Multi-Channel Wireless Bionic Goniometer System

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Abstract

The wireless electronic nervous system known as the Functional Electrical Stimulation-Battery Powered Bion\(^8\) (FES-BPB) System is being developed at the Alfred Mann Foundation. It contains a real time multi-channel magnetically linked distance measuring system\([1]\). This system can be used to measure limb joint angles, and distance in the range 1 to 15cm apart. The system is composed of two or more cylindrical battery powered micro devices (3.2mm x 24mm) that can be injected into the human body. One device can be programmed to be a magnetic field generator, and the other devices can each be programmed to be a receiver. Each receiver measures the signal strength from the generator, and transmits the signal strength via a UHF radio channel about 90 times per second to a receiver in a pocket sized master control unit (MCU) external to the human body. If the receiver and generator are between 1 and 15 cm apart, and properly aligned with each other, the signal strength can be calibrated as a function of the distance between them. Using digital filtering techniques about 16 different frequency channels can operate independently in the same space.

1. INTRODUCTION

The extreme low power and subminiature size constraints versus all the requirements determined the approaches and tradeoffs taken. Besides needing to measure joint angle for functional applications, one has to consider the use of these devices for safety shut-off and turn on situations. For example if there was a situation where the patient might hit his own face with all available force due to a command error, it might be desirable to monitor the distance between the face and the fist with a built in command to turn the stimulation off if the distance closed rapidly between the face and the fist.

This system is intended to be a subset of a more complex one where other implanted devices perform functions like bio-potential sensing, electro-stimulation etc. All the devices are battery powered and are able to communicate with a MCU through a separate, wireless RF link.

2. METHODS

Our distance measurement system is based on generating a low frequency magnetic field by an implanted device and measuring the strength of this field at another point by another implanted device (Fig. 1 and Fig. 2).

Fig. 2 illustrates the use of the implanted goniometry devices in an application for arm movement.

![Fig. 1: Goniometry System Principle.](image1)

![Fig. 2: Application of implantable goniometry for arm movement.](image2)
1) The coil already exists for the purpose of charging the battery.

2) The system is wireless.

3) Unlike high frequency RF fields, the low frequency (quasi-static) magnetic field has very little interaction with the body tissues. It interacts only with magnetic materials and relatively large metallic objects.

4) The strength of the field drops with distance very rapidly, according to an inverse cube law. This has the disadvantage of making it difficult to measure large distances but has also the advantage of reducing the effects of reflections, interactions with far objects, with other patients having similar goniometry systems or with other sources of interference.

5) It can be designed to operate over a reasonable distance with a low power drain. The goniometry system will not be able to work during battery charging but that will happen only about 10 minutes each day for most applications. The coils for the goniometry transmitter and receiver are identical and tuned on 127kHz. For optimal efficiency the coils are made on ferrite cylinders and have the following parameters:
   - Inductance: 540µH
   - Size (approx): L=10mm, OD=2.5mm
   - Quality factor: Q=21

   The tuning is important for the efficiency of both goniometry and charging.

In our implementation, the implanted devices are identical and each of them can function either as a goniometry transmitter or receiver. The relative position of the TX/RX coils is important. The best orientation is if they are parallel or co-axial. If the two devices are coaxial the received signal is twice as large as if they were parallel. Unfortunately, for joint angle measurements they cannot be coaxial for all angles and the signal strength may not be monotonic with the distance. Small misalignments however are not critical. For a 45° misalignment, the signal strength drops by \(\cos(45°)=0.71\) and the distance error is \((0.71)^{1/3}=0.89\) (11% error). For monitoring multiple movements, like the arm and shoulder joints the fixed transmitter can work with multiple receivers. If two different systems must co-exist, such as one for each arm, they must not interfere with each other. Our solution is to use slightly different frequencies (around 127kHz) for each system. All the frequencies (channels) must pass through the limited bandwidth (about 6kHz) of the tuned coil. The channel spacing is 91Hz and we implemented a total of sixteen channels. On the receiver side, a narrow digital filter will select the right channel from the others.

The system is capable of transmitting 90 measurements per second. The fastest arm closure is about a third of a second. Thus the system will provide about 30 measurements when rapidly closed from 180° to about 40°. This provides a data point every 4.0 degrees. Thus even an error of a missing data point is negligible.

A. Transmitter TX

The transmitter must apply a sine wave with a very well controlled frequency on its tuned coil. Synthesizing a sine wave followed by a linear amplifier consumes much power and a square wave applied on an L-C tank is inefficient and generates too many harmonics. Our solution is shown on Fig. 3.

![Fig. 3: Goniometry Transmitter](image)

As the tuned coil is actually a resonator, it tends to keep the sine wave without external intervention. It only requires a small amount of energy on each cycle to compensate the losses during that cycle. That is why we apply short (about 5%), differential current pulses through the FET switches M1-M4 on the coil. The current value (controlled by the resistors R1-R4) and the length of the pulses determine the amplitude of the generated waveform. For better efficiency the supply voltage is down-converted from 2.7V to 0.9V by a switched-capacitor converter. In this way we were able to apply a 1Vpp sine wave on the coil instead of 300mVpp for the same current consumption from the 2.7V supply. The capacitors in series with the coil are for DC isolation and are not necessarily required.

A digital frequency synthesizer clocked by a crystal oscillator generates the exact frequency for each particular channel. The transmitter consumes 15µA from a 2.7V supply.
B. Receiver RX (See Fig. 4)
The receiver has a super-heterodyne architecture for good performance and robustness. The filter can be digitally adjusted to the correct frequency to compensate for process variations.

![Diagram of the goniometer components](image)

A partial block diagram showing the goniometer part of the circuitry is shown in Fig. 4. The 127 KHz magnetic field is picked up by the coil.

The coil has three functions:
1) When picking up a large field it is used to charge the battery.
2) When picking up a weak field it is switched to the goniometer receiver where it is digitized and sent to the programmable band-pass digital filter.
3) The filter is programmed to select up to 16 different frequencies. The output of the filter which contains the distance information is then transmitted to the MCU via the UHF link. It can be used to generate a magnetic field if the MCU assigned a goniometer transmitter function to it.

3. RESULTS
The goniometry system has been implemented and tested.

The transmitter and receiver were incorporated into a microchip.

**Goniometer Transmitter characteristics:**
- Supply voltage: 2.7V
- Current consumption: 15µA from the 2.7V supply
  - (50µA from the 0.9V supply)
- Output amplitude: 900mVpp diff.

**Goniometer Receiver characteristics:**
- Supply voltage: 2.7V
- Current consumption: 15µA
- LO frequency: 131kHz
- Total gain: 37dB
- Maximum distance: 15cm

4. DISCUSSION AND CONCLUSIONS
Our goal was to measure distances of up to 20cm with 15µA drain from the transmitter and 6µA drain from the telemetry and housekeeping circuits the 3mAhr battery will last 6 days when operated 24 hours per day and 8 days when operated 16 hours a day. By doubling the current to the transmitter it is possible to increase the distance closer to the desired 20cm while reducing the battery run down time to about 3 days and 4 days respectively for the 24 hour and 16 hour situation. The range of operation is primarily limited by the total low power consumption requirement from the battery of 100 µW (four days of operation). With the power budget reported above, the maximum range was limited to about 15cm, due to noise on the analog receiver.

A new pre-amplifier was designed with more emphasis on low noise. For slightly more current consumption we expect a noise improvement to increase the measured distance to about 20cm.

References

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