Replication and Advancement of a Functional Electrical Stimulation Device: A Practical Guide

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***Abstract*—In medical rehabilitation, electric stimulation has always been significant. Though it is still a notable technique, Functional Electronic Stimulation (FES) requires to be improved through ongoing research and development. Because implantable devices are more complex, a thorough investigation is required to ensure the most efficient utilization of FES. Following Jarvis and Salmons' original work, this paper examines the developments and difficulties involved in creating FES devices. We introduce improvements to the Jarvis and Salmons original circuit that will maximize power efficiency, prolong battery life, and increase durability. Our innovative technique developed a printable circuit board (PCB) that requires little interference during implantation and is powered by a single lithium-ion coin cell battery. By resolving concerns with PCB manufacture and functioning, our suggested improvements will advance the field of medical rehabilitation by providing useful information for the deployment of FES devices.**

***Index Terms*—Functional Electronic Stimulation (FES), PCB, Medical Rehabilitation, Circuit Improvements, Circuit Design, Lithium-ion Coin Cell Battery, Power Efficiency, Battery Life**

I. Introduction

The prospect of applying electrical stimulation in medical rehabilitation devices is one that has been around for many decades. One of the popular methods for attempting proper rehabilitation is with Functional Electronic Stimulation (FES) [1]. It was as early as 1967 that FES was defined as "electrical stimulation of muscle deprived of nervous control with a view of providing muscular contraction and producing a functionally useful movement" [2]. Although FES and FES devices are not novel approaches to medical rehabilitation, properly constructing an effective FES circuit and comprehensive device requires ongoing research. This problem becomes additionally challenging when an implantable device provides the necessary requirements for studying the effects of FES rehabilitation [3]. In 1991, Salmons and Jarvis proposed an implantable optical switching device [4] which has been used as the basis for many FES applications. This device laid the foundation for an effective device to be used by many separate parties to study the effects of applying FES through an implantable model.

While Callewaert and Puers [5] developed a more technologically advanced, programmable, model that has been successfully demonstrated, the simplicity and low cost of construction, as well as its repeated use in FES approaches, makes the proposed device an ideal framework for building on to use in future FES tests.

Defining an appropriate pulse frequency is a crucial parameter in the design stages and many researchers chose different ranges of frequency. The ability to understand how to change the frequency of the pulses produced by the FES device is of upmost importance due to the differing frequencies used in FES approaches. Nene et al. [6] used a 30 Hz pulse frequency for their FES device tests.

Marsolais and Kobetic [7] demonstrated how functional neuromuscular stimulation (FNS) can be used outside of a controlled laboratory setting to help a patient who was previously unable to walk. They tested the effectiveness of FES devices with frequencies between 20 Hz and 50Hz. Similarly, M.R. Popovic and his colleagues [8] found that a minimum frequency of around 16-20 Hz was needed to effectively induce muscular contractions when the target of FES is on the muscle structure.

Although many of these FES applications use stimulation frequencies in the range of 20-50 Hz, other applications for FES focused on the use of frequencies outside this range. Liu and Grumbles [9] used a 1Hz frequency which showed promising results in improving axon regeneration. On the other hand, Song et al. [10] propose an implantable FES device that provided the ability to apply stimulation in a range of frequencies between 300 and 5000 Hz. As the frequency of stimulation pulses that FES devices are required to produce changes depending on the application, it is important to analyze the method for determining the stimulation frequency of the proposed device.

As FES devices are used in the medical field, creating a proper device often requires interdisciplinary collaboration between the engineering and medical fields [11]. To the extent of our knowledge, implantable FES devices such as the Jarvis and Salmons device are not available to be commercially purchased. This requires those pursuing FES research to implement a custom circuit: a non-ideal challenge for medical experts without a technical background in circuit design and implementation [12]. In response to the need for a custom circuit, there is often a lengthy research and development phase by those tasked to create a functional FES device. This poses increased challenges for the original research team as the increased device lead time prolongs the time before the FES testing can be conducted [13].

