Design of Laser-Assisted Automatic Continuous Distraction Osteogenesis Device for Oral and Maxillofacial Reconstruction Applications

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Received: August 2019 Revised: October 2019 Accepted: November 2019

ABSTRACT:
Distraction Osteogenesis (DO) is a novel limb lengthening technique for bone tissue reconstruction in human. The DO method has got an important role in Maxillofacial Reconstruction Applications (MRA) for reconstruction of skeletal deformities and bone defects. Recently, the application of Automatic Continuous Distraction Osteogenesis (ACDO) devices are emerging; for enabling an automatic and enhanced DO procedure while achieving superior results in terms of bone formation and consolidation quality, compared to conventional manual methods. It has shown that developed ACDO devices could fulfill technical features while providing an automatic continuous procedure based on the standard DO protocol. One of the main limitations in developed ACDO devices is limited distraction vector; in which the positioning of the Bone Segment (BS) has been limited to one-axis or specifically designed curve-linear paths. Enabling moving the BS in more than one axis, while the positioning of the BS is automatically and precisely controlled, could enhance the outcome of the DO treatment and expand the application of this novel reconstruction technique. In addition, using laser therapy during the treatment would enhance the bone formation quality. In this paper, a two-axes automatic continuous controller for using in a novel ACDO device is designed. Design specifications and simulation results have validated the functionality of the proposed system. By using the designed controller as well as the intra-oral distractor, applying two continuous forces onto the BS, and moving the BS in linear and curve-linear paths is possible. The application of developed ACDO devices are still limited to experimental and animal studies. More research and investigations need to be done to fulfill this gap and solve existing limitations; for enabling an ultimate ACDO procedure in human MRA.

KEYWORDS: Automatic Continuous Distractor, Automatic Distraction Osteogenesis, Laser-Assisted Distraction Osteogenesis, Medical Devices.

1. INTRODUCTION

Distraction Osteogenesis (DO) is a novel limb lengthening technique in human Maxillofacial Reconstruction Applications (MRA). By using DO technique various bone defect and skeletal deformities could be reconstructed [1, 2]. In 1987, Ilizarov introduced the manual DO method for MRA [3-5]. In conventional DO methods; manual distractors have been used, where, the activation of the mechanical distractor and moving the Bone Segment (BS) towards the destination position is upon intermitted manual activations by user [6-8]. However, the application of manual DO methods has been limited; various complications are associated with using such manual solutions. The major limitations of using manual DO solutions are low accuracy, reliability, and repeatability. In addition, long treatment period and painful procedure are other disadvantages of using a manual distractor during a DO treatment [9].

Figure 1 illustrates the standard procedure of DO treatment. The DO procedure starts with bone osteotomy and installation of the distractor on the distraction zone (t1). Between t1 and t2 there is a latency phase, in which the device is installed but not activated. After t2, activation phase begins and the BS gradually goes through a predetermined path, which is called Distraction Vector (DV), towards the destination position. In this phase the distractor is activated in predetermined sequences. As soon as the BS reaches the destination position, the activation phase is completed (t3). After t3, there is a consolidation phase, in which the device is left on the distraction zone without activation. At the end of consolidation period (t4) the device is removed and the treatment is completed.

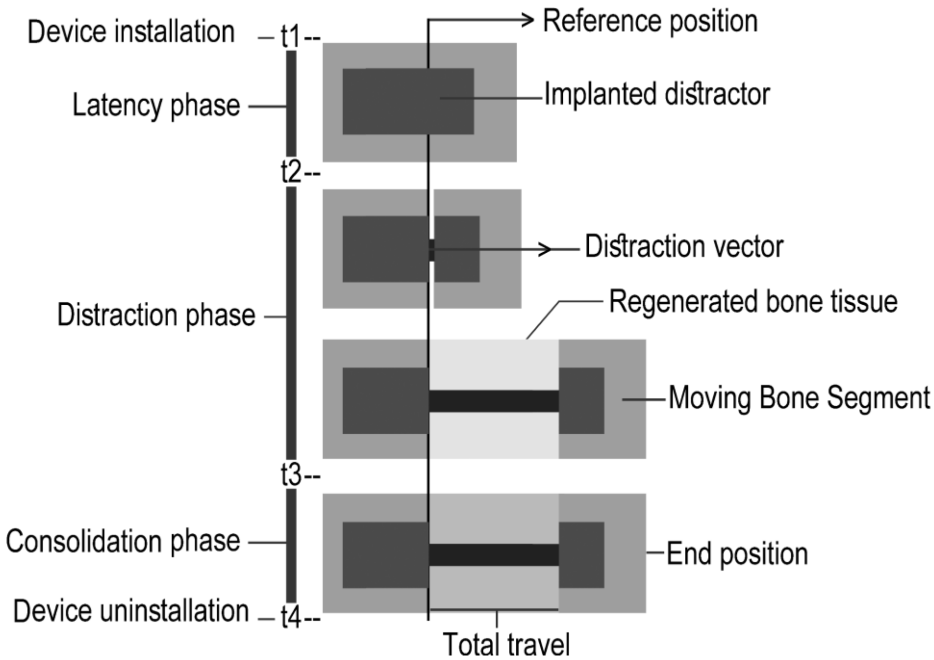

Fig. 1. Standard distraction osteogenesis procedure.

