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An Implantable Myoelectric Sensor Based Prosthesis Control System

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Abstract - **We present progress on the design and testing of an upper-extremity prosthesis control system based on implantable myoelectric sensors. The implant consists of a single silicon chip packaged with transmit and receive coils. Forward control telemetry to, and reverse EMG data telemetry from multiple implants has been demonstrated.**

I. INTRODUCTION

INCREASING the number of mechanical degrees of freedom available from a hand prosthesis beyond the current state of the art will allow a more accurate duplication of the functionality of a human hand. In order to effectively utilize the additional degrees of freedom a complex mechanical design would offer, a larger number of control signals must be collected from the user. It has been proposed that intra-muscular EMG signals from multiple residual muscles could be used to provide simultaneous control of multiple degrees of freedom in the prosthesis [1,2]. Wireless telemetry of EMG signals from sensors implanted in the residual musculature would eliminate the problems associated with percutaneous wires.

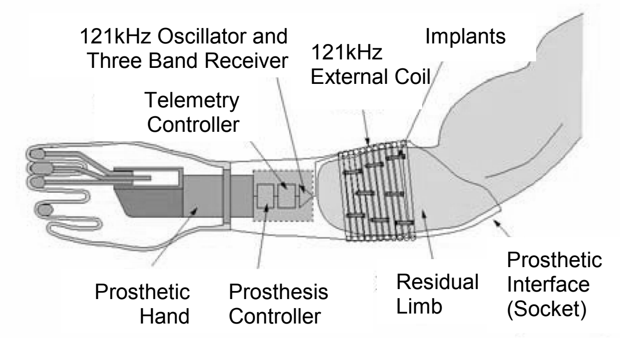

Fig. 1. Diagram of the IMES Prosthesis System (from [1])

A system (Fig. 1) using Implantable Myoelectric Sensors (IMES) would consist of multiple implanted EMG sensors ("implants") and a one-piece prosthesis. The implants are powered transcutaneously with a 121kHz magnetic field generated by an integrated high efficiency Class E power oscillator [2]. This powering magnetic field is modulated to send control signals to the addressable implants. EMG signals generated by the residual muscles at each implant site are amplified and digitized by the implants. A Telemetry Controller within the Prosthesis controls a time division multiplexing (TDM) sequence to orchestrate RF transmissions from each implant so that data from all implants may be sequentially collected by a receiver in the prosthesis. The Telemetry Controller demodulates the received signals and passes the collected multi-channel EMG data to a Prosthesis Controller. The Prosthesis Controller will control the prosthesis mechanisms in a programmed manner depending on the origin and nature of the collected EMG control signals.

This paper discusses the performance of prototype implant devices, the wireless power and data link, and the Telemetry Controller.

II. SYSTEM ARCHITECTURE

A. Overview

The system uses magnetic coupling to allow power and data transfer to, and data transfer from the tissue-encapsulated implants. All implants in the system are identical except for an 8 bit laser-programmed device address. The implant device address is used to assign unique operating parameters to each implant where necessary, including whether or not a particular implant is sending reverse telemetry EMG data ("active"). TDM constraints limit the number of active implants in the system, however implants may be activated and deactivated in several milliseconds, so it is possible to intelligently and dynamically distribute the available EMG telemetry bandwidth among up to 255 implants used with a single prosthesis.

The system architecture is designed to support up to 32 active implants on each of three RF bands of operation, 60kHz (Band1), 6.8MHz (Band2) and 13.5MHz (Band3). Although the architecture will support simultaneous multi-band operation of 96 active implants, the three available bands are intended as alternate real-time options should an external interfering signal preclude reliable data transmission

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on the selected band. Band 1 provides a very robust low rate data link, while Bands 2 and 3 are much higher rate links. The prototype system described herein is capable of data transfer on only one band at a time, but may be dynamically band-switched.

