# Design of Multi-Wavelength Low-Level Laser Therapy Device for Assisting Bone Reconstruction Applications

Toktam Jafarpour[1], Farouk Smith[2*]
1- Department of Mechatronics, Nelson Mandela University, Port Elizabeth, South Africa.
Email: S223513377@mandela.ac.za
2- Department of Mechatronics, Nelson Mandela University, Port Elizabeth, South Africa.
Email: Farouk.Smith@mandela.ac.za (Corresponding Author)

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**ABSTRACT:**
One of the main focus areas in human body reconstruction is the regeneration of bone tissue in different body zones by using various reconstruction applications. In the last two decades, different efforts have been undertaken for developing new bone reconstruction methods, and supporting techniques for stimulating bone healing mechanisms. It has been shown that during different Bone Reconstruction Applications (BRA), the presence of laser light could enhance the bone regeneration and healing mechanisms, while shortening the treatment time and improving the quality of newly formed bone tissue. The application of Low-Level Laser Therapy (LLLT) has recently been used for new bone reconstruction applications in different body parts, including the tibia, fibula, femur, humerus, radius, and mandible. It was shown that by applying a low-power laser light during the bone healing procedure in different treatments, an improved quality of regenerated bone tissue was evident, while accelerating bone healing mechanisms. However, only a few studies have been performed with regard to the development of specific LLLT devices for such advanced bone reconstruction procedures. More research needs to be done towards developing an ideal LLLT device to be used in different bone reconstruction techniques. The purpose of this research is to design a novel multi-wavelength LLLT device with controllable laser light intensity. In addition, by using such a mechanism, generating the laser light in single- and multi-wavelengths in predetermined working sequences is possible. The design specifications and simulation results have shown that the proposed system is functional while meeting all required specifications in terms of generating a single- or multi-wavelength laser light, with controllable power intensity. Therefore, in future developments, the proposed system could be used during BRA for assisting the treatment.

**KEYWORDS:** Low-Level Laser Therapy, Bone Reconstruction, Light therapy, Laser-Assisted Treatment.

## 1. INTRODUCTION

The application of advanced engineering techniques during medical and biological applications has been emerging over the years. In novel reconstruction applications, physical stimulation techniques, using different energy sources, have been used for assisting tissue healing procedures [1-3]. In Bone Reconstruction Applications (BRA), novel assisting techniques have been used for stimulating bone healing mechanisms and accelerating the treatment time [4]. The physical stimulation techniques in BRA could be categorized into four groups: photonic, electromagnetic, electrical, and mechanical techniques [3-8]. Photonic stimulation techniques are well known and have been widely used in different BRAs [9-12]. It was shown that photonic stimulation techniques could positively influence the bone formation mechanisms; by inducing biological effects in cells, including bone cells and surrounding soft tissue cells. The laser light could induce the function of mitochondria in affected cells, while enhancing their performance [13-16].

Low-Level Laser Therapy (LLLT) is a recently developed technique that enables the emission of low-power laser photons onto the targeted cells. LLLT could enhance the metabolic activities of the cells. In BRA, applying LLLT during treatment has shown promising results [17, 18]. In oral and maxillofacial reconstruction applications, including bone graft, distraction osteogenesis, peri-implant tissue healing, and wound healing, the application of LLLT for assisting the treatment is an emerging trend [19], [20].

Laser therapy is a physical stimulation technique that positively influence the bone healing mechanisms and improve the quality of the newly formed bone tissue [3], [4]. The application of LLLT has recently been used during BRA, where, a low-power laser light with a specific intensity and wavelength impact the healing zone and induce bone healing mechanisms [10], [11], [21-25].

The effects of LLLT on bone healing mechanisms during BRA have been studied in different experimental studies, animal trials, and clinical experiments in humans. However, most of applied LLLT techniques were extra-oral solutions. Recently, the application of intra-oral solutions for use in advanced BRAs, such as distraction osteogenesis techniques have been on the increase. Feasibility tests and animal studies have shown the positive effect of applying intra-oral low-level laser light for enhancing the bone healing mechanisms [5], [11], [13], [26-28].

