Development of Wireless-Based Low-Cost Current Controlled Stimulator for Patients with Spinal Cord Injuries

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Abstract—**A spinal cord injury (SCI) has a severe impact on human life in general as well as on the physical status and condition. The use of electrical signals to restore the function of paralyzed muscles is called functional electrical stimulation (FES). FES is a promising way to restore mobility to SCI by applying low-level electrical current to the paralyzed muscles so as to enhance that person's ability to function and live independently. However, due to the limited number of commercially available FES assisted exerciser systems and their rather high cost, the conventional devices are unaffordable for most peoples. It also inconvenient because of wired based system that creates a limitation in performing exercise. Thus, this project is concerned with the development of low-cost current controlled stimulator mainly for the paraplegic subjects. The developed device should be based on a microcontroller, wireless based system using Zigbee module, voltage-to-current converter circuit and should produce proper monophasic and biphasic current pulses, pulse trains, arbitrary current waveforms, and a trigger output for FES applications. The performances of the device will be assessed through simulation study and validated through experimental work. This device will be developed as in the new technique of the stimulator development with low cost and one of the contributing factors in Rehabilitation Engineering for patients with SCI.**

Keywords-Functional electrical stimulation (FES); voltage current converter; wireless; low cost

I. INTRODUCTION

The brain, spinal cord and peripheral nerves make up a complex, integrated information-processing and control system known as central nervous system. It is vital to our existence, controlling voluntary movements and regulates involuntary activities such as breathing and allowing us to function in daily life. As a part of the central nervous system, the spinal cord extends from the base of the brain down the midline of the back and ends at the bottom of the spine. The spinal cord sends signal to the body and serves as a communicator between the body and the brain. These peripheral nerves carry impulse that causes such as muscles to contract and also carry signals up through the spinal cord towards the brain that enable us to experience sensations such as pain and touch to name a few.

However, damage to the spinal cord results in loss of motor or sensory function. A spinal cord injury (SCI) has a severe impact on human life in general as well as on the physical status and condition. Spinal cord injuries (SCI) can be separated into two major categories; complete or partial. A complete injury is defined by complete loss of motor function and sensation below the area of injury. In partial injury, there can be sparing of motor or sensation below the level of the injury. Injury to the spinal cord can be the result of traumatic (road traffic accidents and falls) or non-traumatic (disease such as polio) events.

Spinal cord injury (SCI), based on the level of lesion, results in different degrees of denervation in limbs; however, the limbs and their muscles are physiologically intact. In fact, different researches about the consequent damages of SCI have shown structural transformations in different parts of body e.g., muscles. One of the most efficient rehabilitation methods for restoring muscle function is the use of functional electrical stimulation (FES), by which electrical impulses are applied to muscles in order to produce controlled muscle contractions that result in desired movement patterns. Phisiologically, information in nerve cells is coded and transmitted as series of electrical impulses called action potentials (AP). APs can be artificially generated by inducing electric charge into the nerve cell or nerve axon. The intensity of the signal transmitted is directly proportional to the frequency of APs that occur in the axon per unit of time. When APs are generated using electrical stimulation and are used to produce a body function, it is referred to as FES. During FES, for every AP that propagates towards the end of the axon that is innervating a muscle (orthodromic propagation) one AP will propagate backwards towards the cell body of the motoneuron (antidromic propagation) [1]. FES is typically concerned with orthodromic propagation as they generate muscle contractions in order to produce the desirable body function. In the case when the APs are generated by the central nervous system (instead of FES), the cell body receives AP driven inputs from dendrites, it summates the excitatory and inhibitory APs, processes them and decides whether or not to generate an output AP.

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Following stroke or SCI the motoneurons do not receive appropriate input from the central nervous system therefore inhibiting muscle function. FES replaces this functionality by artificially generating required AP's to elicit a desired muscle function.

