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Voluntary telemetry control of functional electrical stimulators

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With the assistance of crutches and functional electrical stimulation (FES) we are able to restore standing and simple gait in some spinal cord injured (SCI) patients. In the present rehabilitative systems the patient divides the gait cycle into 'stance' and 'swing' phase by using pushbuttons mounted in the handles of the crutches. These are then hard wired to the functional electrical stimulator. We present the development and evaluation of a surface mount technology based telemetry system that provides reliable and interference resistant wireless control of FES assisted walking. The system makes use of radio frequency carriers operating at a frequency of 40 MHz. Crutch pushbutton signals are coded and transferred from the transmitter placed in the crutch to the receiver which is firmly attached to the patient's waist and connected to the stimulator. The telemetry system was found to be of special importance for both complete and incomplete SCI subjects and is currently in use at the Rehabilitation Institute of the Republic of Slovenia.

Introduction

Considerable efforts have been made in the last decade investigating functional electrical stimulation (FES) assisted gait in complete and incomplete spinal cord injured (SCI) subjects [1]. Most of the proposed FES assisted gait patterns are based on control events triggered voluntarily by the paralysed person in order to achieve necessary synchronization of the natural movements of the nonparalysed part of the body with the FES provoked movements of the paralysed lower limbs. In a simple four-channel pattern, the gait cycle is divided into a 'stance' and a 'swing' phase by pressing and releasing the pushbuttons built into the handles of the crutches. In the present FES rehabilitative systems these pushbuttons are hard wired to the stimulator. Interconnecting wires between the crutches and the stimulator are inconvenient in daily activities and are a frequent source of malfunction. They are an obstacle during walking and they hinder a patient when standing up or sitting down. The wire connection was found particularly inappropriate in situations when patients, while sitting, wish to discard the crutches. Finally, these wires are unaesthetic which is an important factor in the patient's acceptance of the rehabilitative system.

When assisting the gait of incompletely paralysed SCI subjects, we expect the development of complex gait patterns which will include muscle groups additional to those stimulated in the minimal reciprocal gait pattern [2]. Additional control events will be introduced during the gait cycle. It seems that the contact force of the crutch may yield valuable information and should therefore, be, included in the FES control synthesis. However, transferring the force signals from the crutch to the stimulator would require additional wires. Such a solution is not acceptable because of the previously mentioned reasons. Therefore, a reliable telemetry system for transferring the control signals from the crutches to the stimulator is of great importance for improved acceptance of functional electrical stimulators.

There have been only a few attempts in the past to develop telemetry systems for FES control. A system using infrared transmission of pushbutton signals from the crutch handles provided on/off switching of the electrical stimulation [3]. The system was specially designed for controlling an FES system which was used in conjunction with a mechanical orthosis. The receiver was attached to the side of the orthosis while the transmitter was clipped onto the shank of the crutch. A reliable communication link was achieved when the positions of the transmitter and receiver remained constant.

A stimulation system employing an ultrasound wireless link was patented [4]. The telemetry link provides transmission of the hand-control module signals to the stimulator. The switches and the transmitter are mounted on the walker which provides support to the patient during walking. The receiver is integrated into the stimulator and the latter is attached to the patient's waist.

A clean line of sight between the transmitter and the receiver is required for error free communication in both telemetry systems mentioned above, due to the narrow emitting and receiving angle of infrared diodes and ultrasound sensors. In cases when the visibility is not assured, neither infrared nor ultrasound communication is possible. As a consequence the receiver cannot be hidden under the patient's clothing and the transmitter cannot be built into the crutch. Due to these deficiencies of ultrasound and infrared media our telemetry system employs a radio-frequency link.

System requirements and methods

At the beginning of the system development, the following requirements and limitations were imposed:

(1) The time delay between pressing the pushbutton and the stimulator response should not exceed 100 ms.
(2) The transmitting system should not consume power while inactive.

