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NEW METHOD FOR LOCOMOTOR ACTIVITY MEASURES IN INSTRUMENTED ANIMALS WITH IMPLANT BASED ON INDUCTIVE COUPLING

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Abstract − This paper presents a new method for locomotor activity (LA) measurement in small laboratory animals. A method was developed in order to add LA measurement capability in biotelemetry systems in which implant powering and communication is based on inductive coupling. That enhacement is done without the need of additional resources in the implanted side. After discussing the mathematical formulation, an example is presented for which are obtained the most adequate parameters for LA measurement in a typical system of biotelemetry in small rodents. Limitations and advantages of the method conceived also are discussed.

Keywords : biotelemetry, inductive coupling, locomotor activity measurement.

1. INTRODUCTION

Spontaneous locomotor activity (LA) is an useful parameter in the animal behavior characterization, and so, it is employed in many biomedical studies involving small laboratory animals. An example is the research field on circadian and diary rhythms, where LA measurement is of paramount importance [1].

In the last decades, several techniques have been developed to automate LA measures, one of which is wireless biotelemetry [2]. In this solution the LA assessment is achieved through counting RF intensity variations originated by active transmitter implanted in the animal. While the animal moves, it gets closer or more distant from the receiver in the cage, and detected RF intensity variations allows quantify the locomotor activity. In this case, the advantage is that the measure is carried out in a system primarily devised for another biological parameter, without the need of any additional hardware in the implanted transmitter, although, the resolution in the LA measurement to be lower than in many other methods.

Another approach to get an instrumented animal is the use of implant with powering and communication based on inductive coupling. This alternative brings some advantages in relation to use of implant built with a RF transmitter [3]. Even though, inductive coupling has been employed in implants for humans for decades, in the case of laboratory animals few development has been carried out until here. Currently, there is only two commercial systems based on inductive coupling (Biomedic Data Systems, Seaford, USA; Mini Mitter, Bend, USA), being both for temperature measument. Recently, this type of system was also proposed for arterial pressure measurement in small rodents [3].

This paper presents a new method for LA measurement in biotelemetry systems based on inductive coupling. Next section describes the configuration of this type of system and how LA measures can be added in it. Section 3 presents a theoretical analysis of the proposal, including the mathematical modeling. To follow results about the determination of system parameters for a typical application of biotelemetry in animals are presented. Section 5 discuss advantages and limitations of the new method and future steps of the work. Finally, Section 6 brings the conclusion.

2. BIOTELEMETRY BASED ON INDUCTIVE COUPLING AND THE LA MEASUREMENT

Fig. 1 shows the concept of telemetry system for small animals that we are developing. Figure terminology employs some terms used in Radio-Frequency IDentification (RFID) systems, which frequently operates by inductive coupling [4]. The main advantage of the architecture under development is the possibility that the implanted sensor can be operated during whole experiment only based on the energy obtained by inductive coupling, that is, a batteryless sensor. In traditional systems the sensor includes a RF transmitter that makes the battery indispensable. Battery discharges, with time and use, imposes limitation to the studies, as long as the experiment must be limited to a time interval significatively shorter than animal lifetime. Therefore, long term studies becomes impossible.

In Fig. 1, the implant RF section is passive and for communication in the downlink direction it employs a technique named load modulation. RF section alters, in a controlled way, the load upon its antenna pads, which will be reflected in the primary magnetic circuit composed by interrogator loop antenna and associated elements. So, the biotelemetry sensor does not spend energy to send data in the downlink sense.

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Although the passive RF interface brings a significant advantage relative to the null energy consumption, it has an important restriction: the limited range. For example, RFID systems operated by inductive coupling, HF band, with data rate in order of thousands of Kbps, has a maximum range of 10-20 cm. Our design employs the RFID standard ISO14443B [5] for the RF interface. In this standard, the short range is related to communication in the downlink sense, i.e., in the range limit, communication errors will occur mainly when the implant send data for the interrogator. As so as the standard uses digital communications techniques, including frames with error checking field, these errors can be faced by high level protocols via retransmission.