Different researches have been carried out in this field. Ross and colleagues designed a PC controlled constant current stimulator for evoked potential studies [2]. De Lima and Coedeiro proposed a constant current neural stimulator capable of controlling the amplitude of stimulation pulses [3]. Cheng and colleagues developed a circuit for functional electrical stimulation [4]. Imani and Erfanian developed a portable microprocessor-based functional neuromuscular stimulator with remote control [5]. Kobravi and Erfanian developed a transcutaneous computer-based closed-loop motor neuroprosthesis for real-time movement control [6]. Erfanian and colleagues developed a portable programmable transcutaneous neuroprosthesis with built-in self-test capability for training and mobility in paraplegic subjects [7]. Maleki and colleagues developed a musculo-skeletal model of arm for FES research studies [8]. Maleki and Shafaee developed a multi-purpose experimental setup for research studies on FES-based rehabilitation of paralyzed arm [9]. Moreover, various researches have been carried out in this area of research which focus on different controlling schemes devised for the system, mental and physiological benefits of using FES cycling system for rehabilitative strategies, and many other relevant issues [10][11].

FES is a promising way to restore mobility to SCI by sending electrical signals to restore the function of paralyzed muscles. In this technique, low-level electrical current is applied to an individual with disability so as to enhance that person's ability to function and live independently [12]. It is important to understand that FES is not a cure for SCI, but it is an assistive device [13]. For SCI, the damage is only to the central nervous system, the muscle and its nerve supply remain healthy. By using FES, the paralyzed muscle is possible to contract due to the reaction of the artificial electrical stimuli. FES system mainly consists of electrodes and a stimulator unit. Current pulses will be generated from the stimulator unit through the electrodes and these cause the paralyzed muscles to make contraction. The main objective of FES in injuries to the central nervous system is the substitution of the absent bioelectric activity with an appropriately formed series of electric pulses, generated by a stimulator, or the elimination of the hyperactivity in paralysis and spastic paresis [14]. Basically, two electrodes are essential to close the current circuit of the stimulation system as shown in Fig.1.

In many years, FES has been applied to restore or maintain muscle activities of paralyzed patients who suffer from spinal cord injuries and related neural impairments [15]. However, due to the limited number of commercially available FES assisted exerciser systems and their rather high cost, the conventional devices are unaffordable for most peoples. Moreover, it also inconvenient because of wired based system that creates a limitation in performing exercise. Thus, this project is concerned with the development of low-cost current controlled stimulator mainly for the paraplegic subjects. A paraplegic is a patient who has lost some or all of the neurological function in their lower body.

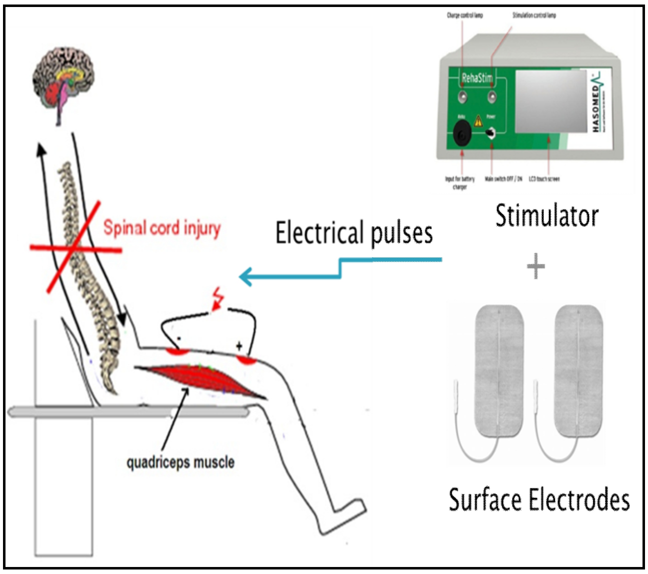

Fig.1: A basic electrical stimulation system

In this paper, a simple low cost current adjustable circuit for electrical stimulator was designed and developed whose output consists of current pulses with a wide range of rectangular waveforms (monophasic/biphasic) ranging from 10-120mA with steps of 2mA and time resolution of 10µs. The circuit also capable of adjusting the current amplitude, frequency and pulse width of the output signals. The main advantages of the device are the high level of output current amplitude controlled by low level of control voltage, the capability of fine time and amplitude tuning, the vast range of output waveforms, wireless based system using zigbee module and the use of low cost electronics components in its structure which makes it economically efficient for being used in various FES research studies as well.

