High-density data acquisition system and signal preprocessor for interfacing with microelectromechanical system-based biosensor arrays

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Microelectromechanical system (MEMS) development has become an active area for research in the last decade. This area has advanced rapidly in recent years due to the potential ability of MEMS devices to perform complex functions in a smaller area. There is also the prospect to develop devices that can (1) be easily manufactured, (2) offer low power consumption, and (3) reduce waste. Especially in the BioMEMS area these advantages are important in terms of applied devices for biosensing, clinical diagnostics, physiological sensing, flow cytometry, and other lab-on-a-chip applications. However, one major obstacle that has been overlooked is the interface of these microdevices with the macroworld. This is critical to enable applications and development of the technology, as currently testing and analysis of data from these devices is mostly limited to generic microprobe stations. New advancements in BioMEMS have to occur in concert with the development of data acquisition systems and signal preprocessors to fully appreciate and test these developing technologies. In this work, we present the development of a cost effective, high throughput data acquisition system (Bio-HD DAQ) and a signal preprocessor for a MEMS-based cell electrophysiology lab-on-a-Chip (CEL-C) device. The signal preprocessor consists of a printed circuit board mounted with the CEL-C device and a 64-channel filter/amplifier circuit array. The data acquisition system includes a high-density crosspoint switching matrix that connects the signal preprocessor to a 16-channel, 18 bit, and 625 kS/s DAQ card. Multimodule custom software designed on LABVIEW 7.0 is used to control the DAQ system. While this version of the Bio-HD DAQ system and accompanying software are designed keeping in view the specific requirements of the CEL-C device, it is highly adaptable and, with minor modifications, can become a generic data acquisition system for MEMS development, testing, and application. © 2007 American Institute of Physics. [DOI: 10.1063/1.2722420]

I. INTRODUCTION

Microelectromechanical systems (MEMSs) have seen great advancement over the last 30 years. Part of the rapid growth in this area can be attributed to their potential for mass production due to the existence of manufacturing facilities in the microelectronics industry. Researchers have been adapting and modifying established processes from the semiconductor industry to fabricate complex structures on a substrate (e.g., silicon), which can act as detectors, sensors, and actuators. Since its inception as a primary research area in the 1970s, we have seen commercial products based on MEMS devices in the mid-1990s such as inkjet printers and accelerometers. MEMSs for applications in biology and medicine (BioMEMS) have evolved into a broad research area. BioMEMS can be manufactured in a similar fashion to MEMS. They bring with them the advantages of low power consumption, less sample waste, smaller analysis times, and enhanced sensitivity due to their smaller size and cost effectiveness because they can be mass produced. Areas of research and applications in BioMEMS include diagnostics such as DNA and protein microarrays, novel materials, mi-
microfluidics, pathogen detection, biosensing, and physiological sensing. Recent developments in BioMEMS include a portable microchip capable of performing polymerase chain reaction (PCR) on a 1 μl sample volume, rapid detection of low number of food pathogens using dielectrophoretic cell concentration, real time monitoring of morphological changes in living cells by electronic cell sensor arrays, and development of lab-on-a-chip systems for single cell studies to name a few.

Given the tremendous potential of these devices and technologies, BioMEMS are now being invented at an amazing pace. Despite this fast pace, testing and application development for these devices is hindered due to limitations in systems that can fully interface with MEMSs in a functional and practical way. As we progress forward towards miniaturizing complex bulky systems into microchips, parallel development in interfacing and testing equipments is also necessary to realize the full potential of such novel devices. In many cases, the devices have to be tested on probe stations to validate proof of concept but this does not afford full parallel testing of the entire microdevice. Currently there are no configurable and adaptable platforms that can be used to fully test these devices. Our goal is to develop a platform that can satisfy this requirement. We also hope to facilitate the adoption of MEMS-based biotechnology for use by nontechnical personnel, in applied research laboratories. In order to facilitate this, the interface needs to be easy to operate with intuitive software controls. The promise of these technologies is that large amounts of previously unavailable data can be collected and analyzed. This will encourage adoption and use of these systems in basic research laboratories where they can be used as tools for discovery. This means that we need to be able to store, manipulate, and analyze large data sets. In such cases, it would be convenient to have a single package for data acquisition and manipulation with simple controls.