## 2. LITERATURE REVIEW

Recently, the application of physical stimulation techniques during different BRA has been an emerging trend in the literature. Different experimental studies, including animal and clinical trials, have been done to understand all the effects of applying LLLT during BRA, and evaluating the laser parameters, including laser intensity and wavelength, on the bone healing mechanisms. In the literature, different wavelengths of laser light have been used during different BRA. In a study in 2007 [29], in an animal study performed on a sheep model, the effect of LLLT on the bone reconstruction procedure was evaluated. In this work, a Gallium-Aluminum-Arsenide laser light with the wavelength of 830 nanometer and intensity of 4 J/cm$^2$ was used for assisting the BRA.

In 2009 [20], the effect of a Gallium-Aluminum-Arsenide laser diode with the intensity of 10 J/cm2 was compared to the effects of Indium-Gallium-Phosphide laser light with a wavelength of 685 nanometer and intensity of 10 J/cm$^2$ during BRA. Results of these studies showed the positive results of applying these ranges of laser wavelength on the healing mechanisms. In addition, it was shown that applying a 685 nanometer laser light displayed more intense inflammation during bone healing mechanisms [20].

Following this research, in 2012 [30], the effect of LLLT on bone healing mechanisms during BRA on a sheep model was again investigated. In this study, the LLLT solution, by using a Gallium-Aluminum-Arsenide laser, was applied during the BRA by using an intermittent emission technique, where low doses of laser light were emitted onto the bone healing zone with predetermined sequences. In another study in 2012 [31], on a rat model, the effect of LLLT was evaluated. Results of these studies have shown that applying LLLT during BRA could significantly improve the quality of regenerated bone tissue and shorten the treatment period.

In 2012, the effect of LLLT on bone regeneration during maxillary-expansion techniques was studied [32]. In this study, 27 humans underwent maxillofacial reconstruction by using maxillary-expansion methods while the LLLT technique was assisting the treatment. During the treatment, a diode laser with 780 nanometer wavelength and output power of 40 mW (TWIN-laser, MMOptic, Italy) was used for generating low-power laser light, in order to stimulate the bone regeneration mechanism. The results of this study revealed that applying LLLT during the treatment would accelerate the bone healing and improve the regenerated bone tissue density.

In a clinical study in 2015, the effect of LLLT on the quality of regenerated bone tissue, the during distraction osteogenesis technique, was evaluated [7]. The radiographic measurements proved that using LLLT during the distraction osteogenesis technique could successfully improve the quality of formed bone tissue, while shortening the treatment time.

In a study in 2016 [5], The effect of intermittent LLLT during a BRA on a rabbit's mandible was evaluated. In this study, a Gallium-Aluminum-Arsenide laser with wavelength of 780 nanometer and output power of 0.2 W, which results in a laser light intensity of 5 J/cm$^2$ per spot, was used. The laser light was emitted onto the healing zone every 48 hours for a total of 10 times. The outcome of this animal study has shown that applying an intermittent LLLT during the BRA could enhance the quality of newly formed bone tissue. In 2018 [13], in an animal study on a dog model, the effects of LLLT on BRA was evaluated. In this study, a diode laser with wavelength of 970 nanometer and 100% duty cycle was used, while providing a total output power of 2 W. The results of the study showed that applying this wavelength could enhance the bone healing mechanisms and improve the outcome of the treatment. Fig. 1 illustrates the application of LLLT during an intra-oral BRA on a dog's mandible.

When considering the literature review, although LLLT solutions were successfully used during the BRA and effectively enhanced the quality of the outcome of the treatment; more research needs to be done to design and develop a specific LLLT system for such advanced reconstruction applications. In addition, in recent studies, the application of intermittent LLLT have become increasingly popular. Therefore, designing and developing a LLLT device with controllable output in terms of generating different wavelengths, output power, and working sequences (continuous or intermittent) will be an ideal choice.