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Further investigations have revealed that increasing the activation sequences for moving the BS (called distraction rhythm) could provide a better formed bone tissue while reducing the treatment period. Therefore, by applying a higher rhythm during the DO treatment, a higher distraction rate for moving the BS could be applied [6, 10-12].

Recently, the application of Automatic Continuous Distraction Osteogenesis (ACDO) devices for MRA are emerging. From 2000, research has been performed for developing automatic devices for enabling an automatic DO procedure, reducing the treatment time, and improving the bone formation quality during the treatment. Different techniques and precise control systems have been developed for enabling a continuous movement of the BS towards the destination position. It has been revealed that developed ACDO devices could successfully enable an automatic DO procedure based on standard requirements. However, the application of developed ACDO devices has been limited to experimental and animal studies. There are major complications and limitations which limit the application of developed devices to be used in human MRA; including force transition techniques, DV, portability, and size [6, 13-19]. In addition, according to performed studies, in some reconstruction applications, non-linear DV for moving the BS is required [20, 21]. For enabling an ultimate ACDO procedure in human MRA; more research and investigations need to be done to expand the functionality of such devices and optimize the working parameters and distraction condition.

On the other hand, different techniques could be used during DO treatment for assisting the bone formation and accelerating DO phases. In last two decades, various non-conventional techniques have been developed and used for enhancing bone healing mechanisms, increasing the quality of newly formed bone tissue, and improving physical and biological properties of bone formation mechanisms during the DO procedure. Physical stimulation is a popular category of non-conventional techniques that could enhance the bone formation mechanisms, while impacting the DO procedure from various aspects. The technologies that have been used for assisting DO procedure include photonic, magnetic, electric, and mechanical stimulation techniques [22-25]. Among mentioned non-conventional technologies, photonic stimulation techniques are from the favor and have shown promising impact on the bone formation mechanisms as well as the outcome of the DO treatment. Photonic stimulations techniques include static laser therapy, Low-Level Laser Therapy (LLLT), and pulsed laser therapy techniques. Photonic stimulation could enhance the bone formation by producing a biochemical effect in cells that strengthens the mitochondria [26-29]. Low-level laser radiation has some photo-stimulatory effects at cellular levels, these effects has been reported in vitro systems [30] and also in vivo [31, 32]. Mentioned techniques could provide optimization on multiple genes expression during bone healing procedure; which could positively affect the cellular proliferation, growth factors, and cellular migration [33]. It has been observed that the cytokine levels are altered after the laser radiation [34]. LLLT has various effects on the mitochondrial of osteoblasts and osteoblastic cell populations activities [35]. This assisting technique has effects on the osteoclast genesis, and could enhance the healing process by activating the receptor of osteoprotegerin (OPG), nuclear factor kappa-B ligand (RANKL), and nuclear factor kappa-B (RANK) [36]. LLLT has beneficial effects in the oral and maxillofacial surgeries; this technique could enhance the healing time and decrease the pain during the process as it shortens the inflammatory process and accelerates the new bone formation [36].

The purpose of this research is to design a two-axes automatic controller to be used in a two-dimensional ACDO device. In the design of this system, a precise control method, called Multi-Axes Automatic Controller [37-39], is implemented for enabling controlling the positioning of two independent miniature linear axes. Using such MAAC method would enable a precise positioning of the BS in a linear or non-linear DV during the DO procedure, while providing a smooth and continuous Distraction Force (DF). Therefore, by using specifically designed intra-oral distractor; moving the BS in various conditions, for reconstructing different oral and maxillofacial areas, is possible. In the following sections; the design of the proposed device, working principles, simulation model, and results have been provided. Subsequently, the simulation results as well as the viability and functionality of the proposed ACDO device are discussed.

2. DESIGN OF DISTRACTOR

The design of the system consists of two miniature lead screw translation mechanisms, two independent Transition System (TS), an intra-oral mechanical distractor, and a control unit. Figure 2 illustrates the block diagram and working principles of the proposed ACDO device. In this system, a Human Machine Interface (HMI), consists of a 4*4 keypad and a 2*16 Liquid Crystal Display (LCD), is implemented for enabling communication with the control unit, setting required DO parameters, and configuring the procedure condition. The input data could be read by implemented microcontroller. Accordingly, the working factors and activation sequences for driving implemented motors in TSs are calculated and set. In addition, by implementing a serial memory (AT24C04), a real-time data backup is enabled. By using two full bridge stepper motor drivers, controlling two independent movement in linear axes while generating two continuous DF is possible. When the motors are driven by the controller, a pushing DF of 38 N [15] in each axis is generated, and then transferred to the BS via implemented TSs. In this device the user could set the desired DO working parameters, including distraction rate, distraction length, DV, and the intensity and frequency of implemented LLLT unit. In following subsections, details and working principles of main units of the proposed ACDO device are introduced and discussed..