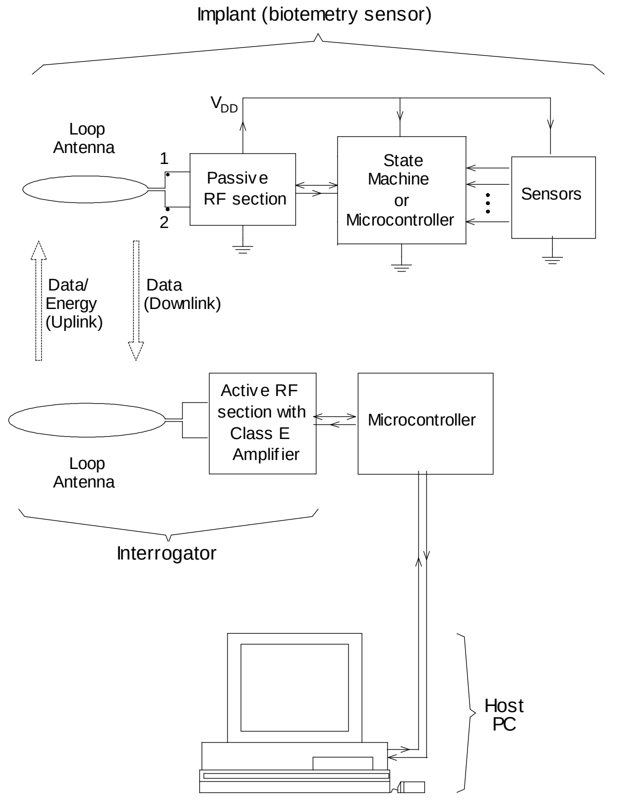

Fig. 1. Architecture of a biotelemetry system devised for use in small animals and based on inductive coupling.

RF passive interface also makes inviable the measurement of LA in a way similar to that in implants where the RF section includes a transmitter, as the inductive coupling with load modulation is unsuitable for detection of variations in the RF intensity. For LA measurement we propose a solution that has ground exactly in the range restriction. As the range is very limited, typically a single interrogator would be unable to cover whole cage. So, it is necessary to use a set of interrogators distributed in the cage base (Fig. 2), i. e., to use space division multiple access technique, where, in each moment, only a interrogator is active. With this approach to workaround the range problem, the new method for LA measurement arises naturally. It consists in quantify the commuting between interrogator blocks as the animal moves in the cage. Being more specific, the value consists of counting of the quantity of transitions between interrogator blocks, in a given fixed time interval.

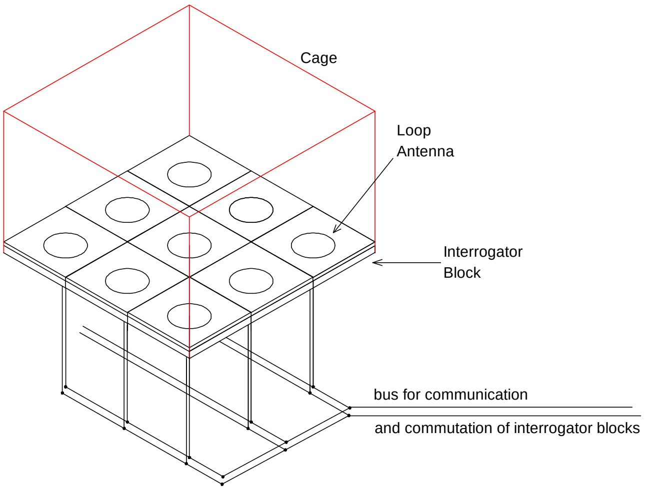

Fig. 2. Method for LA monitoring in the biotelemetry system.

3. ANALYSIS OF THE METHOD

For the technique introduced in the Fig. 2, there is a trade-off between the misalignment of interrogator and sensor antennas, minimum power necessary to implant operation and resolution in the evaluation of the LA measure.

3.1. Resolution in the LA value

The extreme case of a coarse resolution in the LA measures happens when any interrogator block is able to communicate with the implant, independently of the animal localization in the cage. It is not possible to generate LA estimative in this case. Indeed, it would be unnecessary to use several blocks, because only one would be able to cover the whole cage. On other hand, if some interrogators, but not all, are able to get response from the implant, there will be some resolution in the animal localization, and consequently LA measures will be possible. On other extreme, if each block is able to get response from the implant only for positions near to antenna center, the implant will be inaccessible in a great proportion of the cage area, consequently, there might be big shadow areas in the communication. In short, the resolution will be the best when in each moment only a block is able to communicate with the implant and this happens for each localization inside of the block.

