A Low Cost Programmable Hardware for Online Spectroscopy of Lithium Batteries

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***Abstract*—In this work, authors present an innovative low cost hardware for online spectroscopic analysis of lithium based accumulators. Proposed system designed on a TI development board that can be easily programmed using a Matlab-Simulink™ Target Compiler that can be also easily used both for research or teaching activities. Additional interfaces are provided by cheap programmable shield boards of easy usage being programmable using the Arduino IDE™. Proposed System has been successfully assembled and tested at University of Florence on a benchmark test cell. Work is focused on the description of the proposed systems and on the design of an innovative identification procedure, which is verified also experimentally.**

Keywords—Batteries, Accumulators, Spectroscopy, Modal Analysis, Frequency Response Identification, Electrochemical Impedance Spectroscopy, EIS

I. INTRODUCTION

EIS (Electrochemical Impedance Spectroscopy) is a frequency identification procedure that is currently encountering a growing research interests especially for potentially interesting applications in the automotive sector [1],[2],[3],[4].

This growing interest is mainly fuelled by some of known complementary advantages of frequency response identification techniques respect to ampere count methods:

- Test is faster respect to ampere-count methods [5],[6], which need a continuous observation, of the system, and often a model based approach in order to properly converge to a stable estimation of accumulator state.
- Identification of battery impedance with high frequency signals involve relatively modest requirements in terms of exchanged energy. This is not only an advantage for duration and applicability of the testing procedure but also for the overall duration of observed cells which are subjected to lower energy exchanges avoiding to consume a significant amount of their life which is mainly evaluated in terms of equivalent charge and discharge cycles (cycle aging)
- It's possible to demonstrate that different states and parameters of the cell affects different frequency range and feature of battery response making easier a decoupled identification of state of charge[7], aging of the battery[8] and temperature[9].

All these states of the accumulator (charge, health and temperature) have to be normally evaluated by the BMS (Battery Management System) considering the scheme of Figure 1, which is quite common as also stated by scientific literature [10]. In particular, for the so-called Ampere Count system, the identification of different parameters typically involves different observation time-scales. In particular, the estimation of battery state of charge is often performed on a relatively long timescale, assuming that short time variations of some measured or identified variable are mainly correlated to battery state of charge (as example voltage) or temperature (as example impedance) being this parameters affected by state of health only on a long trend scenario that involves prolonged observations.

Clearly, a fast-decoupled estimation of all the overall described parameters is an highly desirable feature especially for vehicles which are subjected to irregular mission profile alternating intensive load cycle to period of prolonged inactivity.

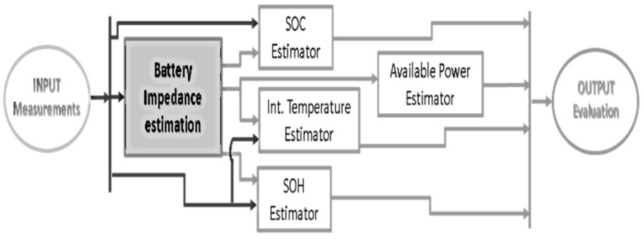

Fig. 1. Typical structure of a BMS aiming to completely identify the state of the battery (example from literature [10])

In this work authors have focused their attention on methodologies and instruments that allows a drastic cost reduction of performed EIS identification activities, also introducing an open platform that conjugates an affordable cost to an easy use and an high level of possible customization both for research or didactical use.

II. Electrochemical Impedance Spectroscopy (EIS)

EIS identification is performed, considering the scheme of Figure 2 and the following preliminary assumptions:

- Tested Battery can be modelled even approximately as LTI system (Linear Time Invariant).
- Exciting current is a stochastic stationary process.

If the over-cited hypothesis are assumed to be valid there is a wide technical literature concerning system identification [11] that can be applied, not only concerning generic dynamical systems but also dealing with specific methods that have been widely applied also to modal analysis of mechanical system[12], exploiting electro-mechanical analogy and bond graph [13] modelling which is still widely adopted for the multidisciplinary study as example of IPT (Inductive Power Transfer) systems that have been recently proposed for vehicular applications[14].