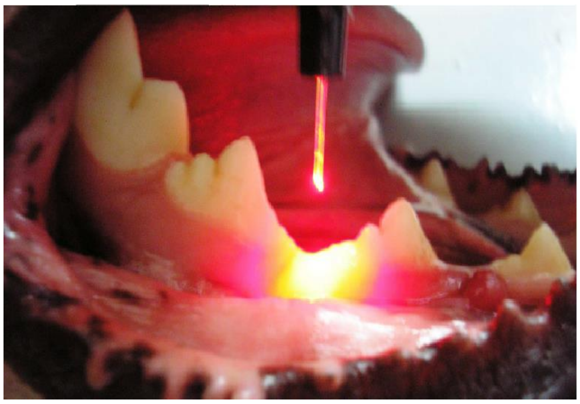

**Fig. 1.** The application of LLLT during BRA in an animal study on a dog's mandible [13].

The purpose of this research is to design and investigate the feasibility of using a Multi-Wavelength Low-Level Laser Therapy (MW-LLLT) device with adjustable output power, and wavelength of the generated laser light, for use in bone healing. This solution could assist BRA by enhancing bone healing mechanisms and shortening the treatment time. The device has the capability of generating three low-power laser beams with different specifications, including wavelength and intensity. The output of the device could be transferred onto the bone healing zone in different intra- and extra-corporeal techniques, via an optical fiber feed. In the following sections, after the design and modeling of the system explained, with its working principles, simulation results are presented for validating the feasibility of the proposed system and assessing the device's performance.

## 3. DESIGN OF THE MULTI-WAVELENGTH LOW-LEVEL LASER THERAPY DEVICE

### 3.1. Description of the System Design

For generating low-power laser light with adjustable output power, in single- and multi-wavelength output modes, the proposed MW-LLLT device consists of several different units. Fig. 2 illustrates the block diagram of the device. Various components used in the implementation and design is shown. In addition, the schematic of the system design is illustrated in Fig. 3. In the design of the MW-LLLT device, a power supply unit is used to provide 5 and 12 VDC voltages to run the system. In the control unit, an Arduino MICRO A000053 development MCU board is used.. This controller board hosts an ATmega32U4. It provides 20 digital input and output ports, including 7 PWM pins with a clock frequency of 16 MHz.

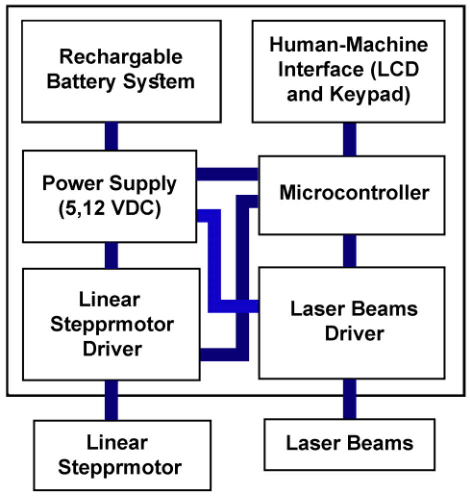


**Fig. 2.** The block diagram of the MW-LLLT device.

**Table. 1.** Specifications of the linear stepper motor.

| D8-MOTOR80 Mini Linear Stepper Motor | |
|---|---|
| Rated voltage | 4-9 VDC |
| Number of Phase | 2 |
| Current | 500 mA |
| Coil DC Resistance | 15 Ω |
| Insulated Resistance | > 50 M (500V) |
| Response Frequency | 1600 PPS |
| Stride Angle | 18º |
| Screw Length | 90 mm |
| Effective Stroke | 80 mm |
| Screw Pitch | 0.5 mm |
| Screw Diameter | 3 mm |

In the design of the MW-LLLT device, three laser modules with different wavelengths are used to generate the laser light with different wavelength. For this purpose, a low-power 0.3 W industrial laser beam, including red laser at 635 nm, green laser at 520 nm, and blue laser at 480 nm, have been used in the design of the system.

A mechatronic system is designed and implemented within this system to combine the generated laser beams. In this system, by designing and using an optical solution, three generated laser beams could be mixed and aligned together in a linear optical path to generate single- or multi-wavelength laser beams. In this mechanism, a three-step alignment technique was designed and used. Two mini right-angle half-silvered mirror (beam splitter, K9 optical glass) were used to align the three laser beams.

In front of the optical system, there is a focus lens which is connected to a miniature linear system, to move the lens in a linear axis, in order to focus the laser beam onto the targeted point. In this system, a linear stepper motor is used to move the focus lens with a movement accuracy in the order of micrometers. The specifications of this stepper motor are shown in Table 1. By using a precise linear control method, a multi-axis automatic controller, driving the implemented linear stepper motor with high precision and smoothness, is possible [33-35]. According to the specifications of the stepper motor, and using such a precise linear control solution, driving it in a linear axis with a maximum accuracy of 0.78 micrometers/step was possible. Therefore, by using this combination, the laser beams could be focused onto the targeted point with a precise linear motion of focus lens.