3.2. Power for implant operation

Operation of the implant circuits implies a determined minimum power in the points 1-2 of the Fig. 1. Namely, there is a determined value $P_{1-2(min)}$ below which the implant does not work anymore. Energy transfer between interrogator and implant can be determined by (1).

$$P_{1-2} \cong V_E \cdot \frac{1}{32R_{EO}R_tR_i} \cdot \left[\omega M \cdot \left(1 + \frac{(\omega M)^2}{8R_tR_i} \right)^{-1} \right]^2 \qquad (1)$$

Establishment of (1) was made grounded on development of equivalent expression published recently [6], however (1) differs of this previous result concerning the number 8 in the denominator [7]. In (1), M is the mutual inductance between the interrogator and sensor antennas, V_E is the sinusoidal voltage peek that the RF amplifier develops in the interrogator antenna circuit, ω is the angular velocity of this voltage, P_{1-2} is the consumed power in the implant (equivalent impedance in the points 1-2, Fig. 1) and R_{EO} is the output impedance of the class E amplifier. R_t and R_i are the radiation and ohmic losses in the antenna circuits for sensor and interrogator, respectively. These losses can be calculated by means of expressions presented in [8] and [9].

Typically, the circuit that delivers power in the interrogator antenna is a Class E RF amplifier [10]. It is possible to control the power through variation of the drain or collector supply voltage, in the single active device of this amplifier. In (1) V_E reflects this power control. So, in some extension, V_E can be adjusted for the purpose of assure the $P_{1-2} > P_{1-2(min)}$ condition. Furthermore, the V_E in each interrogator block can be controlled by the microcontroller in order to assure that the sensor works at any point in the cage. Again, it is important that the energy transfer to the implant respects the following criterion: the implanted sensor must receive $P_{1-2} > P_{1-2(min)}$ only from the block directly below it. It will be counterproductive for the localization problem if, in a given moment, a block generates power enough to operate a implant beyond its perimeter. For the stablishment of localization, when an interrogator block is to be activated its initial V_E must be only the minimum necessary to power the implant, regarding that it stays inside the block perimeter and the animal keeps posture of locomotion (not erect).

3.3. Lateral misalignment

Operation of the system, according to Fig. 2, implies variation of mutual inductance. As the animal moves, mutual inductance varies significativelly due to the changes in relative position between interrogator and implant antennas. At this point it is assumed the simplification of that any animal displacement generates only lateral misalignment between the antennas, i.e., the antennas remains all time in parallel planes and the distance between these planes does not change. Fig. 3 describes the configuration for lateral misalignment analysis, regarding the case of single-turn antennas. In this configuration, when the two circular loop antennas are aligned ($\delta = 0$) the mutual inductance is expressed by (2)[11].

$$M = \mu_o G(n)\sqrt{ab} \qquad (2)$$

In (2), a e b are the radius of interrogator and implant antennas, respectively, and $G(n)$ is given by (3) and (4).

$$G(n) = \left(\frac{2}{n} - 1 \right) K(n) - \frac{2}{n} E(n) \qquad (3)$$

$$n = \sqrt{\frac{4ab}{(a+b)^2 + h^2}} \qquad (4)$$

K(n) and *E(n)* are full elíptical integral of first and second order, respectivelly. h is the distance between the planes of the antennas.

When the antennas are misaligned the relation between misalignment and mutual inductance is complex, and it is not possible to get an analitical expression to describe it. In this case, M only can be determined by numerical resolution of the integral in (5) [12].

$$M = \frac{\mu_o ab}{2\pi} \int_0^{2\pi} \frac{\cos\beta}{\sqrt{ab_L}} G(m) d\phi \qquad (5)$$

G(m) is given by (3), while β, b_L and m correspond to equations (6), (7) and (8), respectivelly.

$$\beta = a \cdot \tan \left(\frac{\delta \cdot sen\phi}{b + \delta \cdot cos\phi} \right) \qquad (6)$$

$$b_L = \left(b^2 + \delta^2 + 2b\delta cos\phi \right)^{1/2} \qquad (7)$$

$$m = \sqrt{\frac{4ab_L}{(a+b_L)^2 + h^2}} \qquad (8)$$

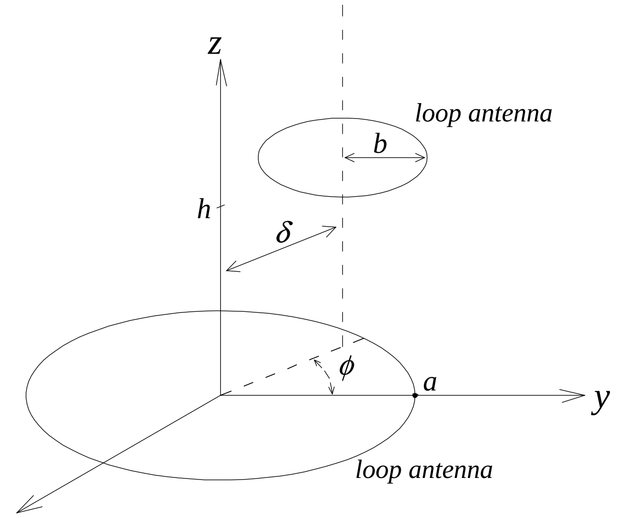

Fig. 3. Configuration for lateral misalignment analysis.