In particular, it's possible to evaluate impedance according to (1) where the power spectral density of current ϕ_{ii} and cross spectral cross density between measured current and voltage ϕ_{vi} are evaluated:

$$\hat{Z} = \frac{\phi_{vi}}{\phi_{ii}} \quad (1)$$

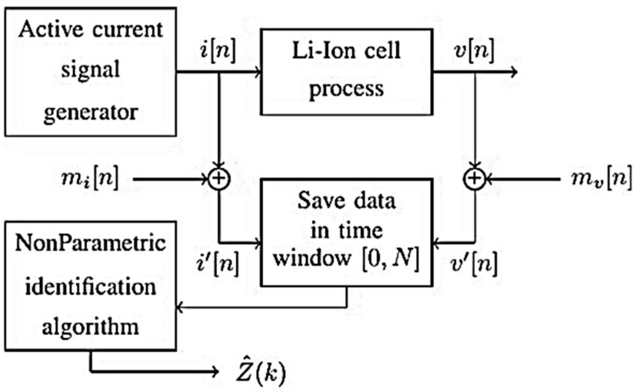

Fig. 2. Typical Testing Procedure for EIS identification

Frequency identification is traditionally performed using continuous sinusoidal or chirp sinusoidal excitation [11][12].

This kind of excitation involves a precise control of complex continuous waveform, which is relatively expensive to be performed, also resulting testing procedure should be quite time-consuming. For this reason, authors preferred the adoption of a PRBS (Pseudo Random Binary Sequence) a large bandwidth signal, which requires a relatively simple hardware both for signal generation and for hardware implementation:

- As visible in Figure 3, the signal can be generated with a simple shift register; so, generation of reference signal involve limited computational resources.
- Generated signal as visible in Figure 4 corresponds to an alternate periodic pseudo random sequence of signals, which can have only two discrete value; as a consequence, hardware implementation is relatively simple.
- Finally, by increasing the number of used shift registers (n_r) is possible to reproduce an almost continuous spectrum which is almost equivalent to a white noise excitation, as visible in Figure 5. By exciting a large range of frequencies it's possible to identify system response with tests of limited duration.

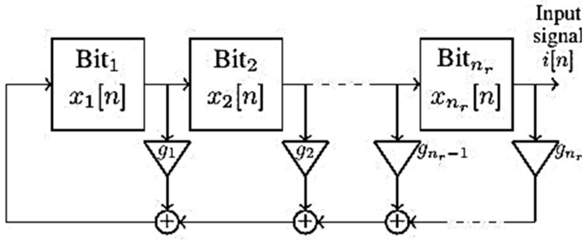

Fig. 3. Generation of PBRS through shift register

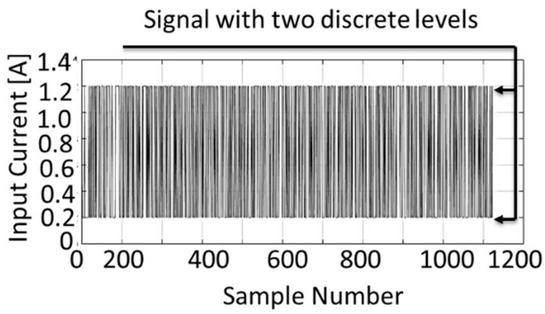

Fig. 4. Example of generated PRBS signal

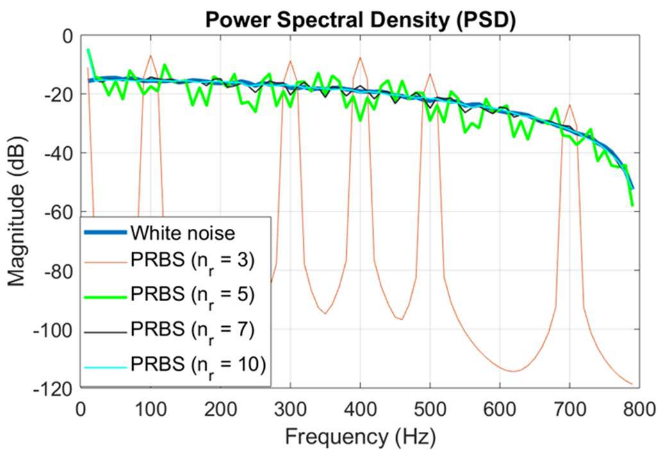

Fig. 5. Power spectral density of genereated PBRS signal as a function of the number n_r of adopted shift registers, compared with the corresponding spectrum of a white noise signal

