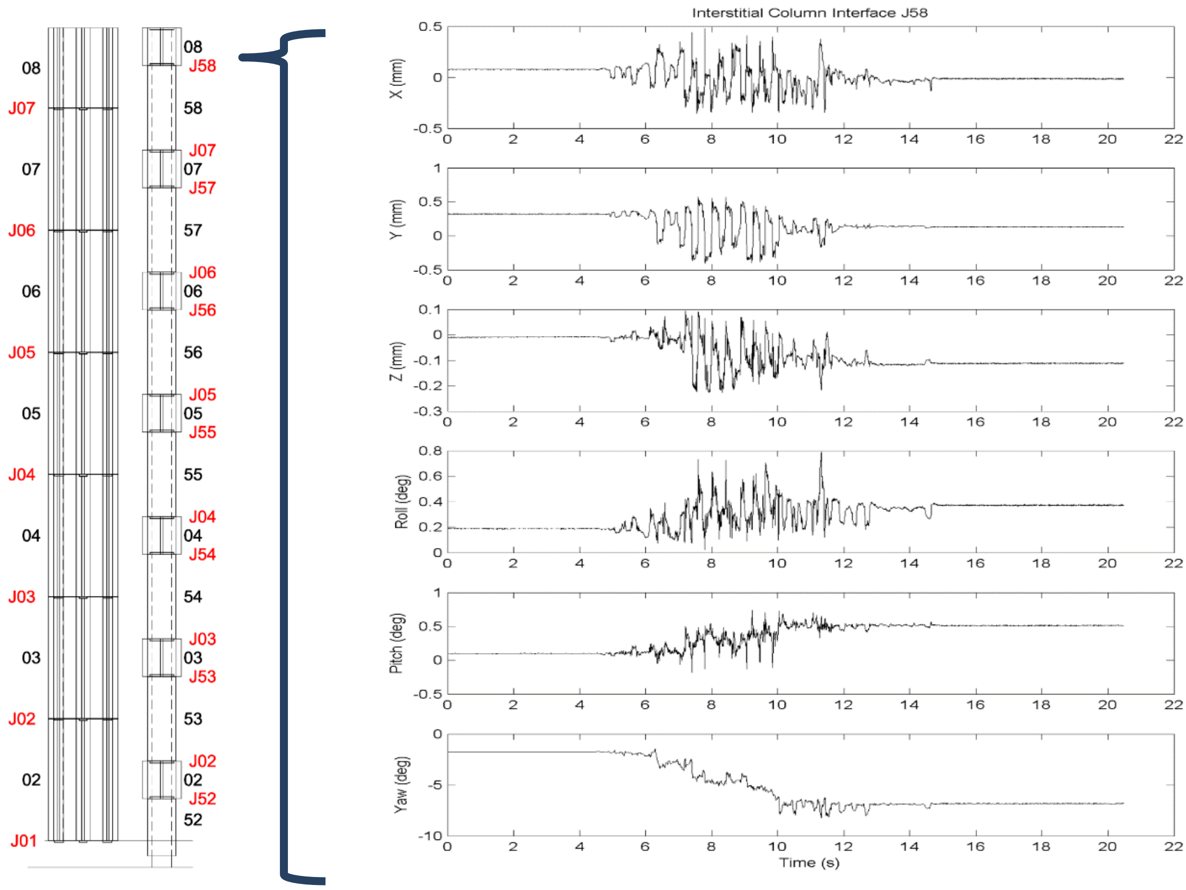


Figure 12. 6DOF interface data for one of the 13 interfaces in an interstitial column

4. PERFORMANCE OF THE μDAQ SYSTEM AND TYPICAL DATA COLLECTED

The μDAQ system deployed on the research project concerned with the performance of the AGR cores comprised 138 μDAQ boards acquiring circa 3,200 channels of data. For each of the 9 AGR test configuration investigated around 300 seismic tests were completed, in a variety of excitation directions, with peak table accelerations ranging from 0.2g to 1.2g. During the tests the μDAQ system generally performed very well but there were a few cases where an individual μDAQ failed to record data during some of the tests at higher excitation levels. The failures of the μDAQs were a result of the connectors between boards working loose due to the very high impact forces (>10g) between the AGR components that the μDAQs were housed in. In this particular application it was not possible (because of space) to use latching connectors, but modifications to use such connectors would make the system more robust for other applications.