Other considerations for interface development include data conditioning by removing undesirable effects such as periodic noise, cross talk, and thermal effects. Similar considerations can be seen in dedicated DAQ systems developed for specific applications. One such system includes multi-channel signal processing and data acquisition for measurement of plantar pressure. Data acquisition of transcellular ion currents through patch clamping is used for making single channel recordings, and advanced data acquisition is also used in fluorescence detection in lab-on-a-chip applications.

In our laboratory, we are actively engaged in innovation of BioMEMS for physiological sensing along with technology development for interfacing infrastructure. In addition to the development of MEMS-based sensor arrays for cell physiological analysis, we report the development of a generic adaptable high-density data acquisition system (Bio-HD DAQ) for interfacing with potentiometry based MEMSs. While our area of interest has been in biological MEMS devices and applications, this system can be used to fully implement and test a broad array of other MEMSs. We have implemented a 16-channel, 18 bit, 625 kS/s DAQ with a high-density crosspoint switching matrix to acquire data from a MEMS array. A 64-channel amplifier and filter circuit was constructed on a printed circuit board (PCB) using inexpensive, low-noise, and low-drift operational amplifiers for signal preconditioning. Customizable LABVIEW 7.0 scripts were used to control the switching matrix, data acquisition and act as a human-machine interface.

II. MATERIALS AND METHODS

A. The overall system

Our goal in this work is to develop a high-density, low-cost, and high throughput signal preprocessor and DAQ system. This novel system was used to interface with our MEMS-based cell electrophysiology lab-on-a-Chip (CEL-C). The CEL-C biochip consists of 16 pores on a chip with four Ag/AgCl electrodes leading into each pore for a total of 64 electrodes. The electrodes are coated with a calcium ion selective membrane. As a result, they will respond only to a change in the calcium ion concentration with a change in the Nernst voltage. Figure 1 illustrates the overall system that was developed in our laboratory and used for a NASA microgravity flight experiment. The system consists of the CEL-C device in the center wire-bonded onto a custom PCB. Surrounding the CEL-C device are 64 operational amplifiers that serve as noise filters, each one serving a single electrode on the CEL-C chip. The operational amplifiers also amplify and precondition the measured signal for further processing by the Bio-HD DAQ system. This PCB is then interfaced to the DAQ system that processes and manipulates the measured signals based on our needs. The Bio-HD DAQ is controlled by a customized program created in LABVIEW 7.0. The software was designed for ease of operation and performance and includes a user friendly interface.
Based on the Nernst equation for Ca\(^{2+}\) ionic activity, the potential difference observed is approximately 28 mV for every decade change of the ionic concentration. Therefore, it is extremely important to verify the sensitivity of the Bio-HD DAQ unit as it dictates the overall sensitivity of our system. By using an 18 bit DAQ card (details in next section), the Bio-HD DAQ system has 2\(^{18}\) quantization levels of resolution operating over a voltage range from −10 to 10 V. This gives us a resolution for the DAQ system of 76.3 \(\mu\)V for the amplified signal. The corresponding potential measured by the electrodes would be 6.94 \(\mu\)V as the operational amplifier circuit has a gain of 11 (detailed on the next page). This is the theoretical sensitivity of the DAQ.