B. Inward Telemetry Link

Commands are sent to the implants in the system by frequency-shift-keying (FSK) modulating the 121kHz powering magnetic field. The Class E 121kHz power oscillator is comprised essentially of a high-Q resonant circuit which is excited by a very short high current pulse once each cycle of 121kHz. The resonant frequency of the circuit may be changed instantaneously from "F_{High}" to "F_{Low}" and with minimal loss by switching passive elements in or out of the resonant circuit at the proper time in the 121kHz cycle.

The implants use a patented method of FSK demodulation which compares the period of the current 121kHz cycle to the average period of the 121kHz magnetic field. To maintain a proper average and thus achieve optimal FSK data demodulation within the implant, a Manchester data encoding scheme is used to maintain an equal number of F_{High} and F_{Low} cycles during the transmission of an implant command. The data format used requires four 121kHz cycles per transmitted bit, so the inward telemetry bit rate is 30k bits per second.

C. Outward Telemetry Link

Implant data transmissions consist of bursts of a modulated RF carrier which occur in a 32 time slot TDM space (Fig. 2). The 32 time slots, 0 through 31, are termed a "Frame". Each implant contains a 32 bit Time Slot Assignment table (TSA table) and its own time slot counter to keep track of the current time slot. A "1" entry in a TSA table position tells the implant to transmit a data sample in the corresponding time slot. If the TSA table contains all 0's, the implant will never send data. 32 active implants may each be assigned a different time slot, or multiple time slots in a frame may be assigned to some implants to increase the EMG sampling rate for signals from those implants. The ability to dynamically allocate signal bandwidth to implants is anticipated to be a valuable attribute during control algorithm development. In Fig. 2 for example, Implant 1 has been assigned all even time slots, while other implants share the remaining frame space. System sampling rates for various numbers of implants is shown in Table I.

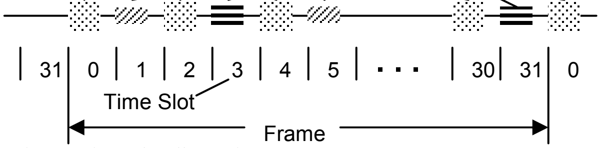

Fig. 2. Time Slot Illustration

Table I. Approximate System Sampling Rates

Number of Implants	32	16	8	1
Band 1	24S/s	48S/s	96S/s	768S/s
Bands 2 & 3	472S/s	945S/s	1.8kS/s	15kS/s

Data is sent by bi-phase shift keying (BPSK), where the phase of the RF carrier is not inverted ("Phase 0") during a Data 0, and inverted ("Phase 1") during a Data 1. The 121kHz magnetic field generated by the Class E power oscillator is used as the frequency reference for all signals generated in the system. By synchronizing the implant RF carriers to the system-wide 121kHz powering field, the RF carrier frequency of all the implants is identical and known, thereby simplifying the task of demodulation. RF carrier generation in the implant is accomplished by division (Band1) or multiplication (Bands 2 & 3) of the 121kHz reference frequency using a divider or phase-locked loop in each implant. The time slot counter in each implant is also clocked by the 121kHz reference frequency, and a global "ReSync" implant command exists which causes all implants to zero their individual time slot counters almost simultaneously, thereby maintaining the time slot alignment of all implants in the system.

Differences in implant physical orientation and position, as well as subtle differences in 121kHz implant coil characteristics may cause a relative phase difference of the detected 121kHz reference between any two implants. For this reason, time slot 0 in one implant may not exactly align with time slot 0 in another. In addition, any 121kHz reference phase difference will result in multiple cycles of phase difference at the multiplied RF carrier frequency.

In order to accommodate this implant-to-implant variation of 121kHz reference phase shift, each implant transmission contains a data preamble and carrier phase reference (Fig. 3). Using the preamble, the demodulator establishes the reference carrier phase ("Phase 0") as well as bit synchronization. During the early portion of the preamble, the Telemetry Controller demodulator also performs I and Q demodulation at the RF frequency to determine the optimal phase with which to synchronously detect the RF carrier.