(3) The telemetry system should be designed in such a way that several patients could use it in the same place at the same time.
(4) The transmitter should be installed in the crutch together with a rechargeable power supply: therefore, its dimensions should be as small as possible.
(5) The energy consumption should be minimal.
(6) The system should provide reliable communication under conditions of radio-frequency disturbances.

It can be seen that some of the requirements are conflicting. The use of the rehabilitative system by several patients in the same place at the same time requires frequency separation of the communication channels, but it is difficult to accomplish minimal dimensions of the system due to the extensive circuitry required. One possibility of achieving this requirement is to introduce the phase locked loop (PLL) principle. However, PLL requires a precise frequency oscillator for producing a reference frequency, a voltage controlled oscillator (VCO), a pre-setable frequency pre-scaler (to enable generation of different frequency channels), a phase comparator and a low pass filter, all solely for generating a suitable carrier frequency. By the application of the aforementioned principle and by using electronic components that are available on the market, we can design a frequency synthesizer from, for example, 143·82 to 148·92 MHz with a channel separation of 20 kHz providing 256 different communication channels. Such a solution would satisfy only the third requirement while disregarding the fourth and the fifth. The power consumption of such a system would be 200 mW, 40 mA at 5 V which is rather high. The system would also consist of a large number of components which would considerably increase its size.

Another means of achieving several communication channels is the use of a crystal oscillator in a frequency range where a wide palette of crystals is commercially available. In this way we could separate channels by simply replacing the crystal resonator in both transmitter and receiver. Manufacturers offer more than sixty frequency channels in the 27 MHz, 40 MHz and 49 MHz bands.

Other important matters in radio-frequency transmission are the transmitting and receiving antennas. Since the patients use a crutch, it seems only natural to make use of the crutch as a transmitting antenna.

Another important issue is the type of modulation used. In today's commercially available telemetry systems two modulation techniques are most frequently employed. Frequency modulation (FM) offers better quality of transmission than amplitude modulation (AM) while the latter results in a substantial reduction in complexity of both modulating and demodulating circuits. In cases when only the state of the signal is relevant (low or high state, i.e. a digital signal) AM is adequate since the quality of transmission is not the main consideration.

Thus, we developed a telemetry system employing the ASK (amplitude shift keying) modulating principle and operating in the 27 MHz band. At the beginning of the development our intention was to use a palette of crystal resonators in order to obtain different communication channels which would fulfil the requirements. The core of the system is two integrated circuits dedicated for wireless control of model air planes. The crutch is cut in half, thus providing a dipole antenna for the transmission. The receiving antenna is a 15 cm long wire. The receiver uses the single superheterodyne conversion principle. The transmitter was placed in the tube of the crutch together with the battery operated power supply, while the receiver was placed in a separate plastic case which was tied to the patient's waist close to the electrical stimulator.

For the purpose of comparison, we also tested a commercial telemetric system operating at 433·92 MHz and using the ASK modulating principle. In this way we investigated the suitability of higher frequencies for our application. The output power of both telemetric system transmitters was 10 mW. The bandwidth of the 27 MHz receiver was set either to 10 kHz or 100 kHz by including or excluding a ceramic filter tuned to the intermediate frequency of 455 kHz. The commercial system had a 400 kHz bandwidth. By pressing the crutch pushbutton, both systems repeatedly transmitted the coded signal until the pushbutton was released.

Evaluation

The evaluation of the reliability of both telemetry systems was carried out in the Republic of Slovenia Institute for Rehabilitation by an FES assisted paraplegic person [5]. The patient wore the receiver firmly attached to a belt close to the four channel stimulator. The pushbuttons in the crutch handles were hard wired to the stimulator during the evaluation process, thus providing a reference for telemetry switch signals. In cases when the telemetry switches triggered the same gait event as those connected by the wires, a successful communication was registered by an evaluation software module running in the four channel microcontroller based stimulator which enabled the gait of the patient. At the end of the evaluation run, the data were transferred to a personal computer via a serial link. The evaluation was carried out in three different environments where paraplegic subjects are most commonly encountered:

In the rehabilitation centre therapy room. The therapy room was about 15 m long and 6 m wide. It was equipped with nonelectric therapeutic equipment, The patient's walking was helped by a supporting rail system powered by an asynchronous motor (for patient safety). The personal computer used for assessing the signals from the wireless and wired pushbuttons, and a surface electrode stimulator were the only electrical apparatus in the room.