The response time of the DAQ dictates the ability to detect and isolate rapid biological phenomena. At the same time, if the phenomenon is known to be slow, it becomes unnecessary to acquire data at a very high rate as that would result in too much data. To account for this, the software has multiple modes and multiple options to select the quantity of data recorded. First, consideration is given to the limitations of the device. The DAQ can sample data at 625 kS/s. The switching matrix has a maximum cycling speed of 2000 cycles/s. The switching matrix limits the DAQ to reading eight channels of data in parallel. If required to read all 64 electrodes at its fastest speed, the Bio-HD DAQ can complete one cycle in 4.02 ms. However, for faster operation, the Bio-HD DAQ can read data from eight electrodes in parallel at 625 kS/s. This equates to a data point every 1.6 \(\mu\)s for each of the eight electrodes. As seen in Fig. 9, the response speed of the CEL-C device is pretty slow. So, the Bio-HD DAQ was programmed to read samples at 1 kS/s. In this case, a complete cycle takes 12 ms to complete. Care was taken to ensure that real time programming techniques were implemented so that the speed of data acquisition is not limited by the computer hardware. The MXI-4 interface between the DAQ and the computer supports a maximum consistent data transfer rate of 78 Mbytes/s. The maximum data transfer rate required by the Bio-HD DAQ is 11.25 Mbytes/s which is well within the limitations of the interface.

It is desirable to electrically isolate the sensor device from the external DAQ system with a high impedance buffer. Also, given that we are measuring an extremely small voltage, preamplification is necessary to be able to distinguish between different biological events measured with the CEL-C device. With the amplified signal, it is easier to observe and analyze various trends over the course of the experiments. The amplified signal is also less susceptible to noise as the magnitude of the signal becomes larger than that of impinging noise. As can be seen above, the design should allow for the amplifier to be physically close to the electrode. This minimizes the addition of noise prior to amplification. The design should also include a very low noise amplifier circuitry. A noninverting amplification system was designed on a custom PCB (manufactured by Advanced Circuits, CO) for the CEL-C device to achieve the above mentioned criteria.

The amplifier circuit must be simple so that it can be replicated in an array form to connect to each electrode on the CEL-C device. This allows us to amplify the signal from

![Image](https://example.com/image.png)

**FIG. 2.** The amplifier circuit built for signal preamplification for each electrode on the CEL-C device. The amplifier is wired in the noninverting configuration. The MAX 437 precision operational amplifier has low noise and low thermal drift associated with it. The dc gain of the noninverting amplifier is \((\text{dc gain}=1+R_2/R_1)\). \(R_1 (R_1)\) is 2.4 kΩ and \(R_2 (R_2)\) is 24 kΩ yielding a dc gain of 11. The capacitors \((C_1, C_2, \text{and} C_3)\) are all 1 \(\mu\)F and act as noise filters and bypass capacitors. \(V^+\) and \(V^-\) are +10 and −10 V, respectively.

**B. Hardware**

1. **Signal preconditioning/preamplification**

The signal generated by our CEL-C device is the membrane potential across an ion selective membrane spray coated on the electrodes of the CEL-C device. Such a device will convert the Ca\(^{2+}\) concentration in a solution into a potential difference across the membrane, measured by the electrodes on the CEL-C device. In other words the electrochemical ion concentration dependent process develops a measurable dc potential. Before designing the preprocessor and the DAQ system, it is crucial that we know the characteristic signal of the CEL-C device. Initial experimentation illustrated that there is a base offset for each of the 64 electrodes in the range of −400 to −600 mV. This variation is attributed to the fact that during metal deposition of the CEL-C device fabrication process, there is a slight variation of deposited metal surface area on the wafer. This results in a slight variation in the half-cell potentials for the individual electrodes. Additionally, the ion-selective membrane coated on the electrodes prior to the measurements is not equally distributed on every electrode.