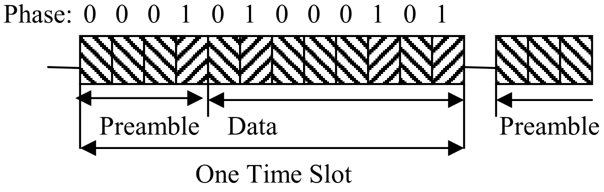

Fig. 3. Implant Transmission Format – Band 1 (60kHz)

In the interest of system optimization, the number of preamble and data bits, as well as the guard gap between time slots is dynamically programmable via the 121kHz FSK command link to the implants.

The data format in Bands 2 and 3 is identical to that in Band 1, but each bit is sent twice in a time interleaved fashion (Fig. 4). The current switching pulses in the Class E oscillator generate appreciable amounts of RF energy at the Band 2 and Band 3 frequencies. This RF interference is large in amplitude but relatively short in duration. To allow data transmission in the presence of this interference, data bits in Band 2 and Band 3 are sent twice. The synchronous nature of the system design insures that one copy of the data will be received. The orientation of the implant in the magnetic field will determine where the noise pulse lies in relation to the data, hence whether the first or second copy will be used.

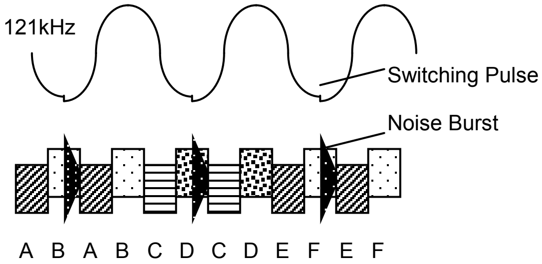

Fig. 4. Redundant Data Transmission – Bands 2 and 3 (6.8MHz and 13.5MHz)

III. THE PROTOTYPE SYSTEM

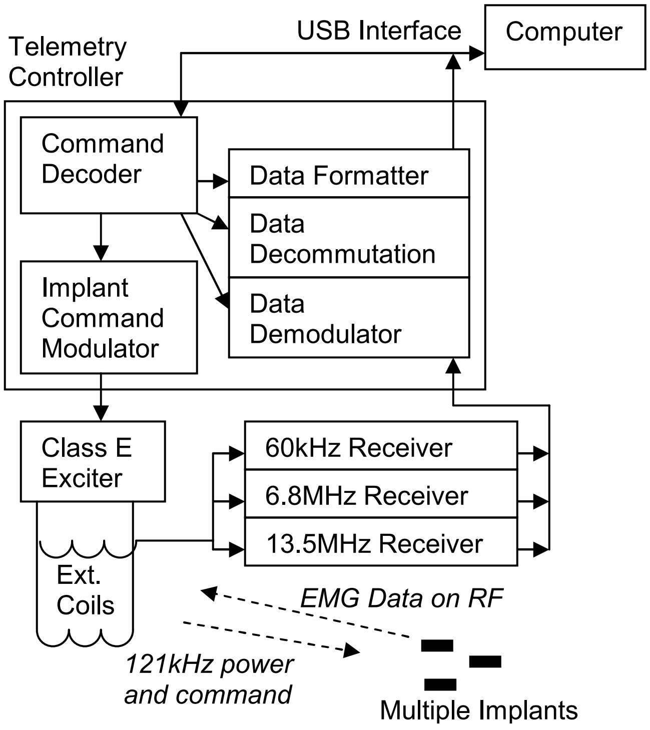

Fig. 5. Prototype System Overview

A. Overview

The prototype system (Fig. 5) is constructed from discrete commercial devices and a custom “S5800b” Class E power oscillator controller device developed by Sigenics Inc. This device includes the Class E oscillator control, FSK modulator, FET drivers, data FIFO and serial interface.