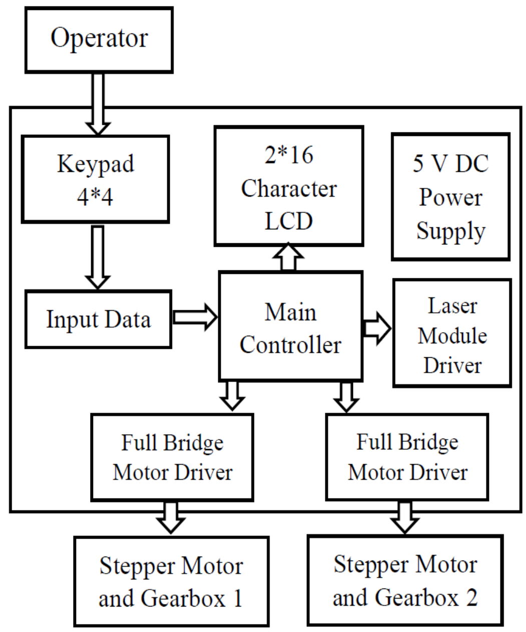

Fig. 2. The block diagram of the ACDO controller.

2.1. Two-Axes Linear Movement Mechanism

This unit consists of two independent miniature lead screw translation mechanisms, for translating the rotational motions of the stepper motors' shafts into the linear movement. In this unit, two Kiatronics 28BYJ-48 mini stepper motor and gearbox are used. Previous studies on one-axis of this linear mechanism have shown that using this stepper motor in the design of ACDO device is viable [15]; the output of this stepper motor is sufficient and precise enough for such a specific DO procedure. The specifications of implemented stepper motors are mentioned in Table 1.

The implemented stepper motors are capable of generating controlled rotational movement with maximum accuracy of 0.176 degree/step, in micro-step driving mode (1/32). Therefore, the output shaft of the stepper motor and gearbox could generate a rotational movement with maximum accuracy of 0.00275 degree/step. The output shaft of each stepper motor and gearbox is connected to a lead screw translation system by using a 4-mm solid shaft coupling. In both translation systems, a miniature lead screw, for translating rotational motion into linear movement, with 4 mm diameter, 1-mm pitch, 1-mm lead, and total length of 4 mm is used. Therefore, achieving a maximum positioning accuracy of 7.63 nm/step, in a controlled linear movement, is possible [15]. Figure 3 illustrates the designed two-axes translation system.

Table 1. Specifications of 28BYJ-48 stepper motor/ 28BYJ-48 stepper motor

Rated voltage	5 VDC
Number of Phase	4
Current	40 mA
DC Resistance	54 Ω
Phase inductance	3 mH
Frequency	100 Hz
Speed Variation Ratio	1/64
Stride Angle	5.625 (degree) / 64
In-traction Torque	> 34.3 mN.m
Friction torque	1200 gf.cm
Pull in torque	600 gf.cm
Insulated resistance	> 10 M (500V)
Noise	< 35 dB

By implementing two independent translation mechanisms which are connected to implemented flexible TSs; two continuous linear DF are generated and transferred to intra-oral distractor placed on the distraction zone for moving the BS in a linear or non-linear DV towards the desired destination. In each translation system, the carriage is connected to a flexible stainless-steel spring-wire guide for transferring the generated DF to the intra-oral distractor for moving the BS.

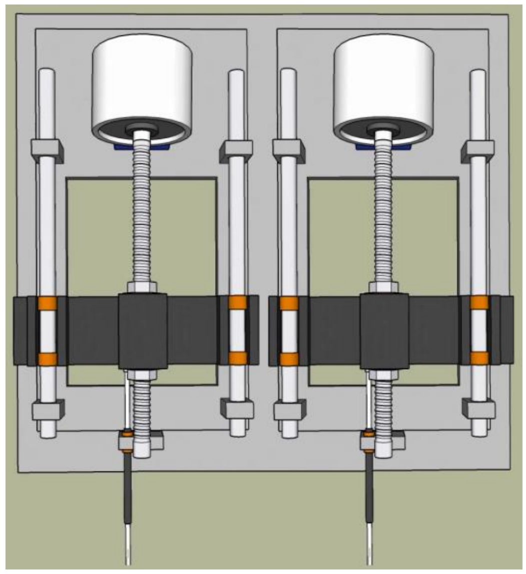

Fig. 3. The designed two-axes translation system.

2.2. Main Control Unit

In the designed system, a high-performance 16-bit RISC-based microcontroller, Arduino MEGA 2560 controller board, with clock frequency of 16 MHz, is used; which would enable a fast data transmission while precisely controlling the position of the BS. In this unit, two full-bridge L298 motor drivers are implemented. These two drivers are connected to stepper motors and could drive each of them in an independent linear axis. Microcontroller could send the predetermined distraction sequences to the motor driver units by using 5V DC control signals. Therefore, controlling the position of stepper motor's shaft and positioning of each carriage in lead screw translation mechanisms is possible.

