

A MODULAR EXTERNAL CONTROL UNIT FOR FUNCTIONAL ELECTRICAL STIMULATION

Stephen C. Trier^{*}, James R. Buckett^{*}, Alexandru Campean⁺, Michael E. Miller⁺,
Fred W. Montague^{*}, Tina L. Vrabec^{*}, Jeff A. Weisgarber^{*}

Cleveland FES Center:

^{*} Case Western Reserve University

⁺ Louis Stokes Cleveland VA Medical Center
MetroHealth Medical Center

Abstract

A modular external control unit (ECU) for Functional Electrical Stimulation (FES) is expected to provide flexibility and capability beyond current ECUs. The earlier units require duplication of effort in design and maintenance, are specialized for a single FES application, and lack sufficient flexibility to serve both laboratory and clinical research needs. The new ECU supports diverse uses through modular hardware and software and a rapid prototyping software system. The completed portions of the new controller function as expected.

Introduction

FES systems at the Cleveland FES Center consist of an external control unit (ECU), an implanted stimulator/telemeter, electrodes and lead wires. The ECU generates stimulus pulses for surface and percutaneous electrodes, monitors sensors and command inputs, and provides power and control signals for implants. The center has previously developed a number of ECUs, the current versions of which are the Neuroprosthetic Stimulator 4 (NPS-4) for hand, wrist and arm control, and the Lower Extremity Control Unit (LECU) for stepping, standing, and respiratory pacing. [1,2] These ECUs have been successful: 22 LECUs and more than 55 NPS-4s have been built.

Despite the success of the NPS-4 and LECU, they suffer from a number of limitations. First, they require duplication of effort in hardware and software. Second, their software has a monolithic structure that has proven to be hard to modify. Third, they are “one size fits all” compromises that cannot fill the full range of needs from laboratory to clinical, “take-home” use. Finally, they are not able to support new FES applications without significant modifications.

Each ECU was developed to serve a specific application with little commonality of design. Each ECU has hardware interfaces unique to the problem area, such as finger switch inputs on the LECU and a shoulder/wrist transducer input on the NPS-4. Furthermore, the software written for each ECU is

specialized for that ECU’s intended application, with no code in common between the systems.

Changing the software in the ECUs is difficult, discouraging their use for research in FES control techniques. Changes must be written in low-level C or assembly language. A tightly integrated software structure means algorithms can be changed only with the assistance of an experienced software engineer. Despite his or her best efforts, the software engineer inevitably becomes a bottleneck, slowing down the rate at which new ideas can be tried and made available to research participants.

The ECUs also must serve an audience with wide-ranging needs. The current ECUs were designed with clinical use in mind and therefore traded off channels and computational power for size, weight, and battery life. Some of the ECU users, however, need maximum flexibility for laboratory use. They seek a large number of input and output channels controlled by a fast and easily programmed processor.

Furthermore, the NPS-4 and LECU do not adapt readily to other FES applications. We would like to be able to explore new FES applications, such as bowel and bladder control, without having to design a new ECU or make major changes to an existing design.

FES applications share fundamental similarities, no matter the parts of the body involved. We therefore decided to develop a multi-purpose ECU useful in all of the problem areas in which the Cleveland FES Center works. This modular Universal External Control Unit (UECU) is intended to replace all of our current ECU designs. It is modular in both the hardware and software senses and may be configured to serve a broad range of users and diverse FES applications.

Methods

The UECU’s modular design (Figure 1) encompasses operation as a wearable stimulation controller, as a personal computer (PC) peripheral, and as a full-featured laboratory stimulation system. Up to sixteen modules can be attached to the Inter-Module Bus (IMB). By varying the module selection, a tradeoff may be made between stimulus and data-acquisition