Receiver components will eventually be integrated into custom silicon to reduce the size and power requirements of the prosthesis electronics. In the prototype, a USB interface is used by an external computer to communicate with the Telemetry controller, allowing external computer control and display of implant parameters and collected EMG data. The USB interface may or may not be present in a final prosthetic system.

B. The Implant

The implant (Fig. 6) is a single-chip integrated silicon device mounted on a ceramic substrate along with a surface-mount power supply filter capacitor. This subassembly is sandwiched between two halves of a cylindrical magnetic core. The 121kHz power coil and the RF coil are then wound over the core. The electronics are encapsulated in a ceramic package which includes metal endcaps at either end between which the EMG signal is measured.

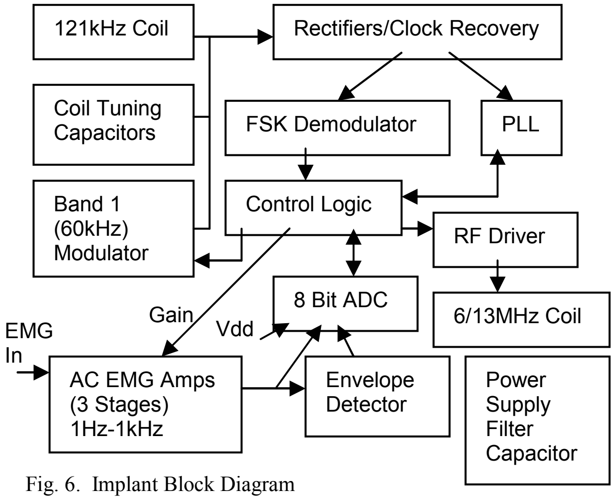

Fig. 6. Implant Block Diagram

As shown in Fig. 6, the EMG potential between the package endcaps is amplified by three stages of AC coupled programmable-gain amplifiers. The gain is programmable via the command link logarithmically with 6 bit resolution as shown in Fig. 7. The amplifier chain has an input-referred noise of 15uVrms with a 1.0Hz – 1kHz bandwidth, and includes 1kHz anti-aliasing filters.

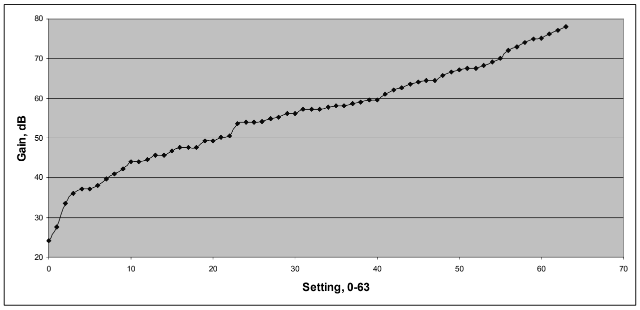

Fig. 7. Amplifier Chain Gain vs. Control Setting

An envelope detector with a 50mS time constant follows the amplifier chain to offer a lower-bandwidth view of EMG activity. Either the envelope-detected or wideband EMG may be dynamically selected. In addition, the chip power supply Vdd, and the implant address may be monitored for system diagnostic purposes. A CAD layout of the silicon device is shown in Fig. 8.

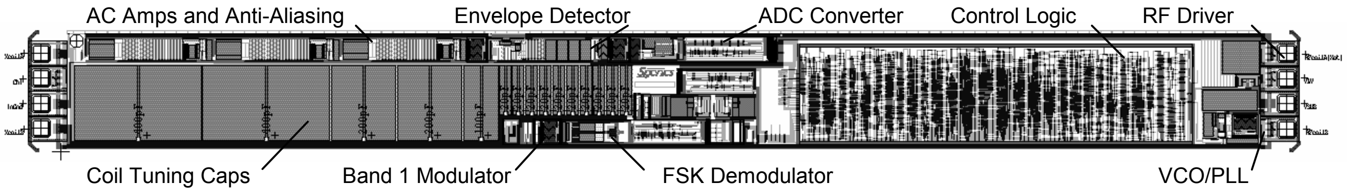

Fig. 8. Implant Silicon Layout

IV. PRELIMINARY PERFORMANCE RESULTS

The package design and assembly, as well as antenna development are still ongoing. Chips were mated to coils using SOIC packages for prototype testing. Fig. 9 is a scope trace showing the operation of two implants. The frame rate is 473Hz. Implant 0 samples a test signal eight times per frame (3780S/s) in time slots 0, 4, 8, …28, while Implant 1 samples its own Vdd once per frame in time slot 31.

