

## Development of an Implantable Networked Neuroprosthesis

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### Abstract

*Neuroprosthetic devices are powerful tools providing functional enhancement for individuals with central nervous system disorders, such as spinal cord injury and stroke. Life sustaining and enhancing independent functions such as breathing, standing, walking, grasping, reaching, micturition, and defecation have all been clinically demonstrated using neuroprostheses. Existing implanted neuroprosthetic systems utilize considerable external powering and signal processing, and each system must be customized to the specific application for which it is intended, severely limiting progress in the field and delaying the introduction of new technology to the end user. The Networked Neuroprosthetic System (NNPS) is based on a network of small implanted modules, distributed throughout the body, and linked to a centralized power source. The modules are connected through a network cable that distributes power to each module from a central rechargeable lithium-ion battery. Each module contains processing capabilities, communicates with other modules via the network cable, and is reprogrammable over the network using a central wireless transcutaneous link. The NNPS is extremely flexible and can be scaled to meet the technical needs of a broad range of neuroprosthetic applications through the selection of the appropriate modules providing the means for broader clinical application of neuroprostheses.*

### 1. INTRODUCTION

Many implantable stimulators have been developed for use in neuroprostheses [1,2]. The fundamental configuration of existing neuroprostheses has remained virtually unchanged since their introduction and have been described as “centralized-link systems” [3]. The neuroprostheses share many features in common. First, major components of the systems are implanted, allowing precise delivery of

the stimulation to the desired neural structure(s) and minimizes much of the external apparatus in order to improve reliability, user acceptance, and cosmesis. Second, many of these neuroprostheses are multi-channel, requiring several stimulus outputs to deliver electrical current to distributed sites, and at least one sensor input for automatic control and/or user command. Third, and most importantly, all of these devices are inflexible “single application” systems, in which the neuroprosthesis addresses only one function and cannot easily be extended beyond the primary indication for which it was intended. Fourth, most of these devices are externally powered and controlled via magnetic induction through tuned coils. While this may be one successful strategy for clinical applications involving only a single organ system (vision, audition, deep brain stimulation), it is not a viable long term strategy for individuals with multi-organ system dysfunction. In contrast to single system disabilities, individuals with central nervous system damage, such as spinal cord injury, stroke, cerebral palsy, and multiple sclerosis, generally have more complex involvement of many organ systems. For example, a spinal cord injury at the thoracic level can be expected to compromise sensory and motor function in the trunk and lower extremities, and simultaneously diminish control of the bladder and bowel. A stroke survivor often will have major involvement of an entire upper extremity as well as the ipsilateral leg. A person with tetraplegia will have significant loss of function in both legs, the bowel and bladder, the hands and arms, and trunk, along with respiratory compromise. For these reasons, currently available neuroprostheses, using the centralized-link configuration, although highly successful under constrained circumstances, are now approaching the limit of what can be reasonably achieved using this architecture [3,4]. A fundamentally different approach to implanted neuroprostheses is needed if the field is to continue to advance and persons with complex multi-system

disabilities are to benefit more extensively from neuroprosthetic interventions.

## 2. METHODS

Several aspects of technology have significantly advanced the capabilities for improved design of implanted neuroprostheses. Neuroprostheses can particularly benefit from the significant advancements in the commercial portable communications and computing products arena. These include: powering (impressive advances in secondary cell technologies e.g. Li-ion), communication methods (abundance of robust, standard, communication protocols), circuitry (major advances in high-level integration and component miniaturization), neural interfaces (increasing selectivity of stimulation and recording sites), and leadwires (introduction of new materials, advances in manufacturing techniques, proven longevity). The availability of new technologies allows us to design and develop a revolutionary new neuroprosthetic system for restoration of motor function. This system is fully implantable and utilizes an open architecture that enables it to be scalable and flexibly employed in a multitude of clinical applications. The system utilizes modules that provide various sensing and stimulation functions, linked together by an intrabody network, enabling reconfiguration for multiple applications or expandability within a particular individual. This Networked Neuroprosthetic System (NNPS), shown schematically in Fig. 1, utilizes small implanted modules distributed throughout the body connected to a central power source. Each module contains processing capabilities in order to minimize the message rate between them, and can be programmed through a bidirectional transcutaneous link. The modules are connected to the network through a multi-conductor lead that distributes power and provides a data link between each module, thus simplifying clinical implementation by minimizing lead routing through the body. Network communication utilizes an extension of the industry standard controller area network (CAN) protocol. The NNPS receives power from an implanted lithium ion battery that is rechargeable through a central transcutaneous inductive link. The design of the NNPS allows the neuroprosthesis user to eliminate all external components during functional activities, resulting in systems that are easy for the users to operate, are robust, are cosmetically acceptable, require no or minimal routine setup (donning of external devices), and are applicable to a broad range

of neurological indications. The open networked architecture allows the NNPS to be applied equally well to modest disabilities using a few components or severe disabilities requiring many more components. More importantly, the open and flexible architecture allows others to develop their own hardware, software, and control schemes specific to their application as additional modules on an existing networked system. This novel architecture also facilitates system expansion, technical upgrades and functional enhancements. The use of implanted power storage, fully implanted sensors, and high performance internal processors will free the user from a multitude of external devices during normal operation while also allowing the development of much more sophisticated and functional control algorithms. Thus, we believe that the NNPS is both a fundamental breakthrough in the design of neuroprostheses as well as being an enabling technology that provides a platform upon which clinical applications can be developed for a multitude of neurological disorders.

