Digitally Controlled Reference Impedance Device for Test and Calibration of the Bio-Impedance Measurement System (BIMS) in a Networked Environment

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Abstract— **With emerging new developments in the scope of the Bio-Impedance Measurement System (BIMS), an automated test of the data acquisition equipment and its proper tuning in conditions of strict accuracy requirements have become a critical issue. Such BIMS, as the one designed by ELIKO Competence Centre and Artec Design LLC, is basically a complex synchronous data acquisition platform, with the base elements being a sine wave excitation signal generator, a multi-channel sampler and a DSP unit. Such a system requires full testing and calibration prior to conducting complicated and expensive biomedical experiments. Thus, the solution was selected, where the observable biological system is replaced with a digitally controlled resistance and capacitance array (DCRCA) during the testing and calibration process. DCRCA is the part of the proposed digitally controlled reference impedance device (DCRID), which emulates the behaviour of biological tissue in a determined manner. The parameter variation is supervised by a microcontroller, which enables to change properties of DCRCA with high resolution and exact timing. As BIMS uses Ethernet for its data transfer, DCRID is designed as a network device as well, utilizing Internet Protocol for communication with a host. The implementation of DCRID is microcontroller-based, providing acceptable calibration error levels. Moreover, DCRID is suitable for basic laboratory simulations, as well as for personnel training.**

Keywords— **bio-impedance measurement system, test and calibration, reference device, microcontroller, Ethernet**

I. Introduction

Electrical bio-impedance (EBI), as the only parameter for characterisation of the living tissue by purely electrical measurement, has increasingly attracted more interest of scientists during the last decade. One of the reasons for an increasing popularity is the appearance of powerful DSP and signal acquisition solutions, enabling for a rapid data analysis and interpretation. ELIKO Competence Centre and Artec Design LLC have developed an inherently synchronous data acquisition platform for bio-impedance measurement [1]. Being the main part of the bio-impedance measurement system (BIMS), it enables for a low cost prototyping and research on advanced signal processing methods. The structure of the developed BIMS is represented in Fig. 1. BIMS consists of a sine wave excitation signal generator, an 8-channel sampler, adders in the mixed-mode feedback loop ADC_1-FPGA-DAC_2-ADC_2 , a packet composer with UDP/IP stack, and an Ethernet network interface.

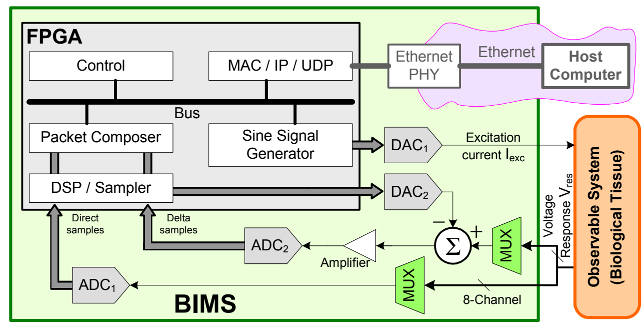

Fig.1 General structure of BIMS. Data acquisition platform is implemented on FPGA basis with Ethernet PHY plug-in.

Evidently, before BIMS can be effectively utilized for a specific application, especially for complicated medical experiments, it should be properly tested and calibrated. For this purpose, instead of an observable object, BIMS is to be connected to an artificial bio-impedance, i.e. to a reference impedance device (RID), properties of which can be controlled in a determined manner. Though similar solutions are already available [2], there exists a motivation to develop a new RID with the aim to achieve a completely automated operation and advanced remote control features.

II. Initial considerations

The digitally controlled reference impedance device (DCRID) is considered to consist of two controllable elements – a resistive and a capacitive element. This simplification is allowable as biological tissue reactance is presumed to be a capacitive one.

As BIMS is implemented as an Ethernet node, DCRID should likewise provide a network interface to communicate with a host machine for providing remote control of its resistance and capacitance properties (Fig. 2). DCRID is suggested to be battery powered, which would mitigate mains interference and simplify wiring – both being important parameters for lab experiments.

