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Safety Measures Implemented for Modular Functioning Electrical Stimulators

Chiun-Fan Chen, Jin-Shin Lai, Shih-Wei Chen, Yin-Tsong Lin and Te-Son Kuo

Abstract—**The modular architecture allows for greater flexibility in the building of neural prostheses with a variety of channels but may result in unpredictable accidents under circumstances such as sensor displacements, improper coordination of the connected modules and malfunction of any individual module. A novel fail-safe interface is offered as a solution that puts in place the necessary safety measures when building a module based functional electrical stimulator. By using a single reference line in the interconnecting bus of the modules, various commands would immediately be directed to each module so that proper actions may be taken.**

I. INTRODUCTION

There have been several studies [1]-[2] proposing safety mechanisms that go beyond standard electrical parameters for use in sending electrical impulses to the paralyzed muscles, i.e., functional electrical stimulation (FES). The evaluation of FES techniques for both safety and effectiveness is usually targeted at a specific use. In situations when different muscle groups are to be controlled for a particular task, channel expansion would be necessary for the FES technique applied to the task. Instead of having to modify the FES hardware each time a different number of muscle groups are to be stimulated, we propose use of a modular architecture that utilizes a 2-channel FES module unit to expand the FES system. Although modular architecture has been applied in the building of neural prostheses [3]-[4], it has yet to be used as a way of providing versatile channels for an FES system. When building an FES system with FES modules, safety should be an issue that requires extra care. This is due to the fact that each FES module (2-channel FES) is actually an independent system, which is interconnected with other modules through additional wiring. Hence, problems may arise due to incorrect coordination of any FES module, which may result in erratic twitches, severe tremors, or overstrain. These incidents are more likely to occur in cases when physically challenged subjects are made to operate neural prostheses with their residual motor abilities, which are applied in the design of the state-of-the-art neural prosthesis [5]. Our proposed study is to build a modular FES that provides a fail-safe interface that is robust, straightforward, and can function independently of control signals that require standard decoding.

II. SYSTEM ARCHITECTURE

Clinical FES is generally designed with all required channels built in a single circuit board. In contrast, the FES applied in this study consists of numerous 2-channel stimulators in modular form. Fig. 1 illustrates the block diagram of the FES including three 2-channel stimulators and a battery unit interconnected with a bus. A key line in the bus, which is coupled to each stimulator's core circuit through a fail-safe interface, serves as the reference line for inter-modular communication. The key line should provide an analog reference that indicates the condition of the FES system. The stimulators are controlled by the attached sensors and are powered on or off by the key line reference voltage.

Fig. 2 illustrates the fail-safe working mechanism of each stimulating module. A power on signal provided by the key line "on" state turns on the modular stimulators connected to the bus. Data is received from the sensors of each stimulator and stimulation is controlled by the processed data. If the key line voltage decreases, the slew rate of the voltage decrease is calculated and responded appropriately by each stimulator. All stimulators are eventually turned off after the key line voltage reaches the key line "off" state. The working mechanism is implemented step by step as set forth in the descriptions of Figs. 3, 4 and 6.

Fig. 3 illustrates a key line voltage generating circuit that generates key line voltage transmitted to all stimulating modules coupled to the bus. The voltage and current of the key line is controlled by a switch and a current limiting circuit. The current limiting circuit limits the maximum current flowing through the key line between the stimulating modules. The switch, on the other hand, turns the key line on or off either through power on/off commands in the local circuitry or through the key line status of the modular system. Only

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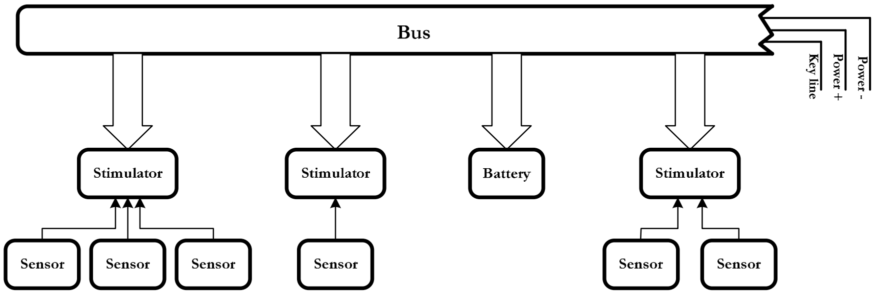


Fig. 1. Block diagram of the modular FES system

one key line voltage generating circuit is required for the entire system

Fig. 4 is an emergency cutoff circuit that is intended to respond to the dead-man-switch (DMS) or a general status alert. An unusual state detected from DMS or calculated result from the attached sensors of any single modular stimulator would pull the key line into the key line "off" state. The key line "off" state also turns off the key line voltage generating circuit of Fig. 3 by means of the key line status signal.