II. FES

A development of the FES stimulator with a new technique which is low cost will be the expected outcome of this research. Fig.2 and 3 are the overall description of the electrical stimulator development in this research. The proposed electrical stimulator can be divided into two units which are controller unit and stimulator unit. The controller unit consists of microcontroller, input interface such as switch and LCD display as an output interface. The stimulator unit will be in construction of microcontroller, output stage circuit and surface electrodes. Both units will be connected with Zigbee wireless network. The controller will generate signal to the stimulator unit via this wireless network in order to make the stimulator generate stimulus for the paralyzed muscle to contract. In safety point of view, the stimulator unit will monitoring the output current level as well as the electrode-tissue impedance and transmit the data via this wireless network to the controller unit as a feedback. Fig.3 shows that the controller unit will be worn at the arm of the paraplegic subject and the stimulator unit will be fixed at a part of the paralyzed leg. Without any wiring interference between the controller and stimulator unit, the movement of the paralyzed lower limbs can easily generated.

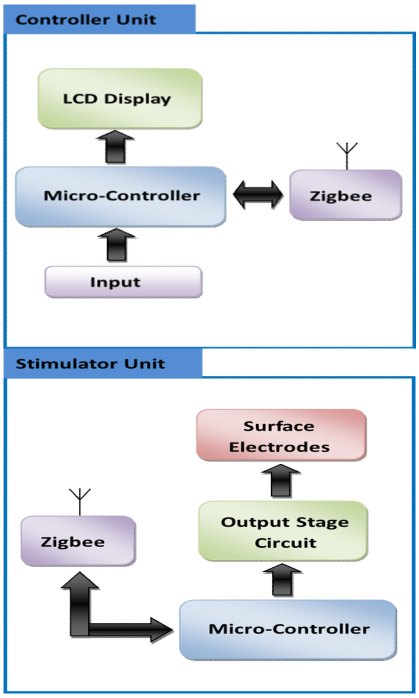

Fig.2: The block diagram of the stimulator system

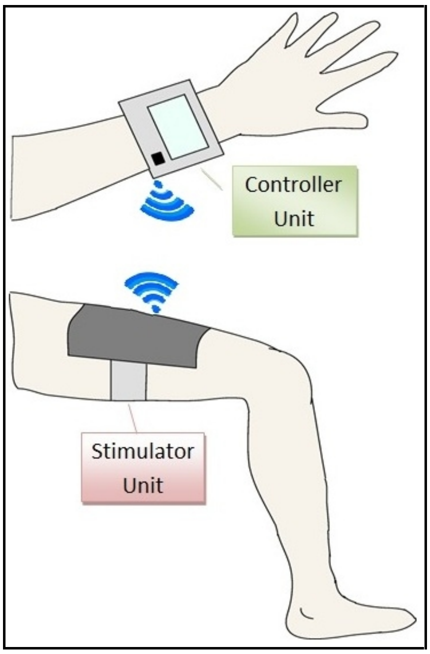

Fig.3: The illustration of the stimulator system

A. Stimulus mode

There are two distinct modes for stimulation which are current-mode and voltage-mode [16]. Current-mode stimulation is widely used in surface as well as implantable stimulator for functional electrical stimulation (FES) applications. The current amplitude is directly controlled by a digital-to-analog converter (DAC) and is not affected by changes in the tissue load. Therefore, the quantity of charge delivered per stimulus pulse is easily controlled. In voltage-mode stimulation, the stimulator output is a voltage, and therefore the magnitude of the current delivered to the tissue is dependent on the inter-electrode impedance (Ohm's law). Thus, it is difficult to control the exact amount of charge supplied to the electrode and tissue because of the impedance variation.

B. Stimulus pattern

Pulse shaped waveforms have contributed to the effectiveness of today's practical FES applications such as transcutaneous electrical nerve stimulation (TENS) for pain management and neuromuscular electrical stimulation (NMES) programs for muscle strengthening. These pulsed current waveforms can be defined as providing discrete electrical pulses of known waveform, frequency, amplitude and pulsewidth. Most of today's FES is done using pulsed stimulation waveforms. Pulse shapes commonly used are rectangular, which rise abruptly (eliminating any concern of nerve accommodation), stays at constant amplitude for a determined period of time and then falls abruptly.