An example of some of the processed sensor data collected with this system for a single interface is shown in Figure 12. This interface data can then be processed into column distortion information (Figure 13) which presents a typical maximum deflection envelope for one representative lattice column and one representative interstitial column. A lattice column in the experimental rig consists of a stack of seven components, six lattice bricks and one shorter hybrid lattice brick at the top of the stack. Horizontal movements at the lattice to lattice brick interfaces are eliminated by keying the two bricks together while still allowing rotations. An interstitial column in the experimental rig consists of a stack of fourteen components, a fixed hybrid filler brick at the bottom with seven interstitial bricks above spaced out by filler bricks. Horizontal movements of the thirteen filler to interstitial brick interfaces are restricted by spigots allowing small horizontal translations and unrestricted rotations at the joint. For both types of columns, the channel profiles show increasing levels of deflection as the input acceleration increases. The columns behave largely like beams restricted at the bottom, with maximum deflection recorded at or towards the top of the array.

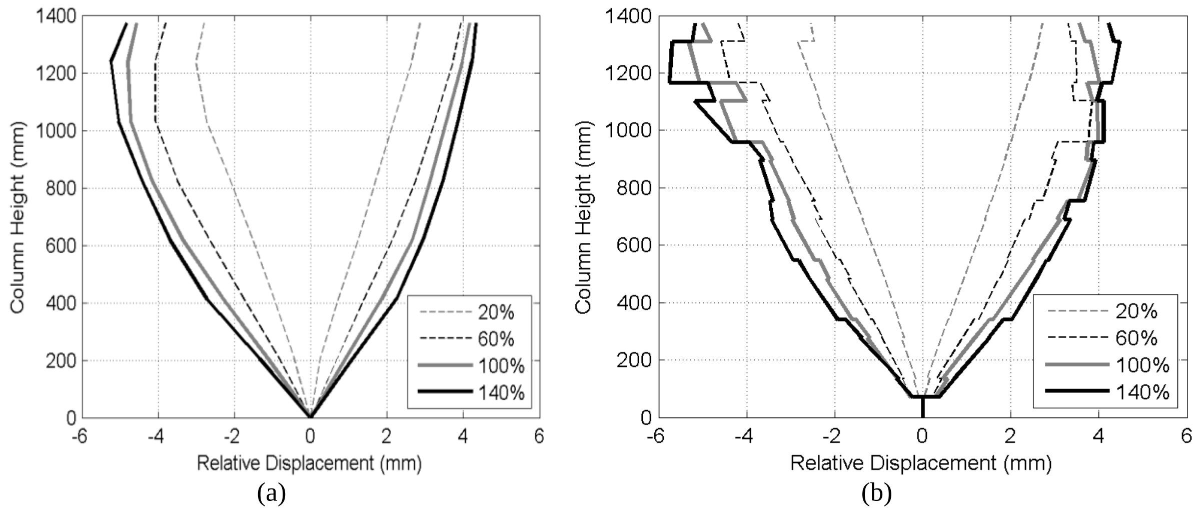


Fig. 13 – Maximum deflection envelopes for (a) a typical lattice column, (b) a typical interstitial column

5. CONCLUSIONS

The novel measurement system introduced herein has been designed and built to meet the challenge of measuring the kinematics within the confines of a scaled AGR core model. Comprised of networks of miniaturised data acquisition units that are themselves distributed throughout the model, the system combines high speed and high channel count data acquisition with a requirement for minimal wiring. For applications where the cabling required by a conventional measurement system would affect the measured phenomena, this system provides a useful alternative when physical restrictions preclude the implementation of wireless sensor technology.

6. ACKNOWLEDGMENTS

The authors would like to thank EDF Energy for financial and technical support. The views expressed in this paper are those of the authors and do not necessarily represent those of EDF Energy.

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