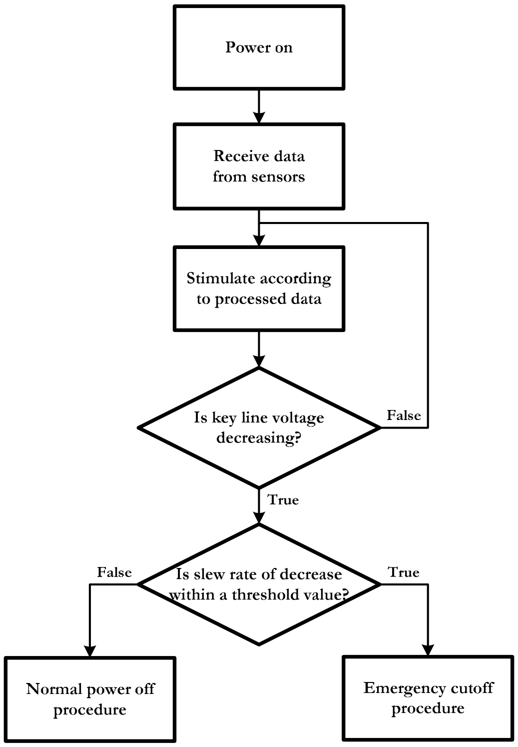


Fig. 2. Flow chart of the fail-safe working mechanism

The power off in Fig. 3 and the emergency cutoff in Fig. 4 should result in the same key line "off" state regardless of their difference in command origins. Nonetheless, the turning off process occurs at different slew rates. Referring to Fig. 5, the emergency cutoff command brings the key line voltage to the "off" state in a faster pace. This is because the emergency cutoff command pulls the key line directly to a reference ground while the power off command merely turns off the power supply of the key line circuitries. Different resistances to the reference ground would result in different key line time constants to reach "off" state. Hence, a slew rate monitoring circuit would be able to differentiate a power off command originated from the key line voltage generating circuit and an emergency cutoff command originated from any of the modular stimulators coupled to the bus. Appropriate actions are then taken by all stimulators when an emergency cutoff command is detected.

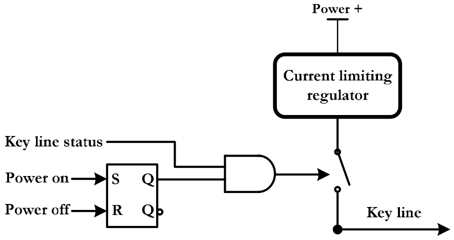


Fig. 3. The key line voltage generating circuit

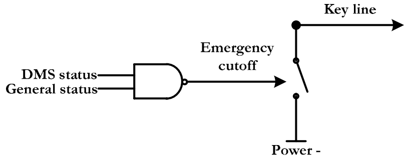


Fig. 4. The emergency cutoff circuit

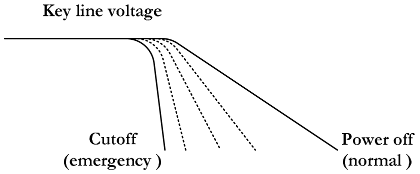


Fig. 5. Different slew rates of the key line being driven into "off" state

Fig. 6 illustrates a slew rate monitoring circuit coupled to the core circuit of a stimulator. The slew rate monitoring circuit outputs a cutoff status signal to inform the core circuit when an emergency cutoff command is detected. A delay circuit composed of resistors and capacitors suspends the key line "off" state that turns off the stimulator to allow the stimulator core circuits sufficient time to take the appropriate corrective actions (e.g., to return an actuating arm to its default position) before the power goes off.