In another subsequent, microcontroller could control and run the implemented laser diode module. By using a MOS Trigger Switch Driver Module, FET PWM Regulator High Power Electronic Switch Control, controlling and driving the laser module for generating laser photons with controlled intensity is possible. By using Pulse Width Modulation (PWM) technique and high-frequency switching, generating various LLLT conditions during the DO procedure is possible. By varying Duty Cycle (D.C.) of the signal, different intensities of the laser photons emission could be achieved. Figure 4 illustrates the designed circuit of the proposed system.

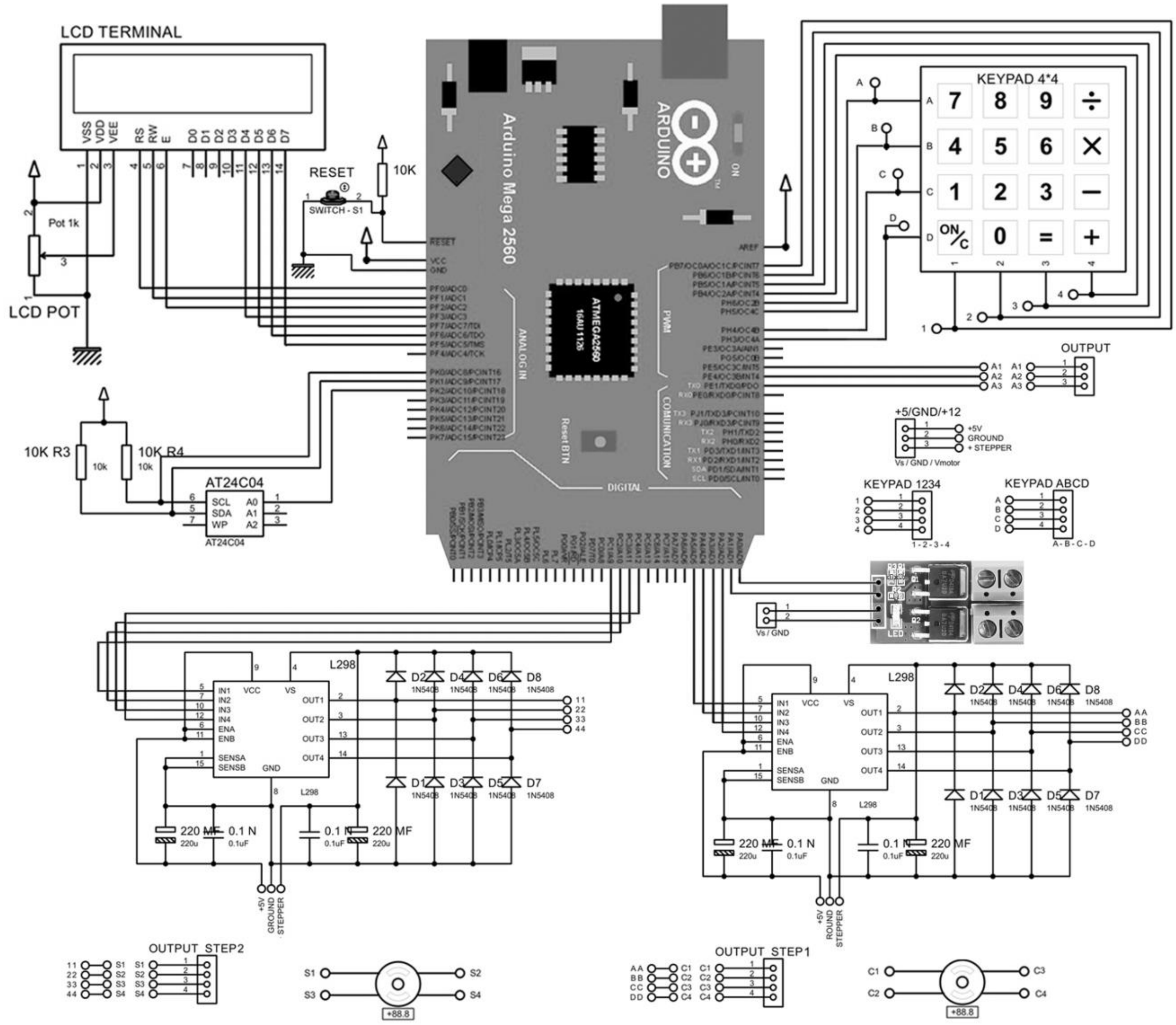

Fig. 4. The designed circuit of proposed automatic continuous distractor.