Although this is true, due to the increase in available technology since Jarvis and Salmons published their original device, there are many areas for improvement which allow for an increase in operating life and durability. Furthermore, although Jarvis and Salmons discuss the functionality of their circuit, correctly replicating their device requires additional considerations and analysis. As the diversity in FES applications requires multiple different stimulation frequencies, analyzing the Jarvis and Salmons design allows their circuit to be adapted to fit the required specifications. It also allows for many advancements in circuit design and construction to be outlined to act as a guide for those who wish to take a similar approach to FES.

This paper acts as a practical guide for implementing the original Salmons and Jarvis device while building on their design. We updated the findings of Salmon's circuit, produced the required material for implementation, and discussed the steps that are needed in order to recreate similar FES devices. Additionally, we analyzed the original circuit to provide the equations for determining the correct resistance and capacitance to use to set the stimulation frequency and provide an updated device that offers increased battery life and implantable durability. Moreover, we also improved the battery life of the device so that it can run for a maximum time and allow for the possibility of being reused in multiple FES tests. As the device is powered by a single lithium-ion coin cell battery, the battery size needs to be reduced as much as possible to be minimally invasive when implanted. The proposed device also solves the problem that Jarvis and Salmons note of lifting of circuit tracks fabricated printable circuit board (PCB) effectively allows for the circuit to be implemented in a durable way. Although this problem is corrected through the use of easily fabricated PCB, the problem of effectively minimizing the PCB will be discussed.

Our main contributions are:

1) We alter the Jarvis and Salmons clock connections to enable the clocking circuit only during stimulation. This leads to an increase in battery life.
2) We provide the circuit analysis required to set the stimulation frequency with the goal of adapting the device for a multitude of FES applications.
3) We provide a complete database of a bill of materials, PCB fabrication files, circuit simulations, and construction materials at an open source Github repository with the goal of reducing development time when this FES device in future applications. These files are available at https://github.com/FESdevice2024/Functional_Electronic_Stimulation

II. TECHNICAL DETAILS

The original circuit designed by Salmons and Jarvis has three main subcircuits. Fig. 1 describes the original Jarvis and Salmons circuit which shows the connection of the Schmitt Trigger NAND oscillator to the 3V source. The three main parts of the circuit include the cross coupled NAND SR latch, a Schmitt Trigger oscillator to create a clock signal, and the stimulator to apply a 200µs duration pulse. When a pulse of light from a 300-lumen flashlight is applied to the SR latch's phototransistors, the SR latch toggles between an on and off state as Jarvis and Salmons describe, this output is connected to another NAND gate along with a resistor and capacitor to create a Schmitt Trigger oscillator to control the frequency of the applied pulses. The output of this NAND gate is connected to an RC differentiator circuit and a bipolar junction transistor (BJT) in order to create a pulse that is approximately 200µs in duration. As the BJT allows current to flow from the collector to the emitter during each pulse, the output voltage is created across the pull-up resistor and allows a pulse to be delivered to the targeted tissue.

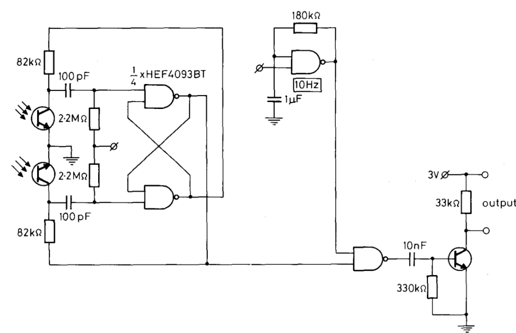

Fig. 1. Original circuit designed by Salmons and Jarvis [4]