The factors which were of utmost importance in designing our system were signal sensitivity, response time, and noise reduction. This version of the Bio-HD DAQ system is based on the CEL-C device, which measures transcellular Ca\(^{2+}\) ionic currents around single cells, and is fundamentally governed by the Nernst equation. This potential of each electrode is on the order of 500 mV. Another important signal in terms of its biological significance is the potential difference measured between any two electrodes, and this ranges between tens of microvolts to tens of millivolts at any time.
each electrode in parallel. It must also have an output range that does not exceed the capacity of the DAQ system so that the signal can be accurately processed. Keeping these criteria in perspective, the amplifier circuitry was designed as depicted in Fig. 2. The circuit is configured in the noninverting amplifier mode. The expected maximum input to the amplifier is 0.9 V and a maximum of 10 V can be read by the DAQ system. With these limitations, the dc gain of the amplifier circuitry was set to be 11. This was done by choosing the feedback resistance ($R_f$) to be 24 kΩ and the input resistance ($R_i$) to be 2.4 kΩ ($gain = 1 + R_f/R_i$). The amplifier system consists of 64 such circuits arranged around the CEL-C device on a PCB, each serving one electrode of the device. The amplifier system is placed as close as possible to the CEL-C device to reduce the noise coupling from antenna effects, parasitic resistances, and stray capacitances. The initial idea was to have the CEL-C device on the same PCB as the operational amplifiers in order to reduce the distance between each electrode and the operational amplifier. However, for cost consideration, a master amplification PCB was built with the operational amplifiers and other accessories. A PCB with the CEL-C chip mounted on it is interfaced with the amplification PCB. This configuration also served our purpose very effectively and did not have any significant impact on the noise introduced into the system.

The operational amplifier chosen for the amplifier circuit in Fig. 2 was the MAXIM MAX 437 precision operational amplifier. This operational amplifier has a very high input impedance of 7 GΩ. Also, this precision operational amplifier has a low gain-bandwidth product and the gain is seen to attenuate beyond 100 Hz. In addition to this, the operational amplifier has a very low noise of 4.5 nV/√Hz at 10 Hz. Since the operational amplifier is the only active device between the chip and the DAQ, the most noise can be expected to be originating at the operational amplifier and a very low noise operational amplifier would help us reduce system noise. Also, as it is a low bandwidth operational amplifier, noise at higher frequencies is filtered out reducing total system noise. In comparison to other devices, such as commercial accelerometer devices which have a noise spectral density of 125 μV/√Hz, this operational amplifier demonstrates extremely low-noise characteristics. Also the thermal drift of this operational amplifier is only 0.8 μV/°C. Such low values of characteristic noise and thermal drift prevent the addition of extensive correction circuitry which is of great importance to our work since it reduces the area of the PCB.

Other noise reduction techniques were also employed to further eliminate noise from the overall system. Bypass capacitors were used between power and ground rails to minimize the inherent ripples in the circuit as existence of ripples is detrimental to the performance of the operational amplifiers. Also a 1 μF capacitor was connected across $R_i$ in Fig. 2. This $RC$ circuit serves the purpose of a first order low pass filter, i.e., it removes the high-frequency noise from the signal prior to amplification. Once the signal is amplified, the impact of external noise would only be around 10% of its initial value. Figure 3 illustrates the gain bandwidth plot of the amplifier’s frequency and phase response.

After employing these noise reduction mechanisms, we tested the noise impact of the overall system by performing the input-referred noise measurement. For this, the input of the amplifier was connected to ground and the spectral density of the output was captured using a HP 35670 signal analyzer (Agilent Technologies, CA). From the spectral density plot in Fig. 4 we can see that the typical inherent dc noise in the system is measured to be 2 μV/√Hz at 100 Hz. From these data, we estimated the error in measurement to be approximately 1 μV. Given that the resolution of the system is 76 μV, we can be assured that the low system noise will not impact the overall performance.