Stimulus waveforms are generally either monophasic or biphasic in shape. Monophasic pulses move current only in one direction. When these pulses are used for TENS or NMES applications, they have the likelihood of causing electrode deterioration and tissue damage (skin irritation or rash when surface stimulation is used) when used for prolonged periods of time (over an hour) [17]. This effect is due to the altering of ionic distributions and causing polarization which leads to tissue breakdown and burns. Although the effect of ionic distribution is not desirable, monophasic waveforms are still used in some short-term therapeutic TENS applications. The unequal ion transfer can be reduced by using biphasic (symmetrical or asymmetrical) stimulation pulses. In the case of asymmetric biphasic waveforms (as shown in fig.4), one direction of current is enough to cause excitable tissue to depolarize, while the opposite direction is lower in amplitude but proportionally longer in duration minimizing neural excitation. The overall effect of the stimulation is similar to the monophasic waveform, but with a reduction of ion redistribution. The area under these pulses indicates the amount of charge that is delivered to the tissue. These waveforms can be either balanced or unbalanced in terms of the area under each pulse within the period. The most common and desirable biphasic waveform is the balanced charge pulse waveform, which further reduces issues of ion build-up. The symmetric biphasic waveform shown in fig.4 has equal amplitude and duration in both directions. Since both the positive and negative pulses are equal, they both are effective in causing depolarization in the excitable tissue and are usually used for the activation of large muscles [17]. Overall most FES applications desire the use of biphasic pulse waveforms, especially when they are used for prolonged periods of time.

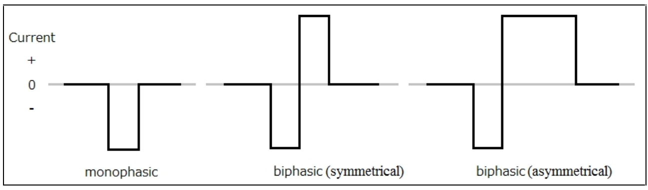

Fig.4: Pulse-shaped stimulation waveform configurations

C. Safety features

Safety is one of prime concern for stimulator output stage design. A failure in the stimulator output stage could pass prolonged DC current through the electrode-nerve interface, causing serious injury to the tissue. There are three commonly used protection methods against electrolysis caused by direct current. The first approach employs continuous monitoring of the electrode-tissue impedance [18], electrode voltage [19] or the stimulus current level [20]. Using the current monitoring circuit with safety relay (as shown in fig.5), the measured result is compared with a pre-defined reference value and if the measured result exceeds the reference, the stimulator output stage is immediately disabled to prevent nerve damage. The advantage of this approach is volume saving since the monitoring circuit can be integrated with the stimulator output stage circuit. However, the monitoring circuit increases the stimulator complexity which itself increases the probability of semiconductor failure.

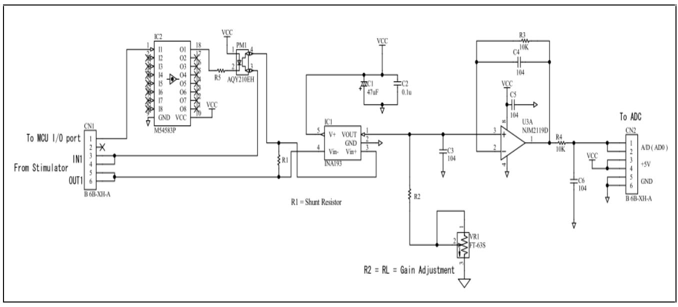

Fig.5: Current monitoring circuit with safety relay

D. Output stage

In general, complicated circuitry and control method are needed for this application which, in turn, imposes designs that are bulky, expensive, and high-power consumption [4]. The required components are small and the required input voltage is low. The circuits have three degrees of controllability which are amplitude, pulsewidth, and frequency and are ideal candidates for improvement of the FES circuit. Conventionally, FES circuit is designed by using an oscillator which generates necessary pulse by using analogue electronics. The output waveforms including amplitude, frequency, and pulsewidth can be regulated. The output is then stepped up to the required voltage by a step-up transformer. The drawback of using transformer is that this increases the device size and cost, and electromagnetic interference due to the transformer. The design of the transformer is also needed to handle the small mark-space ratio of the pulse. The wide range of amplitude is also restricted because of the fixed transformer turns-ratio. Various control strategies and circuit design have been developed to provide enhanced functionality, repeatability, and a wide range of stimulation parameters for FES stimulator [21] in order to provide predictability of muscle responses. The transformer is used to further step up the output voltage. The function of this part is to transfer the output pulses of the multivibrator into a series of current pulses and a current feedback loop is included to ensure the current amplitude.