2.3. Laser Therapy System

In the proposed ACDO device, a diode laser module is implemented for generating laser photons and assisting the bone formation mechanisms during the DO treatment. For impacting the bone healing procedure by using a LLLT solution; a wide range of laser light with wavelengths from 500 to 1064 nm have been used. The major difference between applying different types of laser light is the amount of energy that has been transmitted onto the distraction zone and impact different bone formation mechanisms. Applying a LLLT technique during the DO procedure has shown promising results in the bone healing process [27, 40, 41].

In the design of the proposed system, a laser module, low-power industrial red diode laser, with wavelength 650 nm and output power 800 mW, is used for impacting the bone formation intra-orally during the DO treatment. By using the control unit and laser driver module; the output power could be set between 0 to 800 mW. With using a solid fixture, the body of the laser module is fixed in front of an optical fiber. Therefore, the emitted laser photons could be transferred to the other side of the optical fiber. The other side of the optical fiber is fixed to the intra-oral distractor (inside the oral cavity) while emitting the laser photons onto the distraction zone through an optical lens. The whole light transmission system is sealed with a miniature flexible silicon tube. Figure 5 illustrates the designed and implemented laser module, its TS, and intra-oral fixture of this unit.

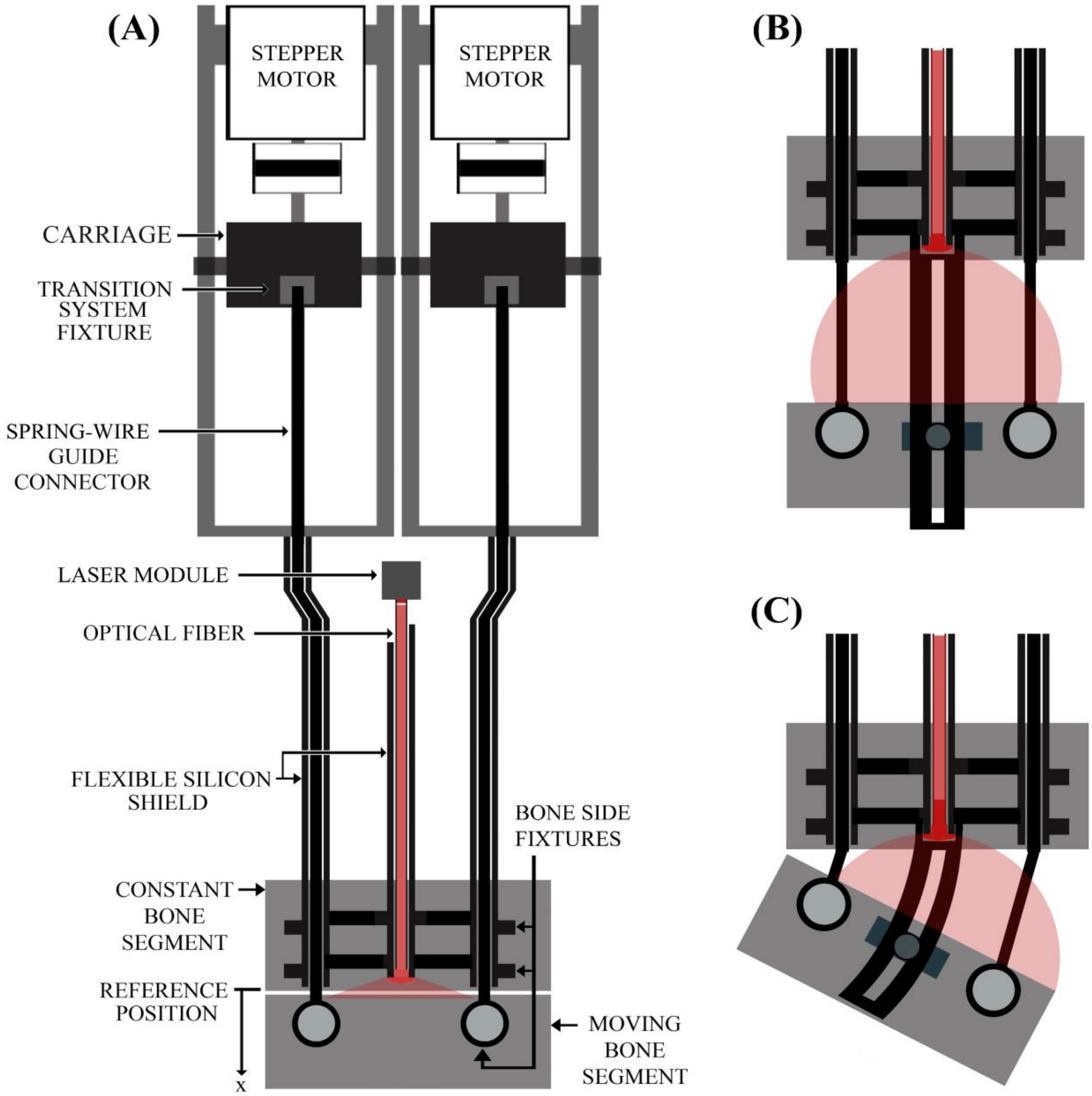

Fig. 5. (A) The schematic design of the proposed system, **(B)** moving the bone segment in a linear distraction vector, **(C)** moving the bone segment in a in a curve-linear distraction vector