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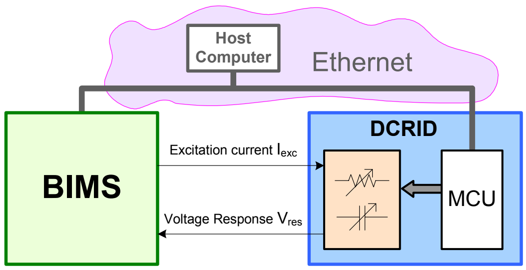

Fig.2 DCRID replaces an observable target

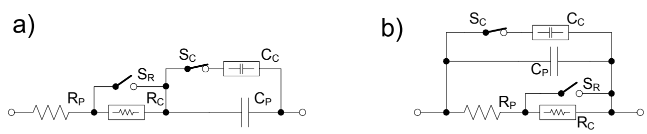

Fig.3 EBI serial (a) and parallel (b) equivalent circuits, which can be realized using DCRID. R_P and C_P represent arrays of multiplexed precision resistors and capacitors, respectively. The switches S_R and S_C are used to enable and disable less precise variable elements R_C and C_C.

DCRID can be used to realise equivalent circuits of the tissue electrical bio-impedance by connecting DCRID's controlled resistive and capacitive circuits in serial (Fig. 3a) or in parallel (Fig. 3b).

DCRID is proposed to integrate a digitally controlled resistance and capacitance array (DCRCA) which includes discretely R_P and continuously R_C variable resistors and capacitors C_P and C_C as well. Microcontroller unit (MCU) will thus implement an IP based communication protocol to adjust the properties of the system in a timely fashion.

III. DESIGN OPTIONS

Taking the above considerations into account, DCRID structure can be further determined, as illustrated in the Fig. 4. Controlled resistance and capacitance are presented as separate blocks, including their discretely and continuously variable units. The discrete part of the controlled resistance contains an array of precision resistors, the continuously variable block of the controlled resistance is meant to modulate the originally selected reference value from a resistor bank. Similarly, the discrete part of the controlled capacitance contains an array of precision capacitors, with the continuously variable block having purpose to modulate the value of a selected element.

For calibration purposes the controlled resistance and capacitance can be connected as shown in Fig. 3, or they can be used as separate elements as well. However, the continuously variable units should be eliminated from the EBI

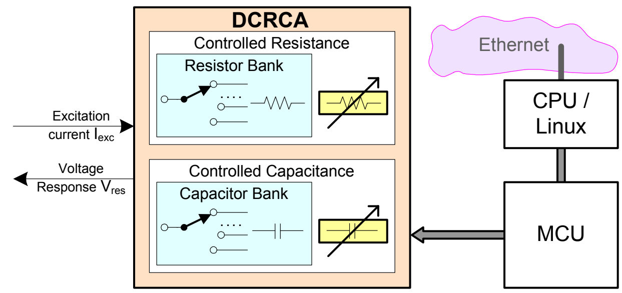

Fig.4 General structure of DCRID

emulating circuit by turning S_R and S_C to opposite positions (Fig. 3) during the calibration process.

The signals processed by BIMS typically lay within microvolt and microampere magnitude up to megahertz frequency range, which implies certain problems for design of the test and calibration equipment. Therefore, the DCRID design is affected with above specifics.

Implementation of the DCRID by means of semiconductor *analogue switches* [3, 4] or a r*elay based R/C bank* did not fully suit the given application because of a large number of R and C components. Low switching speed and high power consumption are the main drawbacks of the latter option. Furthermore, *digital potentiometer IC's* [3, 4] have a limited resistance range combined with relatively poor end-to-end tolerance (up to 30%), and are not suitable as well.

Numerous analogue devices, such as a *controlled impedance, opto-resistor* or *phototransistor, varicap diodes* are other possibilities for implementation of DCRID. But poor unit-to-unit tolerance, non-linear characteristics, and poor parameter variation range are typical drawbacks of such approaches [5-7]. However, this does not apply to such integrated devices as an operational transconductance amplifier (OTA), which can emulate variable impedance [8].