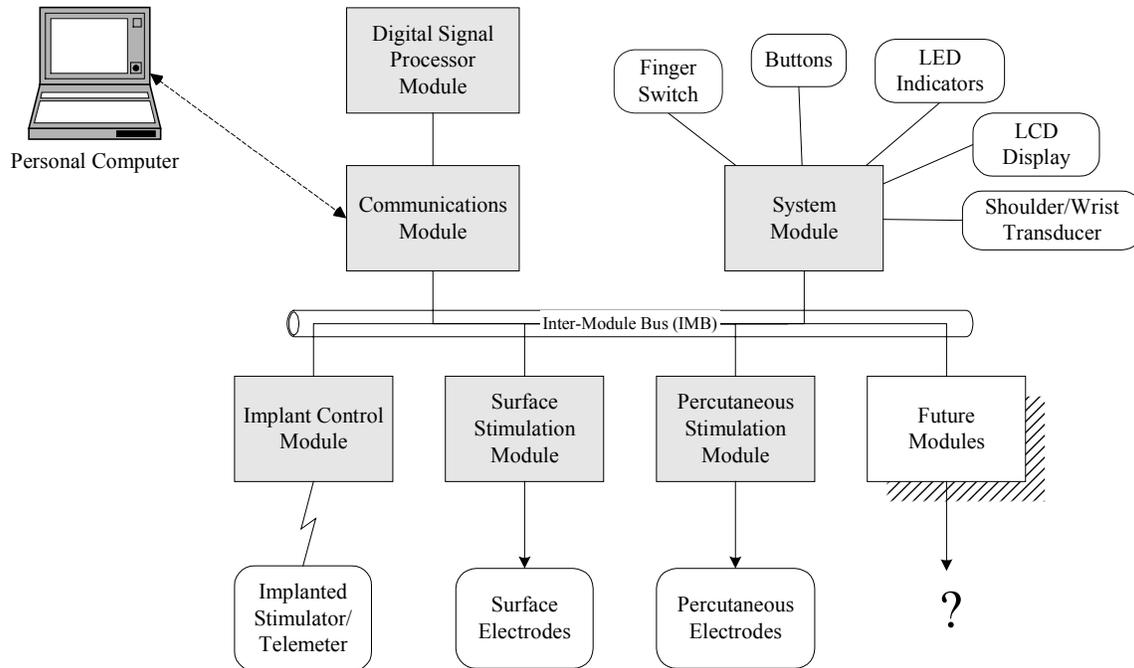


Figure 1: A conceptual diagram of the UECU shows the modules that may be attached. Up to sixteen modules, of any mix of those shown, may be included in the system.

capability, computational resources, and battery lifetime. The UECU may be commanded by an external personal computer, or it may operate as a self-contained system.

The UECU Modules

The Communications Module is the heart of the system. This module provides coordination between the other modules and can relay data to and from a personal computer. The Communications Module has sufficient memory and computational capacity to run typical FES application programs internally, receiving data from the other modules and commanding stimulation as appropriate. In addition to several communications interfaces, the module is equipped with a 16-bit microprocessor and three megabytes of memory.

The Digital Signal Processor (DSP) Module provides high-speed computation capability for the system. The Communications Module acts as an input/output coprocessor for the DSP when the DSP module is present.

The Implant Control Module can control one or two implanted FES devices. It includes a 16-bit microcontroller and the radio frequency (RF) circuitry needed to power, command, and recover data from two Implanted Stimulator/Telemeter [3] or Implanted Receiver/Stimulator devices. [4] The module can retrieve command data from an implanted joint angle transducer or myoelectric signals. It outputs approximately half a watt on each implant channel at a

crystal controlled frequency between 6 and 7 MHz. Communications with the implant uses a mix of on-off keying of binary data at 100 or 200 kilobits per second and pulse duration modulation in 1- μ s steps from 0 to 255 μ s.

The Surface Stimulation Module and Percutaneous Stimulation Module provide stimulation pulses to surface and percutaneous electrodes, respectively. Both use 16-bit microcontrollers.

The System Module connects to the user-interface elements of the system, including switches and buttons, shoulder and wrist position transducers, displays and indicators, and an audio annunciator. The mix of user-interface components included in a given UECU system will vary depending on its application area. The System Module carries a 16-bit microcontroller.

The design of the system does not restrict the type of modules that can be included. Future needs can be met by adding new modules to the system.

Communications

The modularity of the system rests on the Inter-Module Bus and a packet-based network protocol. The bus is a shared serial link that permits any module to send a packet to any other. An arbitration protocol prevents collisions between packets on the bus.