2. The Bio-HD DAQ unit

Figure 5 illustrates the basic process flow of the Bio-HD DAQ unit and its different connections. The central part of the Bio-HD DAQ unit is a PXI-6289 DAQ card (National Instruments, TX) which is an 18 bit, 625 kS/s DAQ with eight pairs of analog to digital (A/D) units. Since the CEL-C device generates 64 dc inputs, a switching matrix was required to accommodate all the signals. Also, in the dual electrode differential coupling (DEDC) mode (described in next section), the potential difference between any two different electrodes within a single pore on the CEL-C device is measured. Ninety-six such combinations of potential differences are possible over the entire chip and this is also addressed by the switching matrix design. A PXI-2532 switching matrix (National Instruments, TX) was selected to serve this purpose in the Bio-HD DAQ unit. The switching matrix is then connected to the amplification board via a SCB-264x connector block (National Instruments, TX). The SCB-264x connector block is also used to route the selected signals from the switching matrix to the DAQ system. A SCB-68 connector block (National Instruments, TX) acts as an adapter between the SCB-264x and the DAQ. Finally, a TB-2644 terminal block (National Instruments, TX) is used to configure the PXI-2532 512-point crosspoint matrix into a dual one-wire 8 × 32 configuration allowing eight differential signals to be read at once. This was accomplished by splitting the 64 inputs into two sets of 32 and 4 differentials can be read from each of these halves (required for the DEDC mode). To reduce cross talk, all inputs are connected to ground through 56 kΩ resistors in the terminal block. The switching matrix and the DAQ card are placed inside a PXI-1031 chassis (National Instruments, TX), separate from the computer, to reduce external noise. These are connected to the computer through PCI/PXI-8331 connectors (National Instruments, TX). All connectors are shielded as far as possible to reduce coupling of external noise.

The DAQ system can be completely controlled from the computer. The switching matrix is configured from the computer using the terminal block so as to choose four pairs of electrodes from each half of the chip. These eight pairs are then routed through the connector block to the DAQ that samples the data and transmits these data to the computer for storage and analysis.

C. Software

A customized program was developed to control the switching matrix, process, store, and measure data from all
64 electrodes, and also provide a user friendly environment to display and manipulate data in real time. LABVIEW 7.0 was chosen to develop custom modules for data acquisition as it is easily interfaced with the data acquisition hardware. Four main software modules were developed to address the most common requirements of our overall goals as described below.

1. **Calibration mode**
   This is the first and basic mode in which the Bio-HD DAQ unit is operated. In this mode the potential of each electrode on the CEL-C device is recorded in response to varying concentrations of calcium ion solutions. The number of solutions used and the number of runs performed per solution can be adjusted as required. A greater number of solutions give a clearer indication of the Nernst slope while a larger number of runs are used to verify the consistency of the electrodes. This mode allows us to determine the Nernstian response of an individual electrode, which demonstrates the sensitivity of each electrode towards a changing concentration of calcium ions.

2. **Picture mode**
   A “picture mode” was developed to allow users to discern activity at the various electrodes pictorially. This is achieved by representing the 16 pores of the CEL-C chip with 16 circles and the 4 electrodes of each pore as four squares surrounding this chip. The color of these squares changes with the potential difference observed by the electrode. A strong positive potential is represented by red while a strong negative one is represented by green. Zero potential is represented by mint green. This color coding allows users to identify activity in the pores. This mode is relatively slow to allow for switching and was developed to provide an easy to understand interface for the user to pinpoint indispensable physiological events. In this case, no data are written to an external file.

3. **All differential mode (dual electrode differential coupling mode)**
   Signals such as the transcellular ion currents being measured by this device often have large offsets that overwhelm the more relevant data. The removal of these extraneous offsets would not only allow for easy assimilation of the biologically relevant data but also opens up the possibilities for greater amplification of the signal of interest. Keeping this in mind, we have developed a novel technique to operate the ion sensors within the CEL-C device called the DEDC method. Earlier, electrode potential was measured against a standard Ag/AgCl reference electrode. Instead, the DEDC...
mode couples pairs of electrodes and measures the potential difference between them, thus eliminating the base line offset while stressing the concentration gradient. With DEDC, the reference is not used for the measurement of potential; instead, one working electrode is used as the reference for the other. A Ag/AgCl reference electrode is used, however, to ground the system to the solution.