## 3. DISCUSSION

The NNPS implementation is appropriate for all existing and proposed motor neuroprosthetic applications currently being pursued worldwide because of its scalable network infrastructure. The internal network topology consists of a central Access Port with one to four Network Segment Cables connected in a star topology. The star topology was selected in part to provide independent network segments to each limb and to let the Access Port perform as the network arbitrator. Each Network Segment Cable has a bus topology where all modules are connected in parallel to the cable. The individual limb network segments operate autonomously and the Access Port arbitrates necessary data transmissions between segments.

Our design is based on four basic components, Fig 1: 1) an Access Port that provides system power and a transcutaneous link for programming, 2) Actuator Modules such as muscle-based or nerve-based stimulators, 3) Sensor Modules, such as myoelectric signal sensors, and 4) one or more Network Segment Cables that deliver the power and communications for the system. These components are modeled in Figure 1. The Access Port contains a Li-Ion rechargeable battery and capacity to support up to four network segments. The actuator and sensor modules contain their own processing capability and network interface. Communication between modules

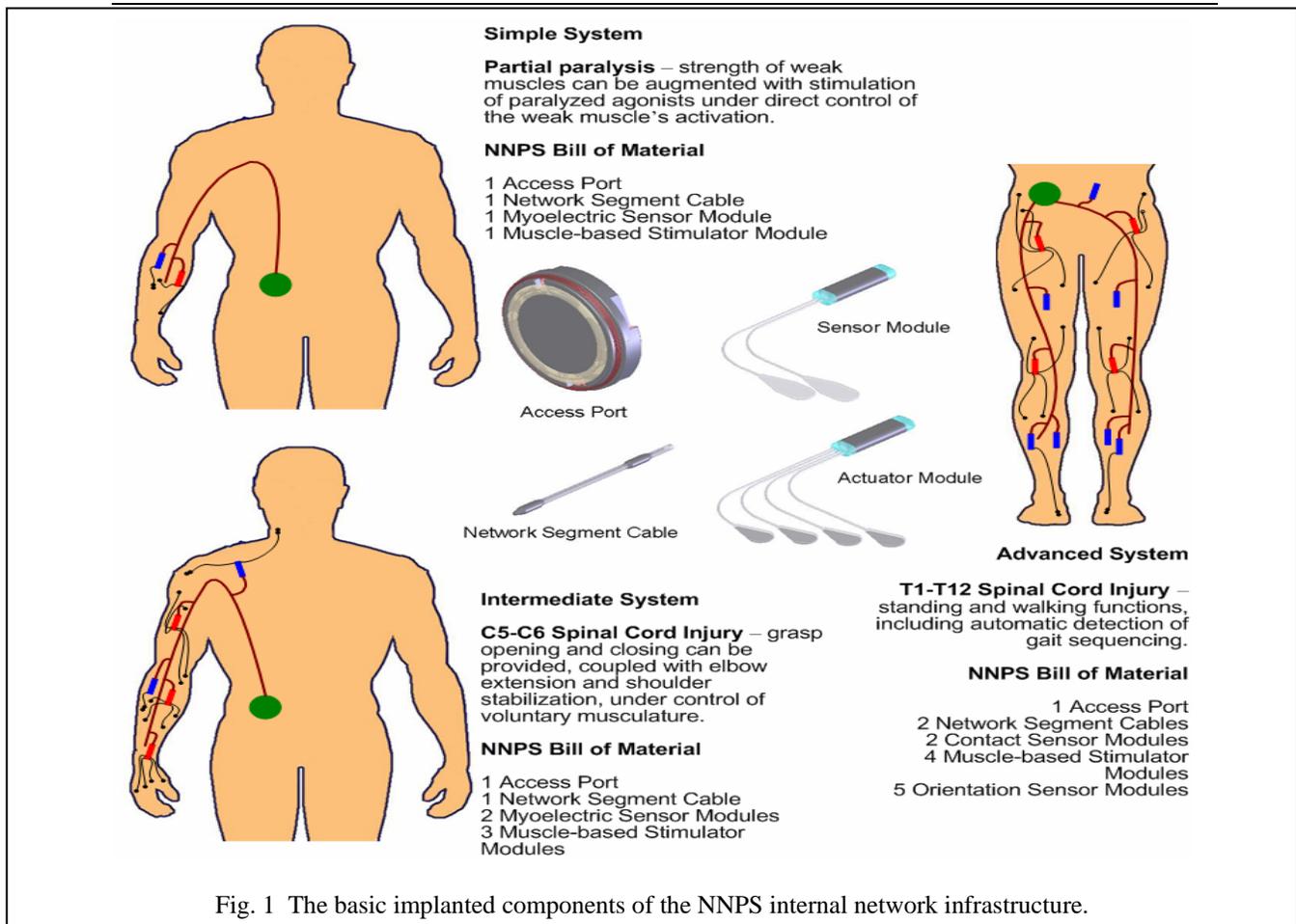


Fig. 1 The basic implanted components of the NNPS internal network infrastructure.

utilizes the Controller Area Network (CAN) protocol, which is commonly used in distributed embedded systems for real-time applications such as industrial control or the automotive industry. The network segment cables are the physical interconnect medium of the network backbone.

#### 4. SUMMARY

Neuroprostheses are an effective means for providing function for individuals with disabilities. Implanted neuroprostheses have been demonstrated to provide a significant improvement over all existing alternatives for treatment, and some of these systems have now become broadly available. There is a great potential for neuroprostheses to provide even more function, and to impact a much broader range of disabilities. However, one major impediment to further progress is the inflexible centralized architecture of existing implantable neuroprostheses. It is necessary to make a step-change in the design of these systems and progress to an architecture that allows flexibility and scalability so that it can be generalized to multiple applications. In addition, it is important that new neuroprosthetic systems eliminate the need for

externally-worn components, while at the same time minimizing the surgical installation and servicing effort. The NNPS can meet these stringent requirements and will enable the field of neuroprosthetics to expand more quickly and more broadly than ever before.

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