III. Hardware Implementation

In Figure 6, it's shown an implementation scheme of the proposed measurement system: all the tests are managed using a Texas instrument development board of the "Delfino" series (exactly a TI LAUNCHXL-F28379D). Proposed board has two 200MHz and 32bit microcontrollers and several I/O ports including A/D, D/A and several different digital communication ports, detailed technical information is available online [15]. Each microcontroller has been designed and it's often used for motor drives [16], but considering available memory and computational resources have been extensively used also for hardware in the loop testing [17] thanks to good Digital Signal Processing Performances. Since only one core is used to manage all testing activities, the second core can be used to directly implement data postprocessing and system identification directly on the same board. Delfino processor series can be directly programmed using Matlab-Simulink through a supported Target Compiler also supporting a direct communication with an host PC through a serial communication port.

In order to store large amount of data a micro SD card is used, in this way it's possible to store and share a large amount of data. The same SD card can be used also to upload testing sequences or other parameters to the board without using any serial communication between TI board and an host/developer PC. Interfacing between SD card reader and TI board is performed trough the Teensy 3.2 board (a 72Mhz microprocessor, which is easily programmed through the Arduino IDE interface).

Finally, TI board also control the solid state relay system that is devoted to generate the desired waveform.

In particular electrical interface, as visible in Figure 7, is designed to perform the following kind of test:

- Battery charge: simple battery recharge can be performed, optionally also PRBS and step test can be performed also during the recharge phase;
- Battery discharge: battery is connected to a resistor or an external calibrated load to perform a continuous discharge or a PRBS-step test ; this is the preferred testing mode.
- Calibration: A reference calibrated Resistive-Capacitive Network is connected to the testing machine in order to properly verify and calibrate the behaviour of the machine.

Once programmed the machine can be used safely also avoiding any additional communication with the host PC that has been used for the development of on board testing applications, since the machine is provided of a panel that assure a known controllable and safe behaviour of the testing equipment through the usage of command button and led for state feedback. Panel is described in the schemes of Figures 8 and 9 and in Table I.