The DEDC technique was tested experimentally on glass electrodes. Two glass electrodes with the same offset and Nernst slope were connected to a head-stage amplifier. Calcium solutions of 0.1, 1, and 10 mM were placed in separate beakers connected by salt bridges. The electrode in the reference position was placed in one beaker while the working electrode was moved between the different dishes. As seen in Fig. 6, we can see that the typical Nernstian offset is no longer measured. In fact, the output is autozeroed when both the electrodes were in the same beaker. Figure 6 depicts the Nernst slopes of the DEDC mode operated on glass electrodes.

The “all differential” module is used to operate the electrodes in the DEDC mode. An offset function in the module zeros out the base line potential difference recorded by each electrode on the CEL-C device. Once this is performed, the four electrodes in each pore of the CEL-C device can be configured as two pairs of differentially coupled electrodes to acquire the biologically important potential difference. The signal is viewed in real time and the electrode combination can be changed at any time during the course of the recordings which can record data continuously for more then a period of 24 h.

4. Polar diff 2 cells

This module also operates the electrodes in the DEDC mode. The mode allows the user to continuously monitor
eight programed differentials for two different cells in two separate pores. The specific DEDC electrode pairs can be customized and the DAQ can accommodate eight differentials without any switching. This mode allows users to run experiments in real time, without the limitation of the slower switching matrix. The speed of data acquisition in this mode is limited only by the speed of the data acquisition system.

As described in Sec. II B above, the response time of the Bio-HD DAQ in each mode is easily calculated. The calibration, picture, and all differential modes take 12 ms each to completely read all outputs once. The “polar diff 2 cell” mode can read a data point for each of eight channels in 1 ms.

III. MEASUREMENTS AND RESULTS

The data acquisition system is shown to be well suited for measuring small signals. In Fig. 7, a 1.2 mV<sub>p-p</sub> periodic signal is applied to the data acquisition system. The strength of the signal in microvolts is displayed pictorially in the picture mode window in the foreground. In the background, a “polar diff 2 cells” window displays the top-left differential for pores 1 and 16. Data are averaged over 100 ms and displayed over a 5 s window.

Figure 8 shows the average of five calibrations performed on the CEL-C device using the Bio-HD DAQ. All electrodes can be calibrated multiple times automatically in the software’s calibration mode. The calibration was done using five standards and the entire process took less than 1 h. For calibrating the CEL-C electrodes, standard CaCl<sub>2</sub> solutions of known concentration were pipetted onto the device. The potentiometric output of each electrode due to the Ca<sup>2+</sup> ion concentration was then recorded. Five readings of the potential were recorded over five complete cycles of the
electrode due to the Ca$^{2+}$ ion concentration was then recorded. Five readings were pipetted onto the device. The potentiometric output of each concentration is present between electrodes. A consistent with the theoretical and an offset of zero when no difference in the Nernstian response as expected. The exact Nernstian slope can subsequently be used to determine the exact concentration measured by each electrode. Calibrations performed on the CEL-C device yield a Nernst slope consistent with the theoretical and an offset of zero when no difference in concentration is present between electrodes.

switching matrix. This was done to ensure that defective electrodes could be identified by their inconsistency. Between standard solutions the chip surface was washed using DI water before adding the next calcium calibration standard. Calibration solutions of 0.1, 0.5, 1.0, 5.0, and 10.0 mM CaCl$_2$ were used as calibration standards. For all of the electrodes calibrated on the chip, the electrode output values were normalized and ranked by slope so that they could all be plotted as a grid plot. The average Nernst slope was determined to be 26.8±3.8 mV. This mode is a test to ensure that our chip demonstrates the Nernstian response as expected. The exact Nernstian slope can subsequently be used to determine the concentration measured by each electrode. Calibrations performed on the CEL-C device yield a Nernst slope consistent with the theoretical and an offset of zero when no difference in concentration is present between electrodes.