4. SYSTEM PARAMETERS DETERMINATION

In view of the proposed LA measurement method the formulation presented above is useful for parameters determination about Fig. 1 and 2. Preliminarily, some requisites or parameters are specified based on animal specie, cage dimensions, desired resolution and implant power consumption. Table 1 relates these specifications originated from an initial analysis, in the case for application of biotelemetry in adult rat, a specie frequently employed in biomedical studies. From these specifications the interest is to get the most adequated radius of interrogator antenna in order to permit the best accuracy for LA measurement. In accordance with (5), as antenna radius grows M increases and, from (1), more power will be transferred to the implant. However, an excessive size for the antenna of the implant will make it inviable. Thus, b was chosen equal to 12 mm, taking into account the bigger antenna that would not be cumbersome to the animal. Furthermore, the parameter vertical distance between antenna planes was estimated at 25 mm, regarding the particular characteristic of the animal gait and the implant localization in the body.

Applying in the mathematical formulation the values indicated in the Table 1, it is possible to find the most adequate values for radius of interrogator antenna and output peek voltage of the Class E amplifier.

Table 1. Initial specifications for an example of inductive coupling biotemetry system for adult rat, in accord with Figures 1 to 3.

Parameter	Value
ω	$2\pi\times13.56\times10^6$ rad/s
b	12 mm
Interrogator block dimensions	12×12 cm
Section of the conductor used in the antennas	$35\mu\text{m}\times1$ mm
h	25 mm
$P_{1\text{-}2(min)}$	6 mW

In the first step, using (5), the mutual inductance variation in function of the lateral misalignment was computed for five different radii of interrogator antenna (Fig. 4). After that, the data for the five curves in the Fig. 4 were applied to (1) to find the curves of power in the equivalent impedance of the implant (Fig. 5). In this solution, a normalized value was considered for V_E.

The characteristic desired for the variation of $P_{1\text{-}2}$ is that it remains above of $P_{1\text{-}2(min)}$ for each point inside of the block. Additionally, it will be better for the system control, about the adjust of V_E, if $P_{1\text{-}2}$ had a lesser variation of value from the center of the block to its perimeter. After these observations, Fig. 5 shows that an interrogator antenna with radius of 30 mm is most adequate to establish communication over the block, with minimum shadow area, and at the same time avoid overlaping in the communication area of adjacent blocks. Furthermore, 2.6 is the multiplier factor for V_E, in order to make the value 0.917 mW in 6 cm scaled to the $P_{1\text{-}2(min)}$ value, as specified in the Table 1.

5. DISCUSSION

The locomotor activity measurement method introduced here, although could has a worse resolution than some others, offers three advantages over the alternatives described in literature.

First, the method allows estimate approximately the animal localization in the cage. Most of systems reported before does not have this capability. Localization, associated or not with LA, can be useful for some studies involving animal behavior. In addition, the method enables estimate the distance traversed.

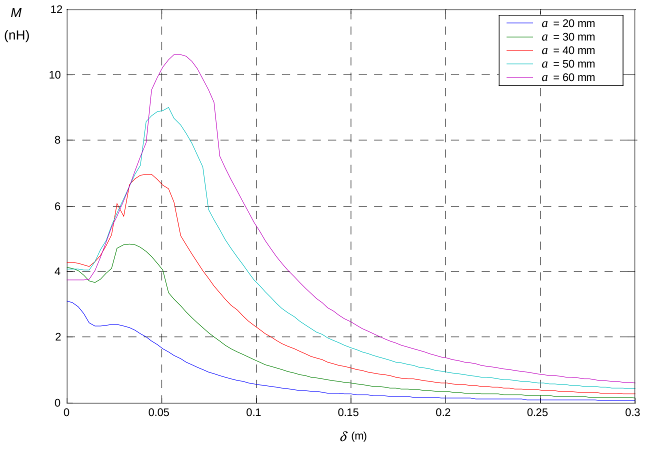

Fig. 4. Mutual inductance versus lateral misalignment for five radii of interrogador antenna.