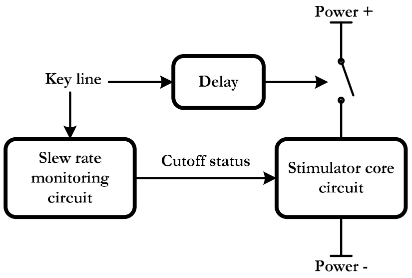


Fig. 6. A stimulating module

Fig. 7 details the operating mechanism of the slew rate monitoring circuit as applied to an on-chip process variation detection [6] function. The circuit includes a window detector, an integrator and a command discriminator. The window detector which can be implemented with two open-drain comparators compares the key line voltage with upper and lower thresholds (upper and lower thresholds are set to levels close to the key line voltage "on" and "off" states) and will open a logic "high" window representing the time when the key line voltage is between upper and lower thresholds. The integrator integrates the logic "high" window to quantify the time required for a key line voltage to fall from near "on" state to near "off" state. The command discriminator of the final stage interprets the integrator output to determine whether it results from a random jitter, a power off command, or an emergency cutoff command.

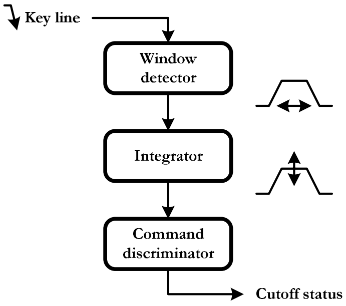


Fig. 7. The mechanism of the slew rate monitoring circuit

Fig. 8 is the implementation of a fail-safe interface with lumped circuits.

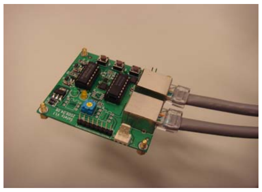
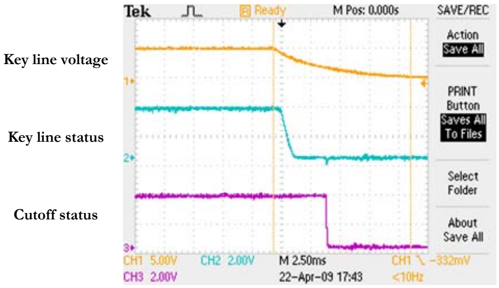


Fig. 8. Fail-safe interface prototype board

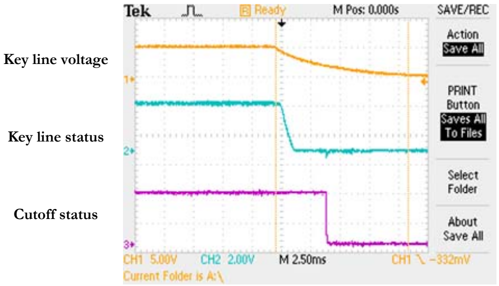
I. RESULTS

Testing results were made by coupling two 2-channel stimulating modules and a battery unit module to a common bus. The key line voltage generating circuit is placed in the battery unit module and the emergency cutoff and slew rate monitoring circuits are placed in each stimulating module.

Fig. 9 and Fig. 10 are respectively the normal power off and emergency cutoff results of the two stimulators. The results are demonstrated in terms of oscilloscope outputs of key line and cutoff statuses. Specific improvements will be detailed in the presentation.

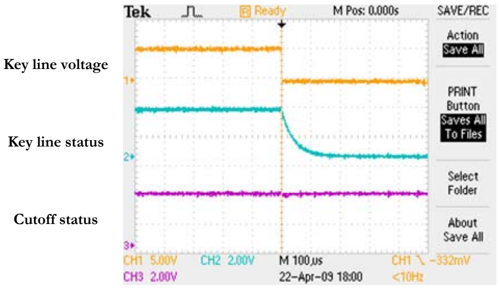


Stimulating module 1

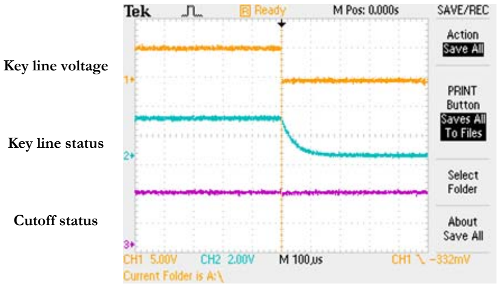


Stimulating module 2

Fig. 9. Key line and cutoff statuses during normal power off



Stimulating module 1



Stimulating module 2

Fig. 10. Key line and cutoff statuses during emergency cutoff

II. DISCUSSIONS

In the results, the fail-safe interface can readily differentiate between normal power off and emergency cutoff commands. This can be accomplished by complying with the following rule:

$t_{min} < R_{cutoff}\, x\, C_{cutoff} < R_{integrator}\, x\, C_{integrator} < R_{key}\, x\, C_{key}$

wherein t_{min} is the minimum required pulse width for switches to react; $C_{integrator}$ is the capacitance of the integrator; C_{cutoff} and C_{key} are the capacitances of the key line to reference ground during emergency cutoff and normal power off, which are nearly equal; $R_{integrator}$, R_{cutoff} and R_{key} are respectively the resistance of the integrator and the resistances of the key line to reference ground during emergency cutoff and normal power off.