In the presence of disturbing radio-frequency sources. We tested the reliability of both telemetry systems in the presence of a BOSCH Radarmed 12 S 150 microwave therapy device. The operating frequency of the device was 2450 MHz, while the power of radiation was the same as during patient therapy (about 77 W). The evaluation was performed at a distance of 1 m from the microwave emitting source antenna, which was first directed to the receiver of our telemetric system. Secondly, the antenna of the microwave emitting device was directed in parallel to the gait path at the same distance.

On the street in the presence of a running car engine The evaluation was carried out at a distance of 0.5 m to 2 m from the car.

Results

The results of the evaluation are presented in figure 1. The evaluation revealed that the narrowband system operating at 27 MHz operated reliably in all environments, while this was not the case with the wider bandwidth configuration. The commercial system, however, only operated reliably in the case of no radio-frequency disturbances. The range of the commercial system was at least 100 m due to the optimal antenna size which was realizable within the wavelength used. It was also demonstrated that reliable communication using the 27 MHz system was only possible when the patient held the crutch and wore the receiver firmly attached to the waist. It also showed the very limited range of the system operation which was expected given the short antennas used within the frequency band employed.

This observation suggested using the patient's body as part of the transmitting antenna being closely coupled to the receiving antenna. In this way a reliable transmission of control signals from the crutch pushbuttons to the stimulator would be obtained. On the other hand the poor sensitivity of the receiver when using a very short antenna as compared to the wavelength is highly desirable in our application. In this case we would not need channel separation since the operating range of the system would be only across the patient's body.

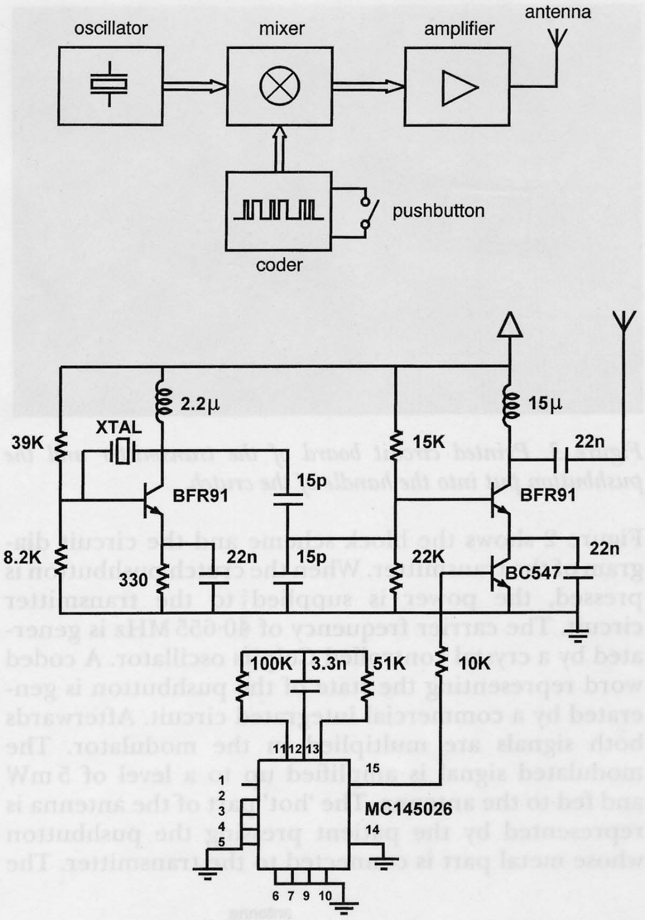

Figure 2(a). Block scheme and (b) circuit diagram of the transmitter.