In the proposed circuit, these core components remain unchanged. Although this is true, the parts list quoted by Salmons and Jarvis contains many components that have been discontinued by their manufacturer. New versions of the discontinued components were selected by comparing datasheets of the discontinued components with those for actively produced components. The benefit of using this circuit is that each of these three subcircuits can be created using a single Quad 2-input NAND gate Schmitt trigger IC. Salmons and Jarvis originally used the HEF4093BT Quad 2-input NAND gate Schmitt trigger, but this does not present the ideal IC due to the range of operating voltage as well as the size. Although the HEF4093BT is still in production, its recommended supply voltage (V_{DD}) is listed by the manufacturer as 3-15V. As the FES device is powered by a 3V coin cell, the standard operating voltage represents the very minimum value recommended for operation. This poses a problem as any induced noise or drop in battery voltage may result in unideal operating conditions for the IC. Similarly, the package size of the HEF4093BT is 8.75 mm by 6.2 mm at its largest tolerance. In the effort to reduce the implants size and reduce invasiveness of the implant, a smaller IC package size is ideal. Due to this, the SN74AHC132 poses an ideal solution as it is available in a quad flat no-lead (QFN) package and has an operating range of 2 – 5.5 V for supply voltage. With the SN74AHC132's QFN package, the layout is reduced to a size of 4.8-4.8 mm which represents a major size reduction from the HEF4093BT.

Another important aspect to note is that the SN74AHC132 recommends that a bypass capacitor should be implemented in order to prevent power disturbance. Adding a bypass capacitor provides system stability from and fluctuations in the source voltage [14], but Salmons and Jarvis do not mention any use of a bypass capacitor. Following the recommendation of the SN74HC's datasheet, a 0.1uF capacitor was implemented across the source voltage.

Observing Jarvis and Salmons method of implementing the NAND gate Schmitt Trigger oscillator shows that the NAND gate provides the use of an enabling input. This is because the NAND gate Schmitt Trigger oscillator is an extension to the more simple inverting Schmitt Trigger oscillator. The NAND gate Schmitt Trigger oscillator provides the same functionality as if the inverting Schmitt Trigger is used, but the second input on the NAND gate allows the clock signal to be enabled and disabled depending on the state of the second input. In connecting this enabling input to the positive source voltage as done by Salmons and Jarvis, the device provides a clock signal as long as it is connected to the battery. Since FES devices are typically used for one-hour intervals per day [1], the battery continuously produces a clock signal by continuously charging the clocking capacitor for 23 hours of unrequired time.

The solution to this lies in connecting the enable input on the Schmitt Trigger Oscillator to the enabling output of the SR latch. A schematic of the proposed circuit after making this change is shown in Fig. 2. This connects the enabling input on the clock to the enabling input of the stimulator meaning that the clocking signal is only produced when stimulation is required. In turn, this reduces the time power consumed by the clocking circuit from 24 hours a day to between 1 to 2 hours a day depending on stimulation requirements.

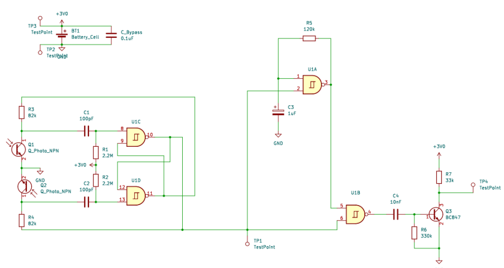

Fig. 2. An updated circuit design

Using (1), the current consumed by the clock can be calculated. In the Schmitt Trigger oscillator, the capacitor continuously charges and discharges between the positive threshold voltage and the negative threshold voltage of the SN74AHC132 due to the hysteresis of the Schmitt trigger.

$$f = \frac{1}{RC \cdot \ln(\frac{V_{DD}-V_N}{V_{DD}-V_P} \times \frac{V_N}{V_P})} \tag{1}$$

Where V_N represents the negative voltage threshold of the Schmitt trigger NAND gate, V_P represents the positive threshold of the NAND gate, and V_{DD} represents the source voltage.