Finally, a *variable capacitance multiplier* based on the Miller effect [9] can be effectively used to realise the variable capacitance.

IV. CONTROLLED RESISTANCE AND CAPACITANCE

The controlled resistance and capacitance blocks consist of arrays of precise resistors R_P and capacitors C_P connected with less precise, but higher resolution continuously tuneable additional resistor R_C and capacitor C_C. The connection diagrams are illustrated in Fig. 5a for the resistors and in Fig. 5b for the capacitors.

MCU controls the multiplexer (Fig. 5), selecting an appropriate precision reference resistor from the array, as well as drives a 12-bit DAC, that generates a control current to adjust the gain of both OTA's (Fig. 6) simultaneously.

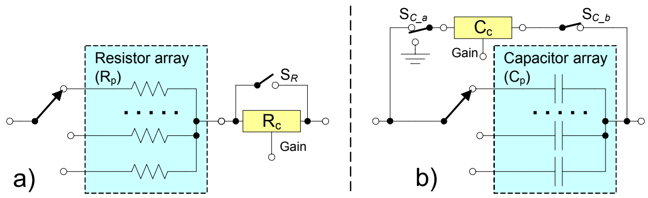

Fig.5 Controlled resistance (a) and capacitance (b) of DCRCA. The resulting resistance (capacitance) equals to the selected Rp (Cp) value plus variable resistance (capacitance).

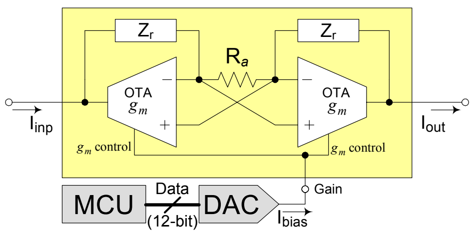

Fig.6 Floating Controlled (FC) Impedance implemented using two OTA's with digitally controllable gain.

The realisation of the continuously variable resistor and capacitor is done using an OTA based floating controlled (FC) impedance circuit (Fig. 6) [8].

The value of the desired equivalent FC impedance is:

$$Z_d = Z_r \frac{2}{g_m R_a} \tag{1}$$

Where g_m is the transconductance of the OTA, Z_r and R_a form a frequency dependant attenuator. A suitable OTA must be chosen that offers acceptable transconductance linearity. The values of g_m and its characteristics are known from the manufacturer's datasheet of a particular device.

A. Floating Controlled (FC) Resistance

In the case of the FC resistance the resulting equivalent resistance is given as:

$$R_d = R_r \frac{2}{g_m R_a} \tag{2}$$

B. Floating Controlled (FC) Capacitance

To construct the FC capacitance circuit the reference impedance Z_r is represented by the parallel connection (3) of a reference resistor R_r and capacitor C_r.

$$Z_r = 1/\left(1/R_r + sC_r\right), \text{ where } s = j\omega \text{ is a complex variable} \tag{3}$$

The resulting impedance for the FC capacitance is:

$$1/sC_d = 2\left[R_r/\left(1+sC_rR_r\right)\right]/g_mR_a \tag{4}$$

To eliminate influence of the resistance R_r, the rule $sC_rR_r \gg 1$ should be satisfied and the nominal value of R_r can be selected accordingly (5):

$$R_r = \alpha/sC_r = \alpha/2\pi f_{\max} C_r \tag{5}$$

where $f_{\max}$ is the maximum operating frequency and α can be selected as $\alpha \le 0.1$ to satisfy the rule $sC_rR_r \gg 1$. Therefore, the resulting FC capacitance is expressed as:

$$C_d \approx C_r\, g_m R_a/2 \tag{6}$$

C. Grounded Controlled (GC) Capacitance

As an alternative solution, the GC capacitance is also implemented to emulate the controlled capacitance of DCRCA (Fig. 4 and Fig. 5b) using a variable capacitance multiplier (VCM), which is shown in the Fig. 7. Reference capacitance is selected from the array of precision capacitance elements using an analogue multiplexer. The amplifier gain is programmed by a microcontroller via a 10-bit multiplying DAC. The resulting equivalent capacitance is given as:

$$C_d = C_p\left(1+1024/D\right) \tag{7}$$

Where C_p is the reference capacitance selected by a multiplexer and D is the decimal representation of DAC data.