2.4. Transition Systems and Intra-Oral Distractor

The designed device has two TSs. The TSs have similar design and structure, and work based on the same principles. Figure 5 illustrates the designed TSs which are connected to intra-oral part of the device; for transferring the carriage movement and generated DF to the BS. Each TS consists of the following components; a flexible stainless-steel spring-wire guide, a flexible shield, linear or curve-linear intra-oral distractor, and specifically designed mechanical fixtures. In both TSs, one side of the spring-wire guide is fixed to the carriage of one of the implemented translation systems. The other side is connected to the intra-oral mechanical distractor, which is fixed to the BS. When the system is generating linear movement, the generated force pushes the spring-wire guide and transfers the DF to the BS in two independent linear axes. Therefore, two controlled pushing forces could move and set the position of the BS in a predetermined DV. This combination allows applying two pushing DF of 38 N onto the BS in two points on the BS. Two types of intra-oral distractor could be used in this mechanism. Linear-path intra-oral distractor; in which two similar DF could apply to the BS and push it in a linear DV towards the desired location. In addition, curve-linear intra-oral distractor with specific designs could be used in this mechanism; for moving the BS in a specific curve-linear DV, or rotating it.

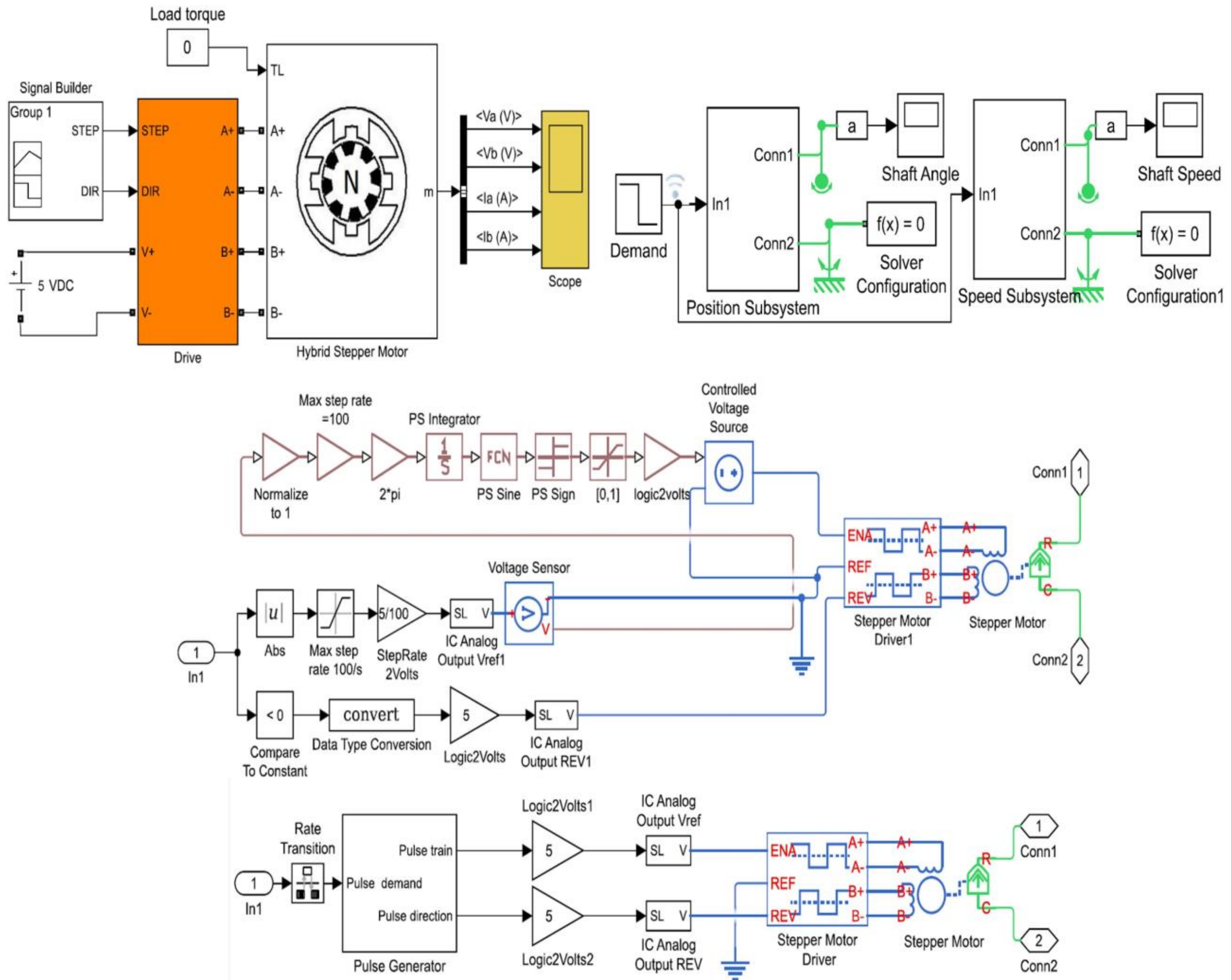

Fig. 6. The designed model of the control system, including speed and position subsystems