Instrumentation

Using the findings of the evaluation, the final version of the telemetric system was developed. The principle employed in the 27 MHz system was retained and surface mount technology electronic components were used in order to reduce the size of the system. Since the 40 MHz frequency band is reserved for general telemetry it was used instead of the 27 MHz band.

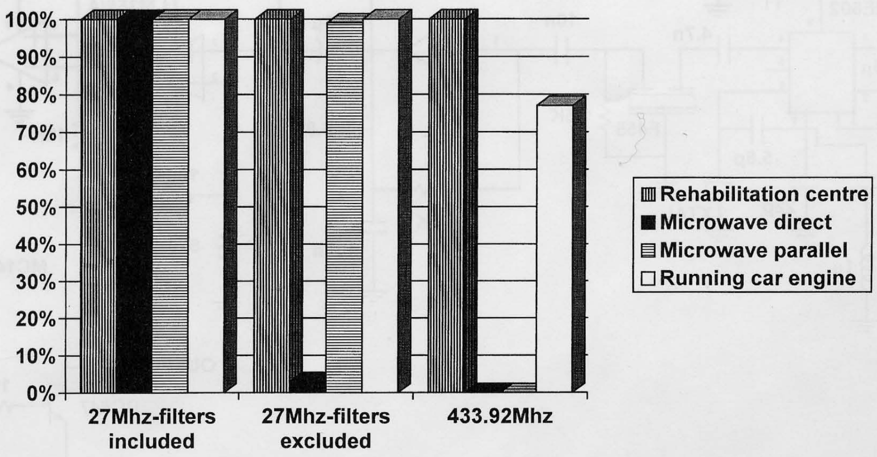

Figure 1. The results of the evaluation. The vertical axis shows the percentage of the successfully transferred patient's commands. It can be observed that the bandwidth of the device plays an important role in its reliability.

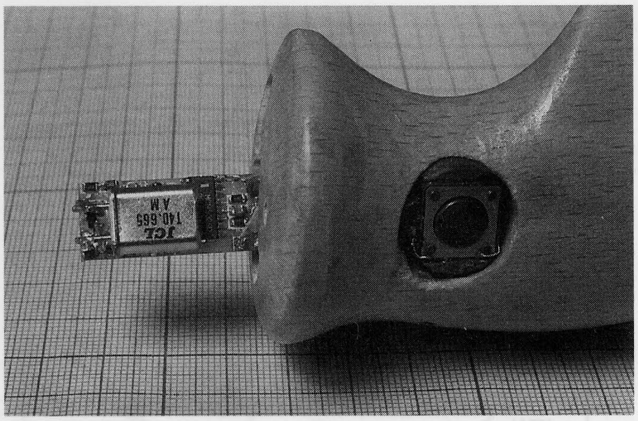

Figure 3. Printed circuit board of the transmitter and the pushbutton put into the handle of the crutch.

Figure 2 shows the block scheme and the circuit diagram of the transmitter. When the crutch pushbutton is pressed, the power is supplied to the transmitter circuit. The carrier frequency of 40·655 MHz is generated by a crystal controlled Colpits oscillator. A coded word representing the state of the pushbutton is generated by a commercial integrated circuit. Afterwards both signals are multiplied in the modulator. The modulated signal is amplified up to a level of 5 mW and fed to the antenna. The 'hot' part of the antenna is represented by the patient pressing the pushbutton whose metal part is connected to the transmitter. The 'cold' part of the antenna is represented by the crutch. Figure 3 shows the printed circuit board of the transmitter placed in the handle of the crutch. The metal part of the pushbutton, which is connected to the output of the transmitter, can be observed. The power consumption of the transmitter while active is 30 mW, 5 mA at the supply voltage of 6 V. The battery is placed in the tube of the crutch.