In this research, voltage-current converter has been used as an output stage of the stimulator. In this research project, power operational amplifier (LM675) is used which can produce current output with 3A as the maximum value. As shown in fig.6, V1 and V2 are the power voltage of the circuit which produce polarity voltage. The V3 is the voltage control of the circuit in producing rated current as an output. V3 is actually controlled by microcontroller through Digital Analog Converter (DAC). Compared to the conventional transformer-based analog circuit, this circuit is only consists of basic electronic components which is low development cost and has no bulky and expensive transformer.

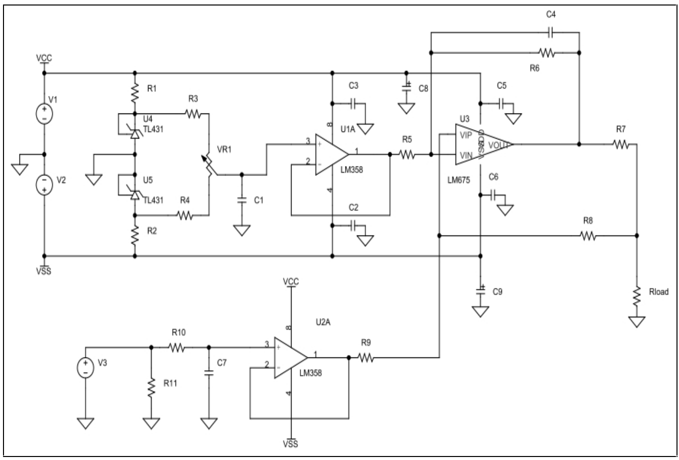

Fig.6: Output stage circuit using voltage-current converter

E. Wireless module

The Wireless Sensor Network (WSN) has a very broad application prospects, and has been considered as one of the most important technologies that can change the future. The main features of this network are real-time transmission, accuracy and comprehensiveness. ZigBee is one of the most popular wireless network technologies in the world [22]. Currently, ZigBee technologies are widely used in various fields such as biological research, control, disaster monitoring and environmental science to name a few. Moreover, ZigBee have many advantages, which determines the tremendous potential of use in medical field [23]. A kind of dynamic and strong integration of ZigBee hybrid system was developed, under wide coverage, low cost and high reliability [24]. In order to provide more conveniences to patients, people developed ZigBee wireless sensor system, whose purpose is to collect the patient's physiological information, such as pulse, temperature, etc. The system not only ensures accurate measurements, but also saves the patient from the time between hospital and home [25]. ZigBee is a new wireless communication technology based on wireless standard 802.15.4. It is an extension of the WPAN. This technology has a number of significant features. The first is short range; ZigBee transmission range is between 10-100m, good enough to meet the needs of mobility equipment. The second is low-power, when data exchange is not needed, the node will enter a very low power consumption sleep mode. Compared to Bluetooth devices, two common batteries can support ZigBee devices from several months to several years. The third is the low transmission rate; ZigBee work in the 2.4GHz (global GM), 915MHz (USA) and 868MHz, with transmission rates 250KB/s, 40KB/s and 20KB/s. The fourth is less complexity, ZigBee network layer structure uses star, tree and mesh structure. A ZigBee node can connect up to 254 nodes and the whole network can support a maximum of 65535 nodes. That has greatly enhanced network scalability. Also, the network is very strong in self-grouping; the join and disconnect of nodes are very fast. Compared to Bluetooth and WI-FI, ZigBee technology has the following advantages such as good security, low cost, low power consumption, flexible working bandwidth, short delay, low data transmission rate, large network capacity and small effective range [22]. As shown in fig.7, wireless Zigbee module has been connected with RS232 serial communication in order to make data transmission between microcontroller in controller unit and stimulator unit of the system.