2.5. Simulation of Control System

The designed two-axes control unit could drive two implemented stepper motors of translation mechanisms independently, with controllable working factors, including the speed and length of the distraction. Micro-stepping drive mode could provide a smooth and soft distraction while enabling moving the BS in desired DV with a soft and continuous DF. The mathematical equations of the implemented hybrid stepper motors are differential equations of the dynamic model of the system, including electrical and mechanical equations. The differential equations of the implemented stepper motor have been introduced and discussed in previous studies on one-axis translation mechanism by using same stepper motor [15, 39]. Simulation of the designed control system has been performed in MATLAB-SIMULINK software. Figure 6 illustrates the designed model of the control system in the simulation software. Figure 6 illustrates the designed model of the control system.

3. RESULTS

After designing the model of the system simulation was run for 0.1 second. Figure 7 illustrated the generated waveforms. *Vph* is the generated voltage waveforms in two phases of the stepper motor. Where, *Va* illustrates the voltage waveform of phase A, and *Vb* illustrates the voltage waveform of phase B. Also, *Iph* is the current of each phase in implemented stepper motors. Where, *Ia* is the current waveform of phase A, and *Ib* is the current waveform of phase B. In addition, in 'shaft angle' and 'ω' graphs, stepper motor's shaft position (degree) and rotational speed (rad/s) are shown. The waveform of voltages in two phases of the stepper motor are 90 degrees displaced. The generated waveform of currents in two phases of the stepper motor are also 90 degrees displaced. It could be deduced from the results of the simulation that generated waveforms are in agreement with theoretical equations and calculated working factors.