Figure 4 shows the scheme and the circuit diagram of the receiver. The receiving antenna is a 4 cm long and 1 cm wide metal clip which is also used for attaching the receiver to the patient's waist, thus providing close coupling between the transmitting (the patient) and the receiving antennas. The input filter matches the impedance of the antenna to the input impedance of the mixer. The double balanced mixer multiplies the input signal with the signal generated by the local crystal-controlled oscillator. The frequency difference of the two signals is 455 kHz which is the resonant frequency of the ceramic filter. The bandwidth of the receiver is determined by the 10 kHz ceramic filter passband. The filtered signal is demodulated and after decoding the signal triggers the FES sequence. The receiver draws 5 mA at the 4·8 V supply voltage. Figure 5 shows the printed circuit board of the receiver. The time delay between issuing the command and the appropriate gait event is 80 ms.

The system was tested by two complete and four

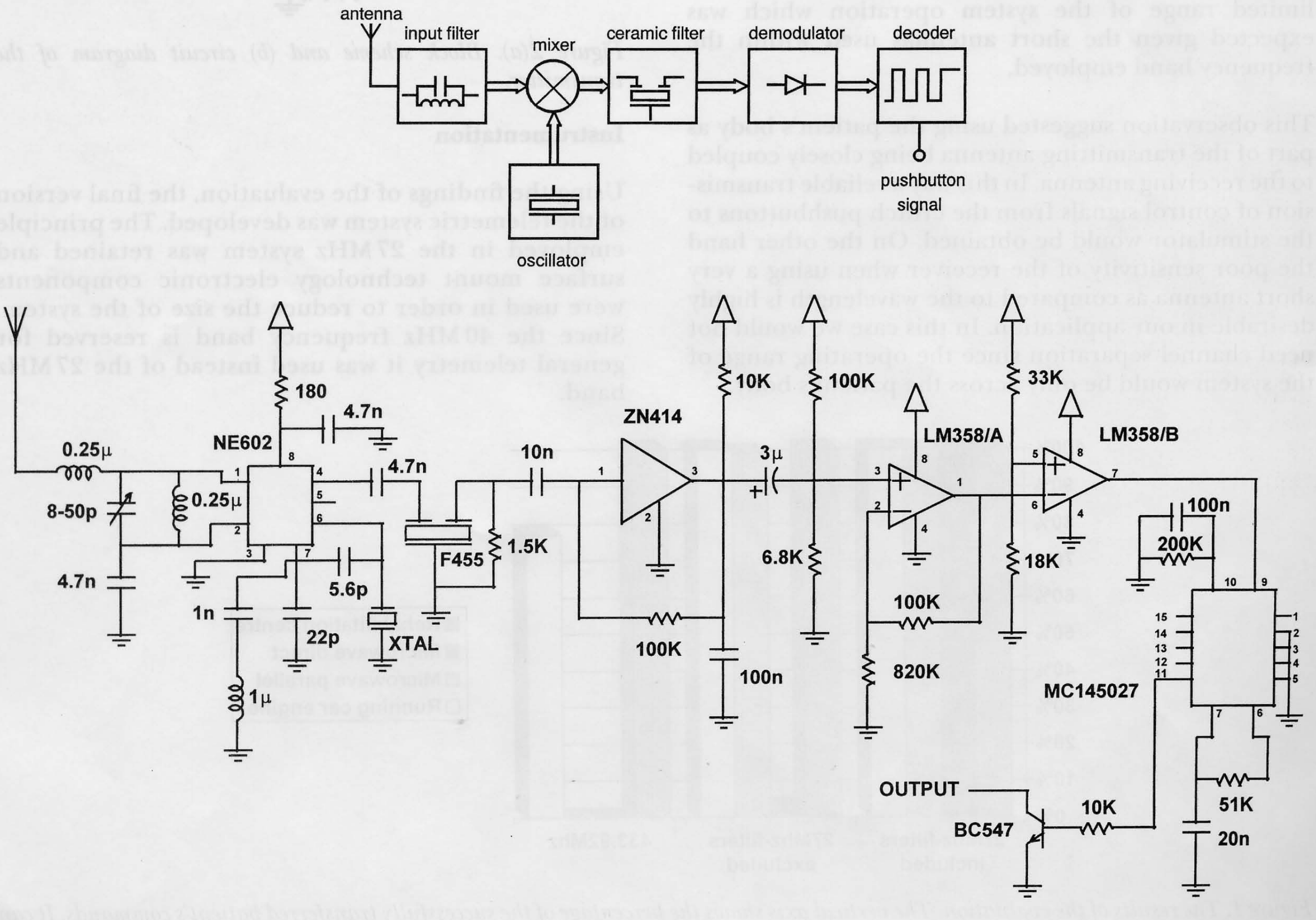

Figure 4. (a) Block scheme and (b) circuit diagram of the receiver

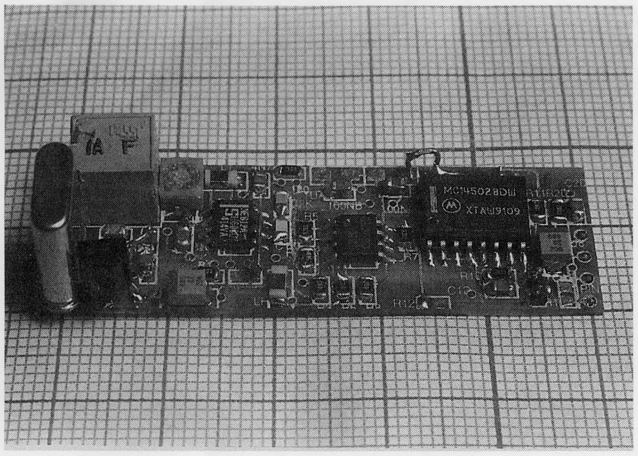

Figure 5. Printed circuit board of the receiver.

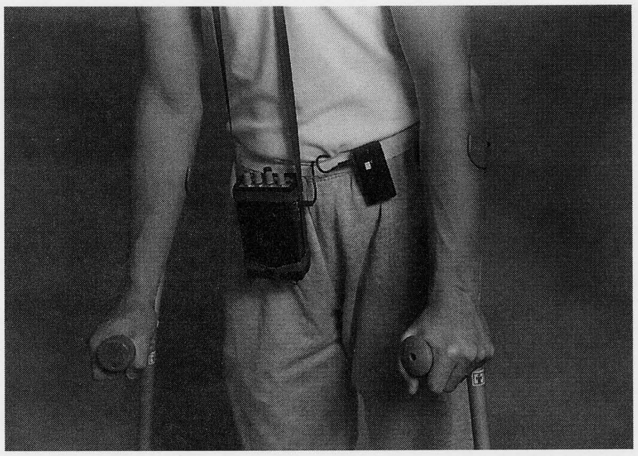

Figure 6. An incomplete paraplegic patient walking with the assistance of a four-channel stimulator and the telemetry system. The receiver module and the stimulator are tied to the patient's waist.

incomplete SCI patients. None of them encountered any problems regarding reliability of the device. Since the patients did not need to pay attention to the interconnecting wires, their walking speed increased. Figure 6 shows an incomplete paraplegic patient while walking with the assistance of a four-channel stimulator and the telemetry system.

Conclusion

A small, interference resistant telemetry system for the wireless control of FES assisted walking has been developed. The system fulfils the requirements imposed and was extremely well accepted by both complete and incomplete SCI subjects. It should be stressed that the telemetric system is specially important for the SCI subjects who use the FES orthotic device for periods of several hours daily. Since the patients are free of hindering wires, many activities of daily living can be undertaken: standing up and sitting down, entering and exiting a vehicle, opening and closing the doors or using the toilet. Another important achievement is the improved appearance, since the stimulator and the receiver can be hidden under the clothing of a patient. Further, it should be noted that the position and orientation of the transmitter and the receiver do not affect transmission reliability as long as the receiver is firmly attached to the patient.

Acknowledgements

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