In Fig. 9, response test was performed on eight electrodes to determine their response to rapidly changing solutions. The output of eight electrodes was monitored continuously while the solution concentration was changed. This was done by pipetting in known volumes of solutions of known concentrations onto the chip. The solutions added were 100 µl of 0.1 mM, 100 µl of 0.5 mM, 200 µl of 1 mM, 400 µl of 5 mM, and 800 µl of 10 mM CaCl$_2$ in that order. The resulting CaCl$_2$ concentrations at the steps are 0.1, 0.3, 0.65, 2.83, and 6.41 mM in increasing order. This experiment is verified by measuring the Nernstian slope obtained. A response time of ~1.5 s is measured and a slope of 41.4 mV is obtained.

Figure 10 shows the measurements from germinating fern spores loaded on the CEL-C device over a period of 24 h. In this experiment, C. richardii fern spores are exposed to light for 2 h to initiate germination. Thirteen spores are then placed in 13 pores of the CEL-C chip leaving 3 empty as a control. A very low calcium germinating (Murashige and Skoog) medium with 1% agarose is pipetted onto the chip to provide nutrition to the spores while holding them in place. The Bio-HD DAQ is run in the DEDC mode and the potential developed by the Ca$^{2+}$ efflux is recorded over a 24 h period. The data from a single spore are shown in Fig. 10 compared to the control. This graph allows us to clearly see the effect of germination on the Ca$^{2+}$ efflux while allowing us to simultaneously filter out external noise phenomena. The inset shows the actual noise measured when the interface is disconnected. It is clearly seen that negligible noise is added to the system through the Bio-HD DAQ. The majority of the noise is seen at certain intervals due to events external to the system. This is a true demonstration of the capability of the Bio-HD DAQ. Note that numerous experiments like this can be conducted simultaneously in real time, while the data are continuously logged and stored.

**IV. DISCUSSION**

The area of BioMEMS research and development continues to expand as scientists and engineers realize the inherent advantages of BioMEMS. These devices offer the potential to develop new technologies to answer a variety of
problems faced in biology and medicine. The foundations of this area emerged about a decade ago as various devices were designed for proof of concept, with some of these devices appearing as viable research tools and commercial products. Though BioMEMS continue to advance and evolve, their full potential has not been realized because of a deficiency in progress in developing generic high-density interface platforms for BioMEMS connectivity with electronic peripherals. Most of the progress has been very substantial in device design and biocompatibility, but further development is still required in DAQ systems which are capable of interfacing with MEMSs. DAQ systems are important for MEMSs because they provide scientists the ability of real-time data acquisition, large volume data manipulation, and complete experiment control which is necessary for analyzing various biological events and drawing conclusions.

The capability of the Bio-HD DAQ to readily interface with BioMEMS has been demonstrated here. In the calibration mode, the Bio-HD DAQ can calibrate a single CEL-C biochip within 15 min (the time needed to exchange various calibration solution), as demonstrated by Fig. 8. This is a process which would have taken more than a day to accomplish using a standard commercially available microprobe station. Figure 9 shows the real time response of the Bio-HD DAQ. The capability of the Bio-HD DAQ to measure millivolt changes in voltage instantaneously is more than adequate for the majority of biological applications. Finally, the importance of the DEDC mode is effectively demonstrated in Fig. 10. In this experiment fern spores were germinated on the CEL-C device. The transcellular calcium currents generated by them were sensed by the CEL-C device. The Bio-HD DAQ recorded these currents in the DEDC mode and the results obtained in Fig. 10 have major implications in the physiological sensing research area. The Bio-HD DAQ gives us the ability to perform numerous experiments on multiple fern spores as well as other biological entities on the CEL-C device simultaneously and in real time, increasing the throughput and efficiency of such experiments.

In conclusion, we have developed a high-density, cost-effective, high-throughput, and generic DAQ system with customizable hardware and software. This enables the scientific community to develop and modify similar systems for a variety of MEMSs. This work provides the instrumentation needed to realize the full potential and impact factor of MEMSs.

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