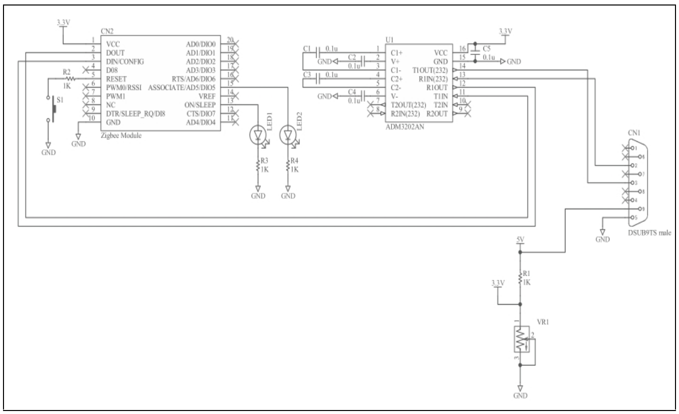

Fig.7: Wireless Zigbee module circuit.

III. RESULT: STIMULATOR OUTPUT

Experimental works have been done to evaluate the output stimulus characteristics of the stimulator. In this experiment, 1k Ω of Rload has been selected and it is assumed as an external load of skin surface. Fig.8 and 9 shown that the amplitude of the current stimulus can be produced from 10mA~120mA in range with steps of 2mA and the pulse width of the stimulus can be produced from 10us~500us in range with steps of 10us.

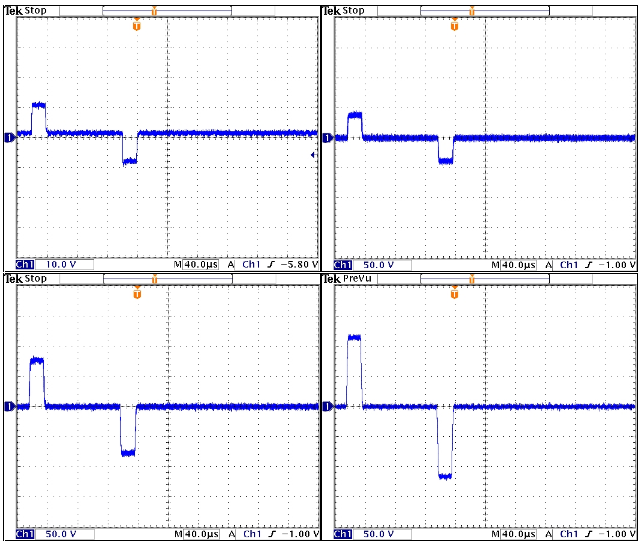

Fig.8: Experimental result of various current amplitude

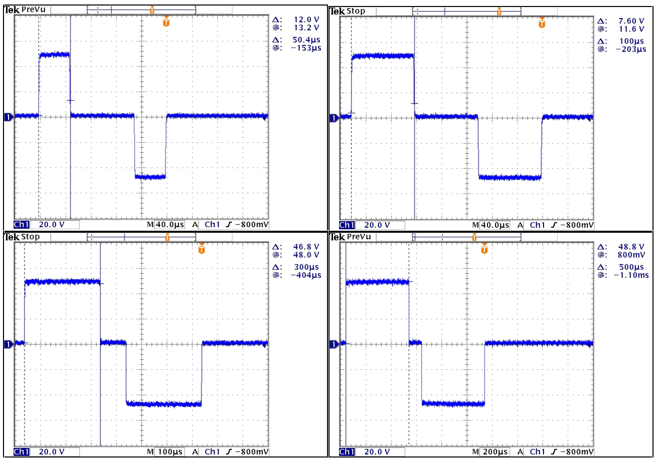

Fig.9: Experimental result of various current pulse width

IV. CONCLUSION

A lot of criteria need to be concerned in developing a safety, accurate, effective and convenient stimulator for patient with SCI. The output stage of the stimulator is the prime criteria to be put in mind which directly affect the safety point of view. The electrode-tissue impedance and the level of the stimulus current are compelled to be monitored. The circuit design of stimulus generator is the major factor contributing to a high development cost as long as using a transformer or DC-DC converter based circuit. In this paper, a simple low cost current adjustable circuit for electrical stimulator was designed and developed whose output consists of current pulses with a wide range of rectangular waveforms (monophasic/biphasic) ranging from 10-120mA with steps of 2mA and time resolution of 10μs. The circuit also capable of adjusting the current amplitude, frequency and pulse width of the output signals. The main advantages of the device are the high level of output current amplitude controlled by low level of control voltage, the capability of fine time and amplitude tuning, the vast range of output waveforms, wireless based system using zigbee module and the use of low cost electronics components in its structure which makes it economically efficient for being used in various FES research studies as well.

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