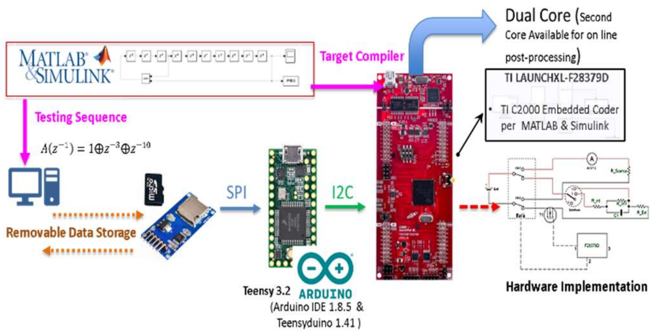

Fig. 6. main components of designed measurement system

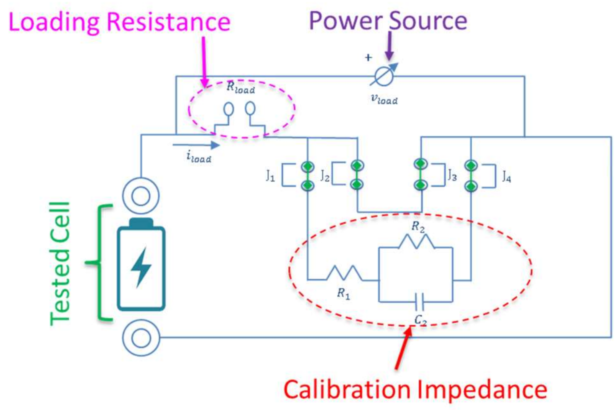

Fig. 7. Power Connections to tested battery

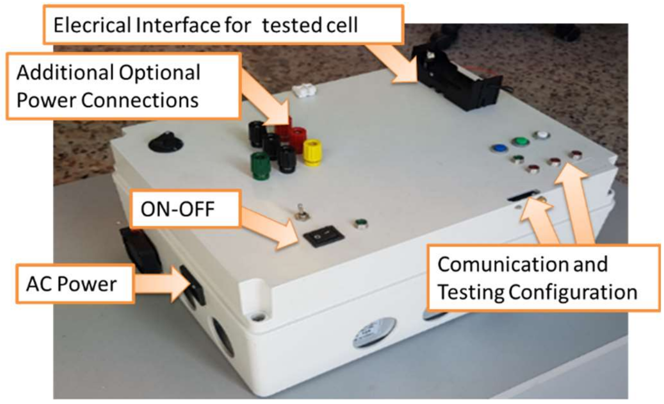

Fig. 8. Assembled Testing System

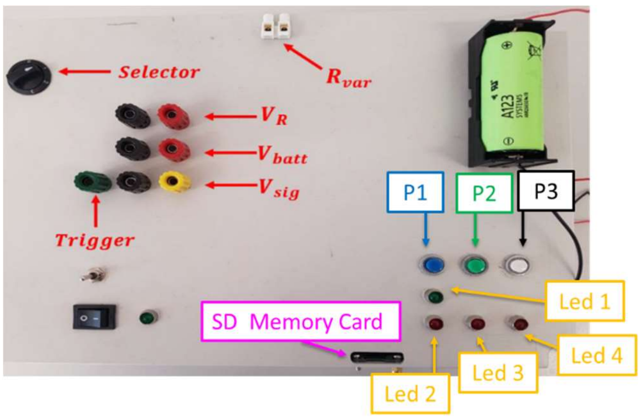

Fig. 9. Detailed View of external panel

TABLE I. MACHINE COMMANDS AND FEEDBAK

Buttons (Manual Commands)		**LED (Machine State Feedback)**	
Name	***Action***	***Name***	***State (when ON)***
P1	Start Battery Excitation Test	Led 1	Battery Discharge
P2	Battery Discharge	Led 2	Temporized waiting between tests
P3	SD Data Refresh	Led 3	Excitation applied to battery (blinking if excitation is not active but data are recorded)
		Led 4	Error on SD card (Blinking during access to card DATA)

IV. Preliminary Testing and Validation Activities

In order to evaluate the functionality of the proposed testing system, authors performed some testing activities with a redundant configuration, in which both measurements and evaluations are performed by two different hardware: the proposed TI board and a DSPACE Microlabbox. This is used, according the scheme of Figure 10, to perform a redundant acquisition of all the variable of interest, in order to completely monitor the behaviour of the proposed (and much cheaper) testing system.

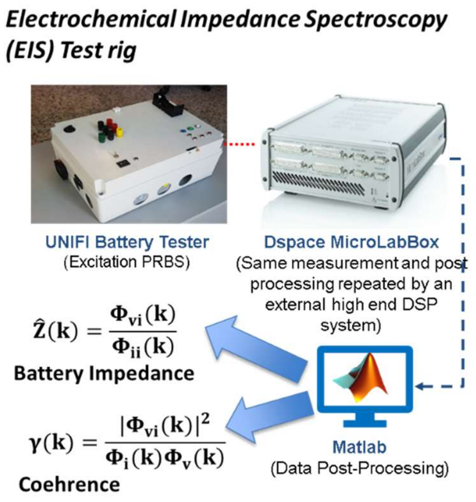

Fig. 10. Instrumentation adopted for preliminary validation activities

Using the over described system, authors perform the following tests:

- Preliminary verification of calibration on a reference resistive and capacitive network.
- Spectroscopy test on a benchmark $LiFePO_4$ cell.

A. Test on Calibration RC network

A calibrated network, composed by a resistance R_1 in series to a parallel composed by a resistance R_2 and capacity C_2, is excited with a PRBS with a clock frequency of 2.5 kHz. Network is also visible in Figure 7 and its main parameters are described in Table II. Excitation is applied using the same power of the cell, whose currents are limited placing in series an additional resistance R_{load}.

All data are acquired with a sampling frequency of 10 kHz.

Appling the proposed PBRS excitation, it's performed a comparison between the identified behaviour of the impedance respect to the expected one. As visible in Figure 11, there is a very good fitting of EIS estimation and expected values, residual errors are compatible with uncertainties and tolerances of the tested calibration circuit.

Results are quite repeatable since performing two or more test. Indeed the coherence function γ, defined according (2), is almost the same and maintain a near to unitary value on a frequency range which is substantially limited by the maximum clock frequency of PRBS and by leakage effects [12] at very low frequencies (about 100 Hz), see Figure 12.

$$\gamma = \underbrace{\frac{\phi_{vi}}{\phi_{ii}}}_{H_1} \underbrace{\frac{\phi_{vi}}{\phi_{vv}}}_{\frac{1}{H_2}} \qquad (2)$$

In particular, a high value of γ implies that the ratio between two different estimators H_1 and H_2 of the same impedance Z are equal. For the definition of the two estimators [12], which respectively minimize errors to noise on output or input, a unitary coherence involves a substantially correct estimation.