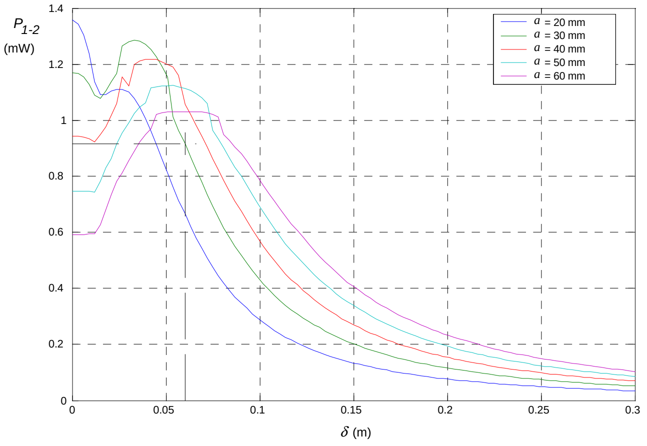

Fig. 5. Power in the implant equivalent impedance in fuction of the lateral misalignment for the five interrogator antenna radii. V_E = 1V.

Second, it was devised to be used in a scalable form. This means that each interrogator is proposed as a block independent of the others and the connections with the commutation controller are carried out via a shared serial bus. So, the user can customize the cage with a base format adequated to specific experiments, through of the fit of several blocks in accord with the geometry of interest.

The third advantage is the possibility of simultaneous monitoring of several specimens in a single cage, without interferences. That is possible as each animal has a implant with an exclusive ID number stored in the RFID IC. Current RFID ICs includes commands that, based on the exclusive ID, allows the interrogator to execute anti-collision algorithms in order to communicate with the implants in a sequential way.

In most of cases, authors believe that the proposed solution for LA measurement will be a complement for the implant main function. That is, as long as device with communication based on inductive coupling will be implanted in the animal for measurement of some parameter, the bonus of LA measures may be obtained without any additional burden for the implant circuit. This enhancement will have cost only for the extern monitoring subsystem, with an increase in the complexity of the commutation controller algorithms.

Additional steps the to present work will include experimental validation of the method, in that concerns to the mathematical modeling presented.

6. CONCLUSION

It was presented the proposal of new method for locomotor activity measurement in biotelemetry systems based on inductive coupling. The new method is naturally scalable regarding the confinement environment for the animal. Additionally, it also will makes possible the monitoring of several specimens in a same cage. These characteristics are absent in the most of the current alternatives. A mathematical modelling adequate to evaluation of parameters for system has been introduced.

REFERENCES

[1] R. Refinetti, "*Circadian physiology*," CRC Press, Boca Raton, FL, USA, ISBN 0-8493-2233, 2006

[2] V. Pasquali, E. Scannapieco and P. Renzi, "Validation of a microwave radar system for the monitoring of locomotor activity in mice", *Journal of Circadian Rhythms*, 4:7, May 2006.

[3] M. T. P. Silva, F.H. Vasconcelos and G.A.S. Pereira, "RF interface for intelligent arterial pressure sensor based in RFID technology," in *Proceedings of IMEKO 2008*, Florence, Italy, pp. 66-71,Sept. 2008.

[4] K. Finkenzeller, "*RFID handbook: fundamentals and applications in contactless smart cards and identification*," 2nd Ed., John Willey & Sons Ltd, England, 2003.

[5] ISO 14443-2:2001, "*Identification Cards – Contactless Integrated Circuit(s) Cards – Proximity Cards – Part 2: Radio frequency power and signal interface*", International Organization for Standardization, Geneva, Switzerland, 2001.

[6] B. Jiang at. al., "Energy scavenging for inductively coupled passive RFID systems," *in Proceedings of IMTC 2005*, Otawa, Canada, pp. 984-985, May 2005.

[7] M. T. P. Silva, "*Measurement, communication and RF powering techniques for implants of biological measures in small laboratory animals,*" development report for PhD Thesis, Electrical Eng. Dept., Federal University of Minas Gerais, Brazil, 2008 (*in Portuguese*).

[8] C. A. Balanis, "*Antenna theory, analysis and design,*" 2nd Ed., Wiley, New York, USA, 1996

[9] M. Loy and I. Sylla, "ISM-Band and short range device antennas," *Application Report SWARA046*, Texas Instruments, Inc., 2005.

[10] N. O. Sokal and A. D. Sokal, "Class E – A new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE Journal of Solid-State Circuits*, Vol. SC-10, No. 3, pp. 168-176, 1975.

[11] S. Ramo and J. R. Whinnery, "*Fields and waves in communication electronics*," 3th ed., John Wiley, New York, USA, 1994.

[12] M. Soma, D. C. Galbraith and R. L. White, "Radio-Frequency coils in implantable devices: misalignment analysis and design procedure," *IEEE Transactions on Biomedical Eng*., No. 4, pp. 276-282, April 1987.