Referring to the window detector in Fig. 7, if the upper and lower thresholds are chosen as $Vdd/2$ and $Vdd/18$, the time required for the emergency cutoff and normal power off to fall across the thresholds would be ln9 x ($R_{cutoff}\, x\, C_{cutoff}$) and ln9 x ($R_{key}\, x\, C_{key}$), respectively. The integrator output should be

$$Vdd - \int_0^t \frac{Vdd - Vdd/2}{R_{integrator}\, xC_{integrator}}\, dt$$

, which is

$$Vdd - Vdd\, \frac{\ln 9x(R_{cutoff}\, xC_{cutoff})}{2x(R_{integrator}\, xC_{integrator})}$$

during emergency cutoff, and

$$Vdd - Vdd\, \frac{\ln 9x(R_{key}\, xC_{key})}{2x(R_{integrator}\, xC_{integrator})}$$

during normal power off.. By setting the capacitances at substantially equal values ($C_{integrator} = C_{cutoff} = C_{key}$) and the resistances at different values varying by an order of magnitude ($10R_{cutoff} = R_{integrator} = R_{key}/10$), the integrator output will turn out to be about $9Vdd/10$ during emergency cutoff and in contrast, the integrator output will be saturated to reference ground voltage during normal power off. The threshold of the command discriminator could be set at a certain level below $9Vdd/10$, and for convenience, it is set to be $Vdd/2$ in the present discriminator circuit.

In contrast with conventional schemes that reserve ports for each additional fail reaction command (e.g., the Dead Man Switch of the Multiple-Master-Multiple-Slave system [3]), the proposed system provides greater flexibility by transmitting such commands via a single port. By applying different resistors in series with the cutoff switch, different key line voltage slew rates (dotted lines of Fig. 5) can be used to represent different commands (different cutoff statuses as shown in Fig. 7). Therefore, instead of automatically going into a default state when something abnormal takes place, responses can be categorized into abnormal control, abrupt changes of adhesive body sensors, prolonged silent commands, etc., which shall in turn trigger different cutoff commands.

III. CONCLUSION

The application of using additional safety measures in the operation of modular FES prevents irreparable harm that may be caused by sensor displacements, circuitry damages, and unpredictable extremes of controlling results. The proposed means for additional safety measures can be applied to a variety of sensors (EMG, accelerometry, speech control, etc.) and actuators (FES, robotics, motor drives, etc.), making a multiple control task safer in a simple and straightforward approach. Despite earlier technical efforts that provide similar insights (e.g. Multiple-Master-Multiple-Slave specifications for wheelchairs [3]), the standardization of safety measures should be raised as an important issue in future developments of non-invasive neural prostheses.

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REFERENCES

[1] P. H. Peckham and Jayme S. Knutson, “Functional electrical stimulation for neuromuscular applications,” *Annu. Rev. Biomed. Eng.* 2005. 7:327–60

[2] D. G. Graupe and K. H. Kohn, *Functional electrical stimulation for ambulation by paraplegics.* Malabar, FL: Kreiger Publishing Company, 1994, pp.63–90.

[3] “*M3S: An intelligent integrated and modular system for the rehabilitation environment.*” Working group: ISO/TC-173/SC-1/WG-7. Version: 2.00-revision 9 July 1997 – COMMITTEE DRAFT

[4] S.C. Trier, J.R. Buckett, A. Campean, M.E. Miller, F.W. Montague, T.L. Vrabec and J.A. Weisgarber, “A modular external control unit for functional electrical stimulation,” *Proc. of IFESS 2001,* June 2001, p3.22

[5] E. H. Miller, “Interfacing the body's own sensing receptors into neural prosthesis devices,” *Technology and Health Care* 7 (1999) 393–399

[6] A. Ghosh, R. M. Rao, J.-J. Kim, C.-T. Chuang and R. B. Brown, “On-chip process variation detection using slew-rate monitoring circuit,” *Proc. of the 21st Int. Conf. on VLSI Design,* 2008, pp.143-149