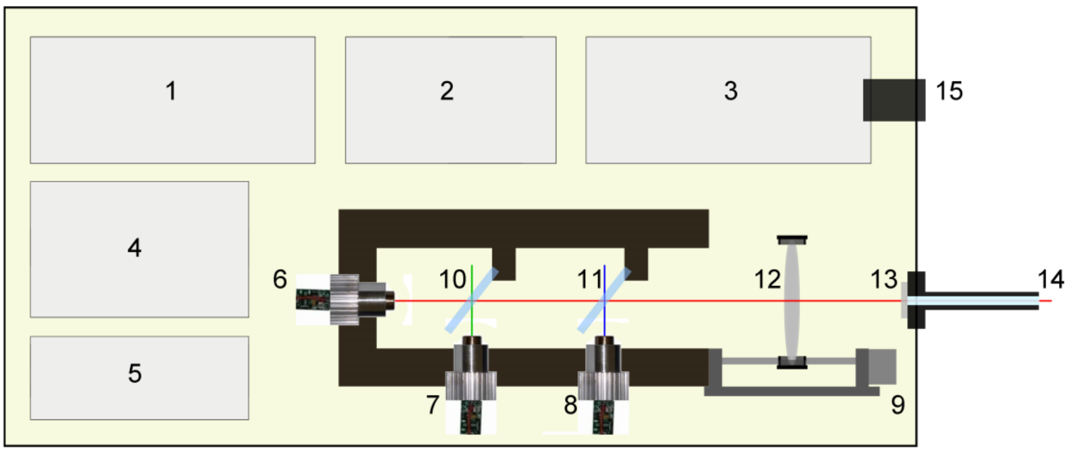


**Fig. 3.** The principles of the designed MWLLLT device.

As a result of the precise linear control, the laser beams are focused onto the entrance of a multi-mode optical fiber, which is placed in front of the center of a lens, aligned to the laser beam, to enable the transfer with high efficiency. The generated and aligned single- or multi-wavelength laser light could be guided to the healing zone in different intra- and extra-corporeal BRA via an optical fiber cable. In the optical system, all components need to be precisely placed in the correct position to enable an efficient alignment of the laser beams in a linear optical path.

Three L298 dual full-bridge drivers with 2 A maximum drive current are implemented and controlled by the microcontroller. One driver is connected to the linear stepper motor to drive the linear mechanism. Two other drivers are used to control the 5 and 12 VDC voltages that supply and drive the laser modules. This combination could enable controlling four DC currents up to 2 A with an operational voltage of up to 46 VDC. The outputs of the drivers provide four controllable power supplies to drive the laser modules.

In this mechanism, by adjusting the output power with PWM trigger signals, the intensity of the laser light, and driving sequences for generating laser beams, could be controlled. In addition, the frequency of the control signals and functionality could be set through the human-machine interface of the device.

In this device, a 1*4 keypad is connected to the microcontroller to set the process parameters and laser beam specifications. In addition, a I2C 2*16 character LCD is connected to the device to monitor the working parameters during operation.

The control unit has the capability of controlling the performance of each laser module and their intensity. In addition, by using this system, generating intermittent and pulsed laser beams could be enabled, where, the predetermined emission sequences could be set, and the controller could precisely control the system conditions with the desired working parameters.