The network protocol is the foundation of the modular software architecture. It is used by all of the modules and by the external PC to exchange commands

and data. Carefully documented, it serves as a fundamental programming interface for FES software development.

Software

A system of this complexity requires appropriate software support. In addition to conventional programming in the C language, a rapid prototyping tool based on the *Simulink* and *Real-Time Workshop* tools from The MathWorks will provide a simple way to investigate new control algorithms. [5] The cost for the convenience of rapid prototyping is reduced power efficiency and shorter battery life. Therefore, we expect that before moving to clinical use, algorithms that have proven themselves in the rapid prototyping system will be re-implemented in hand-written C.

Because the network protocol is documented for external use, the system can also be commanded by a program running on an external personal computer.

Typical Configurations

Multiple modules of each type can be included in a UECU, making possible systems that control hundreds of stimulus channels of various types. The design can accommodate parallel processing with multiple Communications and DSP modules, though we do not currently plan to take advantage of this capability.

A typical "take-home" wearable system will consist of a Communications Module, a System Module, and an Implant Control Module. Some users will need a Percutaneous Stimulation Module as well. If advanced algorithms are to be used, a DSP Module will be included. The modules and a rechargeable battery will be mounted in a plastic box 8 x 5.5 x 14 cm and will weigh less than 0.5 kg.

Laboratory-oriented configurations will trade off size for flexibility by combining the Communications and DSP modules with multiple implant, percutaneous, and surface modules.

The Implant Control, Percutaneous Stimulation, and Surface Stimulation modules are also capable of stand-alone operation as a peripheral to an external computer.

Phased Development

UECU is being constructed and released to its users in a phased manner. Portions of the system have been constructed and tested, and development is proceeding on the remaining portions.

The rapid prototyping software was developed as a proof-of-concept system and tested by creating and compiling Simulink models of an upper-extremity FES algorithm used by NPS-4.

Because all communication within the system relies on the network protocol, the protocol has been implicitly tested as the rest of the system was developed.

Results

Three Implant Control Modules have been built. One is in use as an implant development tool, controlled by a personal computer running software written in Tcl/Tk. The other two are being used in further UECU development.

The rapid prototyping software system, in its proof-of-concept form, has generated control programs for a Communications Module, Implant Control Module, and IST-10. The generated programs ran successfully.

Discussion

Because the realized UECU modules and software have worked as designed, we expect to be able to eventually replace the NPS-4 and LECU with UECU.

Design and prototyping of the communications, percutaneous, and surface modules is proceeding. The DSP and System Modules are expected to follow soon.

The rapid prototyping software and documented network protocol provide two levels of control for which FES application software can be written. Both have been demonstrated to work. We are expanding and revising the rapid prototyping software to take into account the lessons learned from the proof-of-concept version.

References

- [1] Keith, M.W., *et al.* "Implantable Functional Neuromuscular Stimulation in the Tetraplegic Hand". *Journal of Hand Surgery* (Jan. 1989) 14A; 3. (524-530).
- [2] Buckett, J.R., *et al.* "A Wearable Controller for Clinical Studies Involving Multi-Implant FNS Systems". *The Journal of Spinal Cord Medicine* (April 1998) 21; 2 (179).
- [3] Smith, B., *et al.* "An Externally Powered, Multichannel, Implantable Stimulator-Telemeter for Control of Paralyzed Muscle". *IEEE Transactions on Biomedical Engineering* (1998) 45; 4 (463-475).
- [4] Smith, B., *et al.* "An Externally Powered, Multichannel, Implantable Stimulator for Versatile Control of Paralyzed Muscle". *IEEE Transactions on Biomedical Engineering* (1987) 34; 7.
- [5] *Simulink* and *Real-Time Workshop*, version 3, The MathWorks, Natick, MA, 1999.

Acknowledgments: This work was supported by the Office of Research and Development, Rehabilitation Research and Development Service, Department of Veterans Affairs and the Neural Prosthesis Program, National Institute on Neurological Disorders and Stroke, National Institutes of Health.