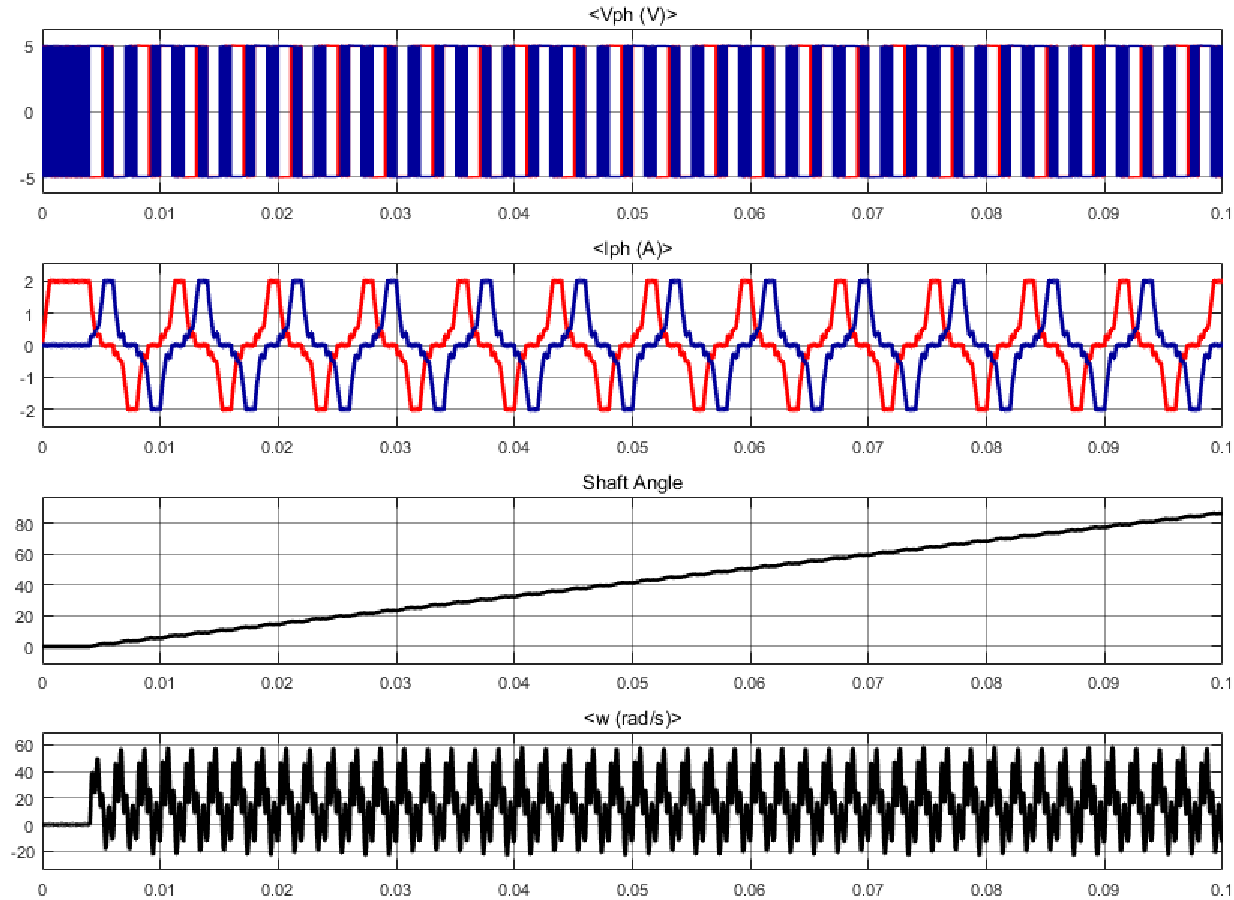

Fig. 7. Simulation results of the voltages, currents, shaft angle, and shaft speed of the stepper motor.

It could be deduced from the design principles and simulation results that the system could successfully generate control signals for driving the stepper motors. The implemented drivers are capable to drive the stepper motors in their linear axes. Therefore, the control unit has a full control on linear movement mechanisms. By driving the stepper motors in micro-step drive mode; precise movements (7.63 nm/step) in two independent linear axes, while generating two smooth DF of 38 N, is achievable. Therefore, the BS could be moved in an automatic and controlled DO procedure while the BS is moving in a linear or curve-linear DV.

4. DISCUSSION

With respect to recent developments of ACDO devices, it could be realised that all required standard working parameters have been covered by recently developed solutions. Therefore, future studies should be concentrated on optimization of developed techniques, while reducing existing limitations including DV [15]. One of the current limitations in developed ACDO devices is the implantable intra-oral part of the distractor is usually limited to moving the BS in a linear DV. However, in some reconstruction applications in specific maxillofacial areas, a curve-linear path for moving the BS is required [20, 21].

In the proposed device, by designing a precise control system, by implementing MAAC control method [15], two smooth and reliable movement mechanisms with maximum accuracy of 7.63 nm/step are enabled. By using miniature TSs, two generated DFs are transferred to the intra-oral distractor (installed on the distraction zone). These two continuous forces could smoothly push two points of the BS and move it towards the desired location in a specific path. In case both movement mechanisms are working with same working parameters and a linear DV is used, the BS travels in a linear path. By varying the working parameters of movement mechanisms while using a specific curve-linear DV, the BS could travel in various curve-linear DVs or rotate around a specific point in a limited angle.

In addition, recent contributions have shown that applying non-conventional techniques during the DO treatment could improve the bone formation quality and enhance the outcome of the treatment. In a DO procedure, applying photonic stimulation could enhance the bone formation by producing a biochemical effect in cells that strengthens the mitochondria, in which, cells could make more adenosine triphosphate. With more energy, cells could function more efficiently, rejuvenate themselves, and repair damage. LLLT is a novel technique that could enhance the outcome of bone formation mechanisms by improving the metabolic activities and shortening the treatment period [26-29]. Different in vivo and in vitro studies have been performed for evaluating the effects of LLLT as well as discovering constructive and destructive effects of this assisting technique. The positive effects of LLLT on bone formation/healing procedures are shown in different oral and maxillofacial applications and tissue healing procedures, including autogenous bone graft, bovine bone graft, DO, peri-implant tissue healing, and wound healing [42-47]. It has shown that using a LLLT solution during the bone healing process would also result in decreasing the pain and bone swelling [48]. However, more research needs to be undertaken for developing standard protocols for LLLT activation and working parameters during the DO treatment, including specific laser power, and activation sequences and duration.

In the proposed system, by implementing laser module, optical fiber, optical lens, and flexible miniature shield, the generated laser light could transfer onto the distraction zone; in which the DO procedure benefits from a photonic stimulation during the treatment. This would result in an improved formed bone tissue during the treatment. In this system, the control unit could adjust the output power and frequency of generated laser light by using PWM technique while enabling a LLLT solution for assisting the bone formation.

5. CONCLUSIONS

DO is a novel solution in oral and maxillofacial reconstruction applications for reconstructing bone defects. The proposed ACDO device has the capability to enable an automatic continuous distraction while moving the BS in a controlled linear or curve-linear DV; with sufficient distraction accuracy and continuous DF. In addition, by implementing HMI, the control unit could receive the input data from the user, set the parameters, calculate the required values, save them, and recover them.

In addition, using a non-conventional technique, LLLT, during the treatment period would enhance the results by improving the quality of the formed bone tissue. For applying LLLT during the DO procedure, no anesthesia or sedation is needed. Appling laser light onto the DO zone is painless. Therefore, the application of LLLT during ACDO procedure in MRA is feasible [22].

The designed device has the potential to be used in various DO conditions in MRA with the capability of moving the BS with adjustable parameters for various DO conditions. By implementing high-performance control unit, and specifically designed intra-oral distractor; various non-linear DVs could be achieved for moving the BS towards the desired position in two-dimensions. It is also possible to rotate the BS around specific points in a limited range.

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