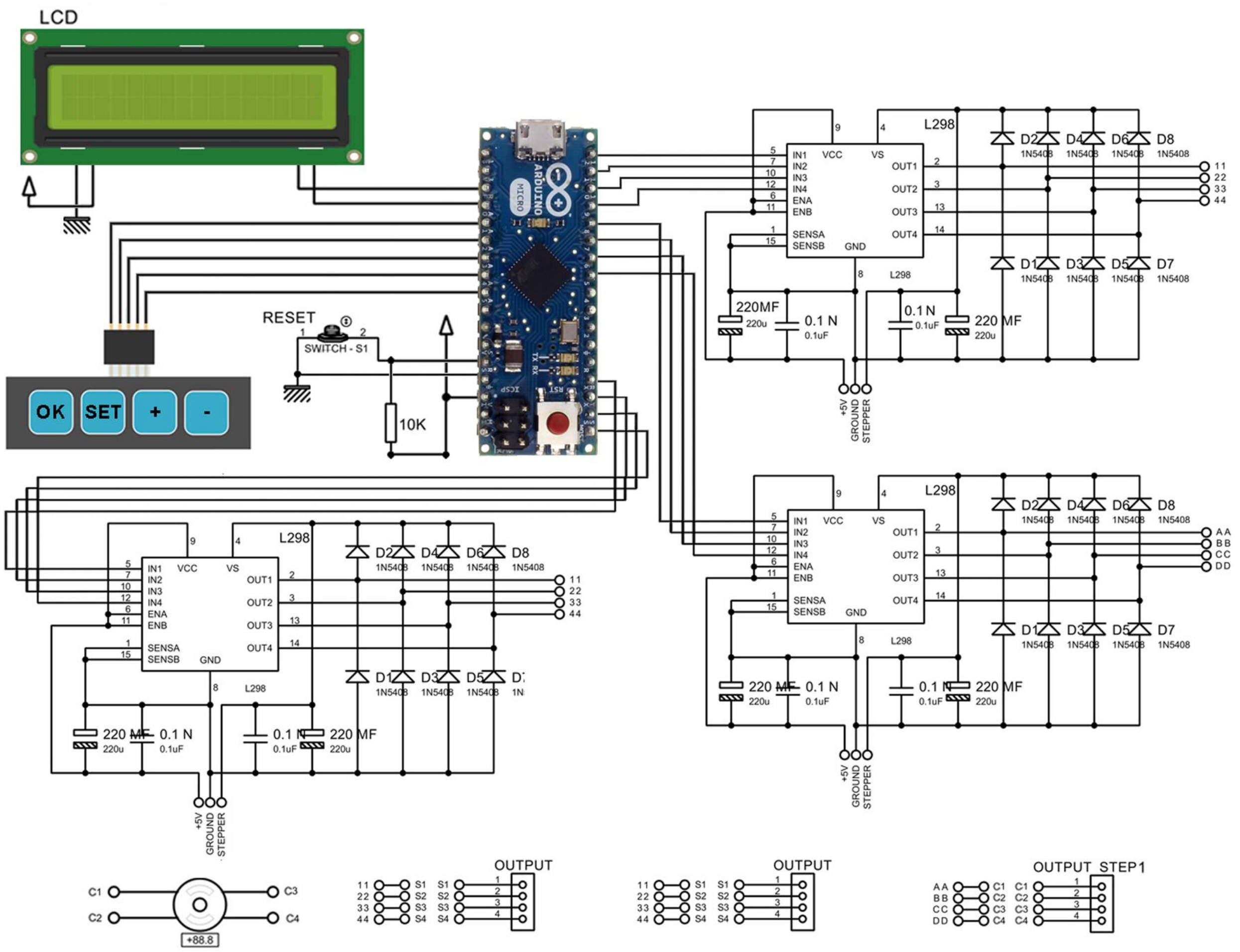


**Fig. 4.** The overall design of the circuits.

A rechargeable battery system is also included in the design and connected to the device to provide the required power supply during mobile applications. This rechargeable system could get connected to a 12 VDC charger to recharge the lithium-ion batteries and is connected to the power supply unit of the device. This feature could extent the application of this device for future clinical studies as a mobile device during the BRA. Fig. 4 illustrates the detailed design of the system.

### 3.2. Modeling and Simulation

After the design of the concept, simulation was performed to evaluate and analyze the performance of the control system, in terms of the generated control signals with the desired specifications. The system is capable of generating control signals to drive stepper motors with high precision, in different working modes, including microstepping drive mode. In our system, a hybrid linear stepper motor is used. The differential equations for these motors are mentioned as follow:

$$\frac{dia}{dt} = \frac{va + km.\omega.sin(N.\theta) - Ria}{L} \quad (1)$$

$$\frac{dib}{dt} = \frac{vb + Km.\omega.cos(N.\theta) - Ria}{L} \quad (2)$$

$$\frac{d\omega}{dt} = \frac{Km.ib.cos(N.\theta) - T - Km.ia.sin(N.\theta) - Kv.\omega}{J} \quad (3)$$

$$\frac{d\theta}{dt} = \omega \quad (4)$$

In equations (1-4), $i_a$ and $v_a$ are the voltage and current of phase A of the stepper motor, and, $i_b$ and $v_b$ are voltage and currents of phase B. $\omega$ is the rotor's rotational speed, $\theta$ is the angular position of the rotor, and $T$ is the load torque of the stepper motor. Other parameters including detent torque, magnetic coupling, and unstable inductance are neglected in the model, and simulation.

The proposed control system was modeled in MATLAB-SIMULINK software to simulate the output waveforms and evaluating the performance of the control system. Fig. 5 illustrates the sub-systems in the software.