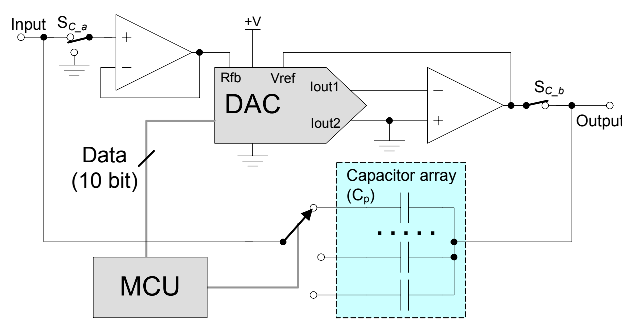

Fig. 7 Simplified circuit of the Grounded Controlled (GC) capacitance.

V. Microcontroller

The supervisor of the DCRCA runs on a low-power MCU with no operating system and strictly limited resources (Fig. 8). The second microcontroller (CPU) is more powerful, runs an operating system, and is designated for communication to the outside world. Such approach is proposed to enable rapid prototype development and to provide

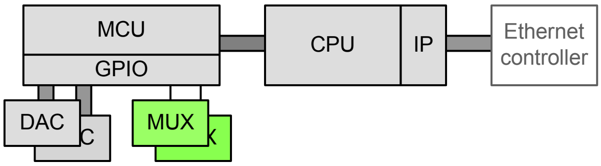

Fig.8 Processing and supervisor units

a stable platform for application deployment. Linux operating system is used to implement a fully capable IP network node.

MCU integrates a TTL or CMOS type GPIO interface to control the onboard DAC and MUX devices. There are 2 DAC units with parallel or serial interfaces connected to controlled resistance and capacitance devices correspondingly. Also, there are 2 multiplexer units for selecting appropriate references from resistance and capacitance arrays.

DCRID is suggested to have a multi-board construction, enabling for modular and scalable design. Separate boards for CPU, MCU and controlled impedance allow for reuse of existing components and reduce development costs. It is proposed to use the Gumstix modular platform [10] for the first implementation of DCRID.

VI. Software

The software part of the DCRID should be designed to resolve the following issues.

- *Communication to host*. TCP stack is used to implement an application-level protocol. The protocol should include commands for changing DAC and MUX settings explicitly, as well as for calculating them automatically, basing on the given desirable impedance, resistance or capacitance values.
- *Timing synchronization*. DCRID should provide means to synchronize the internal clock to the host source, enabling for precisely timed adjustment of resistance and capacitance values. Utilizing internal MCU timers, DCRID is also capable of generating basic modulation patterns for both variable resistance and capacitance units. MCU must therefore conform to strict real-time requirements and process commands in determined time intervals.
- *Offset and nonlinearity correction*. DCRID processing units should provide a way of constant offset and nonlinearity correction for variable resistance and capacitance devices to improve accuracy. The calibration data should be updated externally from the host.

VII. Conclusions

The controlled artificial impedance device has been designed to simulate the basic behaviour of a biological tissue. DCRID circuit includes an array of reference resistors and capacitors dynamically selected by analogue multiplexers and continuous resistance and capacitance emulating circuits for modulation of reference values. DCRID integrates a supervisor with a network interface that allows for rapid and time synchronized change of DCRCA properties.

The newly developed DCRID enables for a remote testing and calibration of BIMS, as well as generic laboratory training and simulations. The device is currently in an early prototyping phase.

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