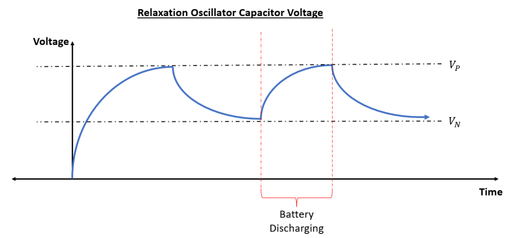

Fig. 3. Charging cycle of the Schmitt Trigger oscillator's capacitor

Fig. 3 represents the waveform depicting the charging cycle of the Schmitt Trigger oscillators capacitor. As the battery discharges during the charging of the capacitor, the equation for the voltage over a charging capacitor can be found using equation (2) to calculate the time of one charge.

Here,

$$V_C(t) = V_S\left(1 - e^{-\frac{t}{RC}}\right) \tag{2}$$

V_C(t) & V_S are voltage across the capacitor & the source voltage or the initial voltage supplied to the capacitor. R denotes the resistance in the circuit & C is the capacitance of capacitor. As the resistance value for the Schmitt Trigger oscillator is known from (1), the average current can be found by integrating the charging voltage divided by the resistance from the time to voltage V_N to the time to voltage V_P. This calculation produces the number of coulombs consumed for each charge of the capacitor which is helpful as the 3V coin batteries are labeled by their total charge in milliamp hours (mAh). Multiplying this result by the frequency and converting it to hours gives the number of mAh the clock consumes per hour operation. This calculation can also be conducted for the simulator and the SR latch. The sum of this value provides the total number of mAh consumed during an hour of operation. This can then be used to calculate the number of hours of operation that can be expected based on the chosen number of hours operating a day and the chosen battery size.

III. RESULTS

The proposed device was created using a 2-layer PCB and the layout diagram is depicted in Fig. 4. A 40-gauge silicone-coated stainless-steel medical wire (Cooner Wire Company AS-631) was used for connecting the device to the stimulating electrodes as well as running through a small port in the body to test whether the device is in the on or off state. The total cost of the circuit components, PCB, and approximately 12 inches of AS-631 that were used to create a device is $29.61. In order to implant the devices, each PCB is coated in the DOWSIL 3140 room-temperature vulcanizing (RTV) Silicone coating. A 90-milliliter tube of this coating was available to be purchased for around $40.00.

Due to its simplicity and cost effectiveness, the two-layer board was chosen over a multilayered board. When attempting to create a 4-layer design, the increase in the number of

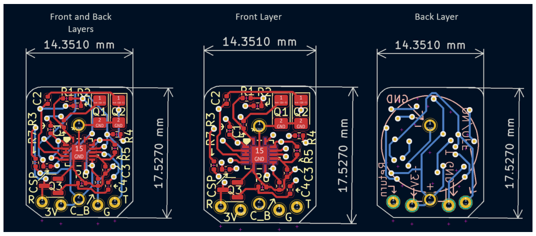

Fig. 4. Layout design of the proposed device

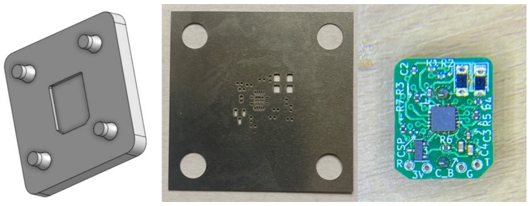

Fig. 5. Fabrication and assembly materials for the proposed device

via placements restricted the design from being minimized by an impactful amount. The design in Fig. 4 was created using the free version of the KiCad EDA 7.0 layout design environment which allowed the needed files to be created for fabrication. The design files can then be submitted to a chosen fabricator for board construction. The proposed design was fabricated by the JLCPCB: PCB Prototype & PCB Fabrication Manufacturer. All of the files used to fabricate the device are located in the provided GitHub repository to recreate the device or alter the proposed design for a desired application. After fabrication, many PCB fabricators offer the ability to populate the design with the required components, but in order to save costs, this step was done by the design team. The files for the 3D printable PCB mount, solder paste stencil used in the component fabrication process and the populated PCB of the proposed design are depicted in Fig. 5.