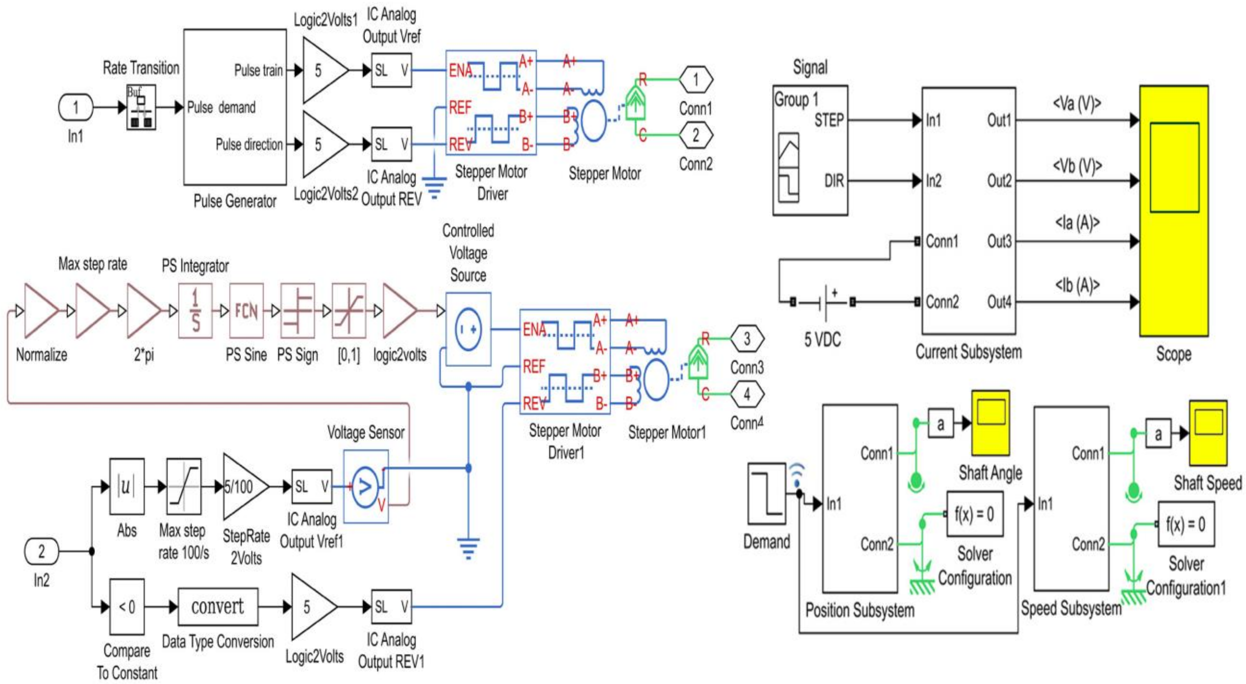


**Fig. 5.** The design of subsystems in MATLAB-SIMULINK software.

## 4. RESULTS AND DISCUSSION

The control system is capable of driving the stepper motor with an open-loop motor control technique. In addition, by generating PWM waveforms, controlling and driving the laser modules is possible. After modeling the proposed system in MATLAB-SIMULINK software, the required parameters and working factors of the control system are set. Subsequently, the simulation is run for 0.1 second.

The results of the simulation, including four detailed waveforms, are illustrated in Fig. 6. In the simulation results, the waveforms of voltages (*Vph*) and current (*Iph*) of the hybrid motor phases, shaft angle, and shaft position are illustrated. Where *Va* illustrates the waveform of the DC voltage in phase A of the stepper motor (blue waveform), and *Vb* illustrates the waveform of the DC voltage in phase B (red waveform). In addition, *Ia* and *Ib* are current waveforms of the A and B phases of the stepper motor, *T* illustrates the shaft position, and *w* the shaft speed.

It can be deduced from the waveforms, that between the phases of the stepper motor (phase A and B), voltage and current waveforms are 90 degree displaced. Therefore, the generated waveforms agree with differential equations of the stepper motor, equations (1) to (4).

In addition, the positioning of the stepper motor's shaft illustrates that the system can execute a precise linear motion while the shaft's position and speed are under precise control. Thus, the control system can enable a precise position control of focus lens (No. 12 in Fig. 3), with maximum positioning accuracy of 0.78 micrometer.