TABLE II. Parameters of The Calibration RC Network

Parameter	Value
R_1	0.2[Ω]
R_2	1[Ω]
C_2	820[pF]
R_{load}	4.4[Ω]

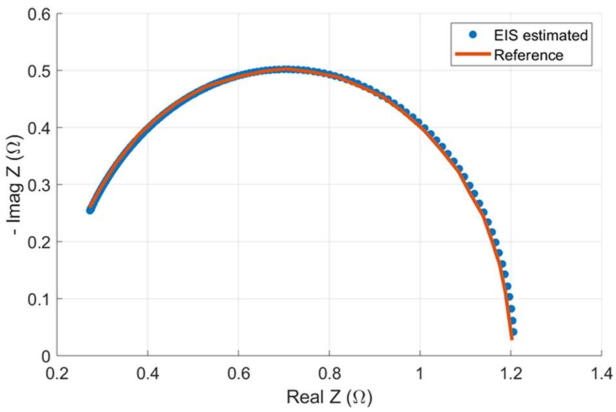

Fig. 11. Instrumentation adopted for preliminary validation activities

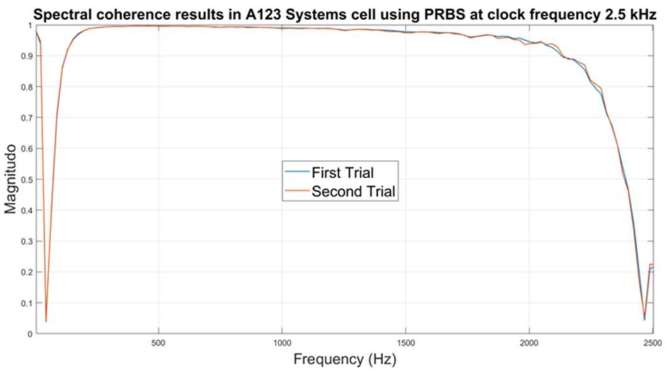

Fig. 12. Behaviour of Coherence of performed estimation respect to frequency

B. Test on a Benchmark $LiFePO_4$ Cell

After verifying the behaviour of the measurement system on a calibration RC network, authors repeated the same tests on a known benchmark $LiFePO_4$ cell (Lithium Werks, Former A123 Systems model ANR26650M1ultra-B), whose behaviour is known by authors from previous research activities [4] and literature [18].

In this case, for PRBS, a clock frequency of 800 Hz is adopted, all acquired data are recorded with a sampling frequency of 8 kHz starting with an initial state of charge of the battery of about 60%. PRBS excitation is performed with a discharge test, battery is alternatively connected and disconnected on a resistive load of 4.4 Ω. Range of investigated frequencies is chosen, to evaluate mainly the state of health of the battery since according literature. Impedance behaviour of batteries, as visible in the scheme of Figure 13, is correlated to different phenomena according the observed frequency range. In order to be relatively sure of observing a part of the response, which mostly depends on state of health a band between 10^2 and 10^3 Hz should be considered. Tests are performed considering a discharge current which is about 0.3C (0.3 times lower respect to the nominal cell current).

In this work four PRBS excitation tests are repeated:

- First two tests are repeated after few seconds, with almost the same testing conditions; the only difference between the two tests is the considered duration which is doubled for the second tests.
- Then the cell after some further charge and discharge cycles (few equivalent cycles able to produce a near to negligible aging of the cell) is tested again (third and fourth tests).

In Figure 14 , it's shown the behaviour of coherence for the performed tests: it's clearly noticeable that test coherence is almost the same for every performed tests, so the signal to noise ratio and more generally the precision of the performed identification is good and almost constant respect to performed tests.

For what concern estimated Impedance behaviour, some results are shown in Figure 15: results concerning identification tests with a test duration of 60 seconds are compared with the ones performed over a doubled period of 120 s. The results are almost the same, test with larger durations (120 s) exhibit a bit lower scatter of results respect to shorter tests (60 s). However resulting impedance behaviour is quite similar also in terms of approximating Nyquist circumferences calculated with a least square fitting method; so it can be concluded that also approximated poles that fit approximately experimental results are almost the same, as visible in Table III, where approximated poles associated to Nyquist interpolating circumferences are shown.