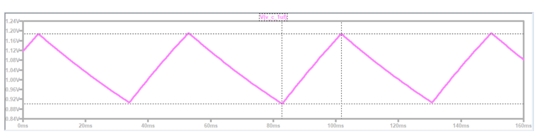

Fig. 6. Simulated clock capacitor voltage to determine Schmitt Trigger threshold voltages

The datasheet of the SN74AHC132 lists the positive and negative thresholds at a 3V supply voltage, but only the maximum and minimum values are shown. In order to determine the frequency, these values were found by measuring the voltage over the clock's capacitor. Fig. 6 depicts these results and shows that the V_P value is 1.185V and the V_N value is 905.817mV when powered by a 3V source. With these threshold values, the system produced a simulated frequency of 20.24 Hz. Fig. 7 depicts the resulting pulsing frequency used when a 120 kOhm resistor and a 1 μF capacitor are used. This led to an output stimulation frequency of 18.87 Hz. Additionally, it resulted in a percent error of 6.77% between the theoretical frequency and the measured frequency. Similarly, Fig. 8 depicts the resultant pulse that was used for stimulation. As Salmons originally notes, this pulse is close to 200μs in duration with the proposed duration of a pulse 90% of the maximum pulse voltage lasting for 218.0μs.

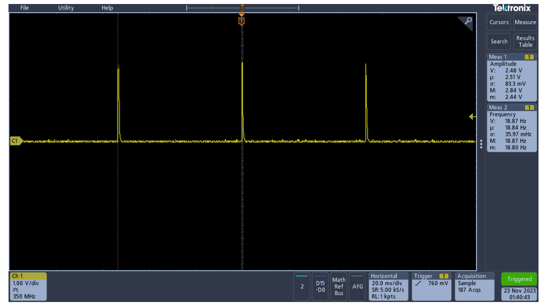

Fig. 7. Resulting pulsing frequency of the proposed device

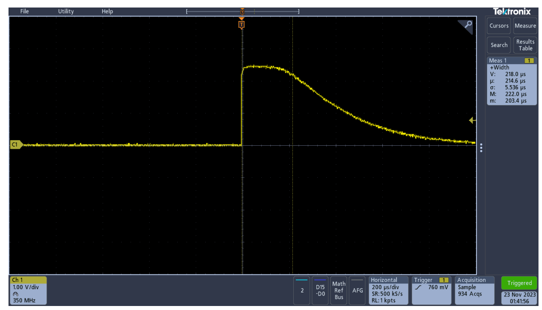

Fig. 8. Pulse width of produced device

IV. CONCLUSION

To summarize, this paper explains improvements in the design of FES devices by utilizing knowledge from the foundational work of Jarvis and Salmons. With the files provided in the https://github.com/FESdevice2024/Functional_Electronic_Stimulation, the proposed design can be implemented into future FES applications and decrease the lead time required to create an implantable device. Additionally, the files allow for future advancements and alternations to be added to the proposed design to increase the functionality of FES implants to a larger range of applications than the proposed device has. We have significantly improved performance and durability by modernizing Salmons' circuit architecture. The proposed device will be used in FES research where the device will supply pulses for two hours a day for a duration of seven continuous weeks. In all cases where the FES device is not required to supply a continuous pulse train throughout an entire day, operating the Schmitt Trigger oscillator for the entire day causes an unnecessary use of power which decreases the battery life of the device. We improved the battery life of the device by adding the functionality to enable the clocking circuit and reduced power consumption. These are both critical for implanted devices. We overcame issues found in previous models by effectively implementing an improved hardware arrangement. These contributions lead to a practical guide for implementing a functional FES device to be created.

V. Acknowledgment

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