The results of the modeling and simulation in MATLAB-SIMULKINK software have shown that the generated control signals are precise enough to drive the hybrid stepper motor with predetermined working parameters. The proposed control system is functional and could provide the necessary requirements to drive the linear stepper motor, as well as generating control signals to drive the laser beams.

By using the MW-LLLT device, different single and multi- wavelength modes of laser beams with adjustable intensity and output power could be generated. In single-wavelength mode, green, blue, and red laser beams could be generated independently. In multi-wavelength mode, these laser beams could be combined by using half-silvered mirrors (beam splitter). Therefore, different conditions of LLLT treatment could be enabled for assisting different reconstruction applications of the bone tissue.

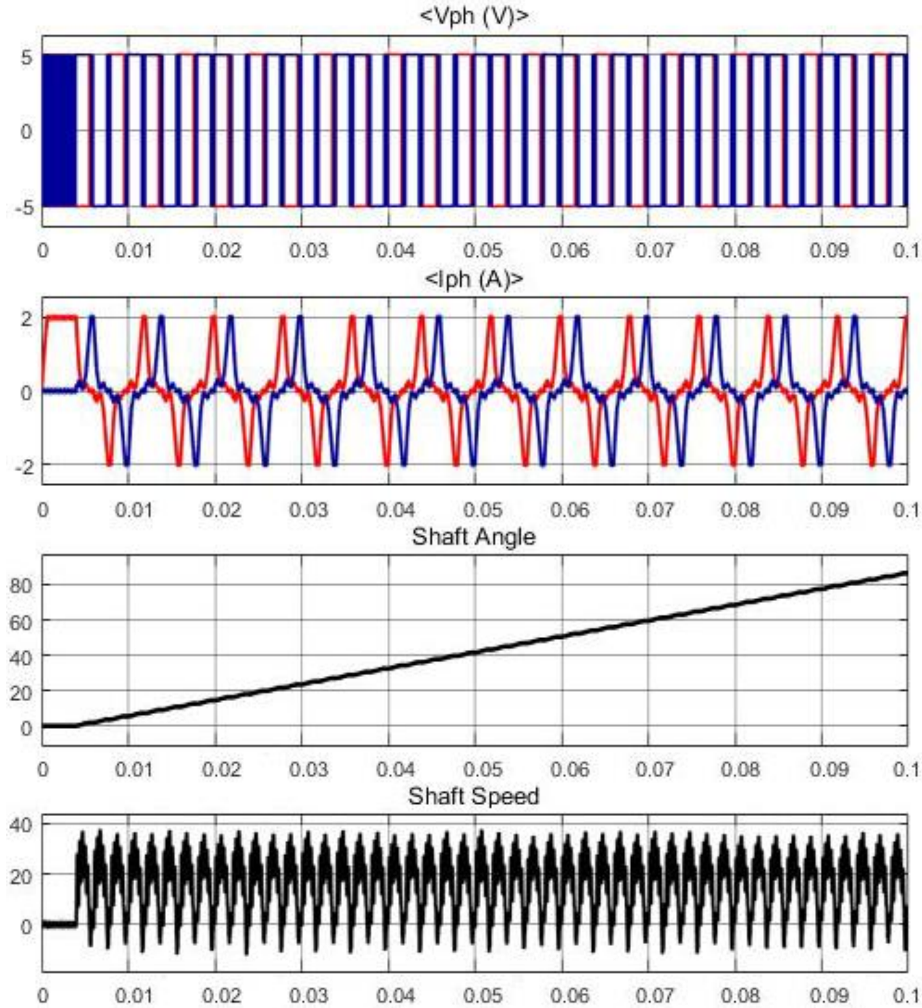


**Fig. 6.** Simulation results of linear stepper motor.

## 5. CONCLUSIONS

In this paper, a novel MW-LLLT device was designed and simulated to generate three different wavelength of laser beams with a controllable output. The device has the capability of driving each laser beam independently with adjustable working parameters. Therefore, single- and multi-wavelength LLLT during BRA is possible. In addition, by implementing a precise control system using electronic drivers and switching, and a precise linear movement mechanism, adjusting the intensity of the laser beam and focusing it onto the targeted zone is possible. A multi-mode optical fiber was used to guide the laser beam onto the healing zone. Also, a human-machine interface was connected to the mechanism to enable the setting of the working parameters of the system.

By implementing a rechargeable battery system, this design could be used as a mobile solution for future experimental and clinical studies. In the future, the MW-LLLT device could be used as an ideal solution in terms of applying LLLT during BRA.

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