TABLE III. DATA OF TESTED A123 BENCHMARK CELL

Parameter	Value
Encumbrances (φh)	26x65[mm]
Weight	76[g]
Nominal Capacity	2.5[Ah]
Minimal Capacity	2.2[Ω]
Nominal Open Circuit Voltage	3.3[V]
Maximum Discharge Current	70[A]
Declared, Nominal Internal Impedance (1kHz)	6[mΩ]

TABLE IV. POLES CORRESPONDING TO INTERPOLATING CIRCUMFERENCE OF THE NYQUIST PLOT IN FIG.15

Circumference	Poles
Duration 120[s]	[0.062, 325]Hz
Duration 60[s]	[0.026, 319]Hz

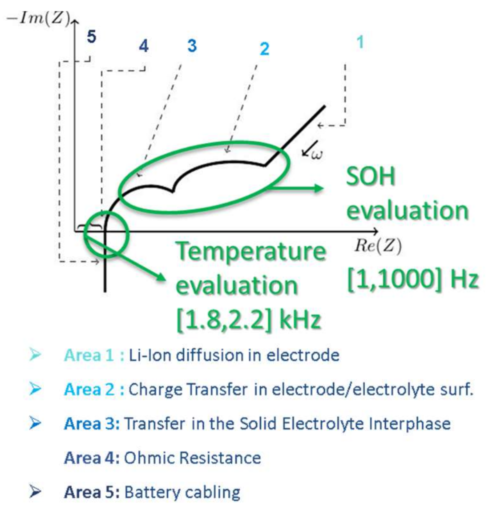

Fig. 13. Different frequency range in which impedance behavior is associated to various phisical phenomena [9],[10].

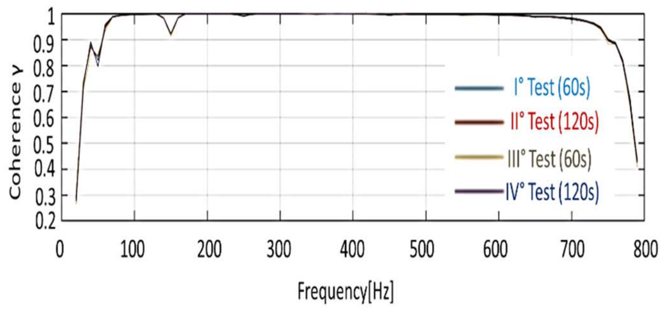

Fig. 14. Different frequency range in which impedance behavior is associated to various phisical phenomena [9],[10].

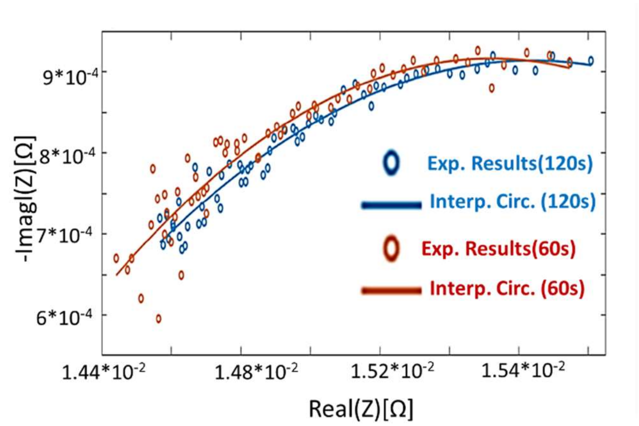

Fig. 15. Impedance behaviour of impedance Z comparison between tests with different durations (60s vs. 120s)

CONCLUSIONS AND FUTURE DEVELOPMENTS

In this work authors have proposed an open platform that it's ideal to perform both research and teaching activities concerning Electrochemical Impedance Spectroscopy. The system have been designed assembled and tested on a benchmark test cell, obtaining results that are aligned to recent studies that have been performed with far more expensive equipment.

Currently Authors are working to further extensions of testing capabilities especially for what concern real time processing and implementation of complex routines related to the identification of multiple battery parameters related to state of charge, health and temperature of the battery.

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