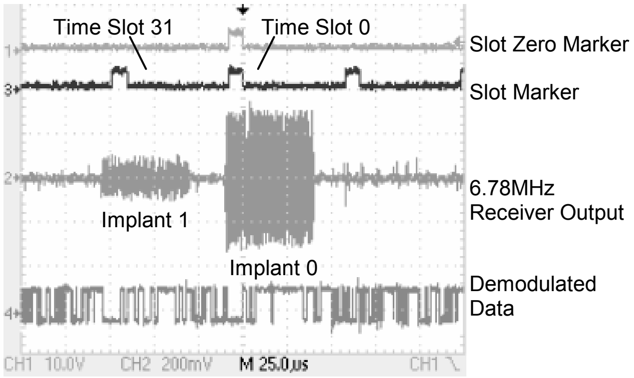

Fig. 9: Two Implants, One Frame

Telemetered signal waveforms were captured via the USB port on the prototype, where a significant amount of wild-point noise was observed. This noise is caused by unanticipated variations in the implant VCO frequency and phase, which reduce the data noise margin in the demodulator. The VCO jitter is about 14 degrees rms, and the VCO also demonstrates a frequency step (about 3%) during Vdd variation during the outward telemetry. These issues will be addressed in the next version of silicon. Representative waveforms are shown in **Figs.10-12**. These waveforms were taken with the implant sampling eight times per frame and a frame rate of 473Hz.

Outward telemetry on Band 1 displayed no wild-point noise because the 121kHz/2 used as the RF carrier is unaffected by VCO/PLL jitter.

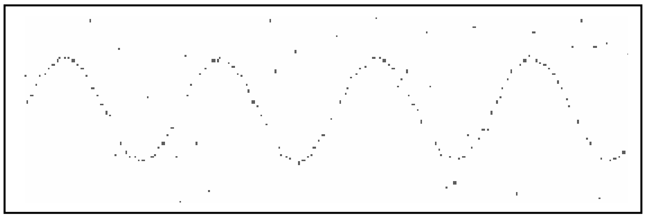

Fig. 10. Telemetered Data Output: Vin=1.3mVp-p, 100Hz sine wave. Gain=59dB.

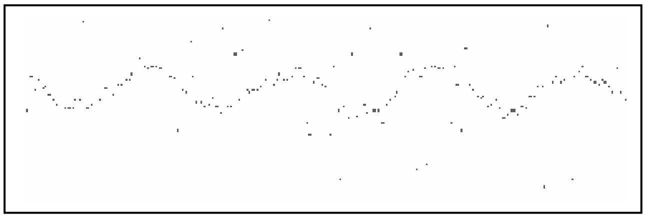

Fig. 11. Telemetered Data Output: Vin=100uVp-p, 100Hz sine wave. Gain=70dB.

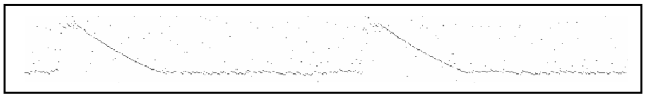

Fig. 12. Telemetered Data Output: Envelope Detected Vin=1.3mVp-p, Gain=58dB. Signal is a burst of 5 cycles of 400Hz at a 5Hz burst rate.

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[3] Schwan, M., Troyk, P., "Suspended carrier modulation for transcutaneous telemetry links", Proceedings 13th International Symposium on Biotelemetry, March, Williamsburg, VA pp. 27-32 (1995).