FIRMWARE FOR LASER SURGICAL OPHTALMIC MICROSCOPES

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This work presents the technical aspects for the development of a firmware for a Nd:YAG laser based ophthalmic surgery microscope. The software design was developed for a Microchip® PIC18F4550 microcontroller. It interfaces the electronic blocks of the device and allows the calibration of the laser energy attenuator. The calibration data are stored into EEPROM's for each Nd:YAG laser unit. The fast developing time of the software is achieved by using of Flowcode® 4 – a graphical programming tool for microcontrollers with customizable code software blocks. The software undertakes the specific requirements of a medical device.

1. INTRODUCTION

The last years' studies targeted the development of new equipments for healing a larger range of ophthalmic diseases. This represents a necessity because of the current aging population trend in developed countries (Western Europe, USA, Japan) which is leading to an increase of the incidence of ocular diseases (*e.g.*, cataracts and glaucoma). Following this situation, many researches have been made on the instruments which use laser radiation as an active tool in ophthalmic surgery. The lasers mostly used for this purpose are the Nd:YAG ones [1,4-5]. By using these equipments the medical procedures became simpler, decreasing both the unsuccessful surgeries and the costs related to hospitalization.

Improving medical services from prevention and monitoring to treatment and rehabilitation is supported by the rapid development of interdisciplinary sciences of bioengineering and medical informatics [6].

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The aim of this work is to present the development of a genuine firmware that can be used to control the ophthalmic laser and all its electronic blocks, including some newly developed ones, like the energy attenuator. A fast development of this software is achieved by using Flowcode® 4 which is a graphical programming tool for microcontrollers with customizable C++ code software blocks.

2. **EXPERIMENTAL**

The microcontroller chosen for this firmware implementation is PIC18F4550 from Microchip® due to its large number of digital I/O ports (15 ports) and analog input channels (13 channels), high memory capacity (32 Kbytes program memory and 255 bytes EEPROM) and 10 bits resolution of the CCP (Capture/Compare/PWM) modules[2]. Further are described the main functions implemented in the software, together with their specific hardware.

2.1. INITIALIZATION

After the successful initialization of the microcontroller's software, a continuous 5 Vcc output voltage is generated at its E0 port. External hardware is signaled this way that the microcontroller's software has started well and continues the initialization of other hardware blocks.

2.2. SETTING THE ENERGY LEVEL

The system uses an innovative way of setting the laser energy. In order to continuously control the laser energy to a required value, without using moving parts, or to setting a different voltage for the laser's flash lamp, we used a Pockels cell. Its functioning is based on the rotation of the polarization plane of the laser beam which passes through it. The incident laser beam is already polarized at the laser output so the rotation of polarization plane will produce an attenuation of the beam's power. In order to explain the modulation, the Pockels cell is assimilated to a wave plate as can be seen in Fig. 1.

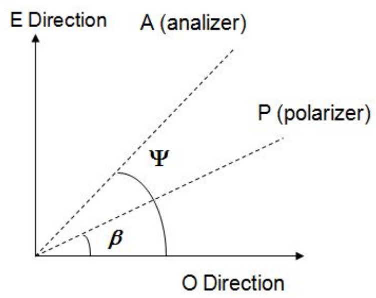

Fig. 1 – Intensity transmission using a polarizer-wave plate – polarizer assembly.

Let us consider a wave passing through a linear polarizer (P) with the preferential direction at angle β. When passing the laser beam through a second linear polarizer (A) acting as the analyzer, with the preferential axis at the angle Ψ, the P-W-P (Polarizer-Wave plate-Polarizer) combination stands as an adjustable attenuator [3].

For the incident waveform $D = A\cos(\omega t - kr)$, linearly polarized at the angle β which respect to the ordinary polarization direction, the ordinary wave (D_0)and the extraordinary one (D_e) components have the expressions:

$$D_o = A\cos\beta\cos(\omega t - k_0 r) = A\cos\beta\cos(\omega t - \phi_0), \quad (1)$$

$$D_e = A\sin\beta\cos(\omega t - k_e r) = A\sin\beta\cos(\omega t - \phi_e). \quad (2)$$

The transmitted wave (D_t) through the polarizer is given by:

$$D_t = A\cos\beta\cos(\omega t - \phi_0)\cos\Psi + A\sin\beta\cos(\omega t - \phi_e)\sin\phi, \quad (3)$$

$$D_t = D_0\cos(\omega t - \phi_e + \chi). \quad (4)$$

where:

$$D_0 = A\sqrt{(\cos\beta\cos\Psi\cos\Delta\phi + \sin\beta\sin\Psi)^2 + (\cos\beta\cos\Psi\sin\Delta\phi)^2}; \quad (5)$$

$$\tan\chi = \frac{\cos\beta\cos\Psi\sin\Delta\phi}{\cos\beta\cos\Psi\cos\Delta\phi + \sin\beta\sin\Psi}; \quad (6)$$

$$\Delta\phi = \phi_e - \phi_o, \quad (7)$$

where: A is the amplitude intensity of the beam; k_0 is the coefficient constant of the oridinary beam; k_e is the coefficient constant of the extraordinary beam; r is the vector position; ϕ is the phase shift; ϕ_0 is the ordinary phase shift; ϕ_e is the extraordinary pahse shift.

For surgical use, the energy of the laser should be set between 0.5 mJ and 9 mJ, whereas the pulse width is fixed at 5 ns because of to the Q-switch working regime. This function is achieved by modifying the duty cycle of a 15 kHz square wave signal which is generated by CCP1module of the microcontroller. The duty cycle is modified with a 10 bits resolution in function of desired energy and of the correction offsets.

Fig. 2 shows the theoretical energy variation *versus* the duty cycle, without taking into account the specific properties of the attenuator. The correspondence of the output energy to the duty cycle fill factor has been chosen 0.1 mJ for 1 %, in the range 0.5–9 mJ. The peripheral hardware block which uses this signal integrates the square wave in function of its duty cycle and gives a high voltage output in the range 0 to 6 kV. This high voltage is applied to a Pockels cell which, together with the two polarizers, determines the desired energy attenuation. The energy can be incremented from the menu with selectable step of 0.1 mJ or 1 mJ.

Both the step and the energy values are recorded in the EEPROM. When the microscope is on, it will recall the last energy used and the last selected energy step from the EEPROM [5].

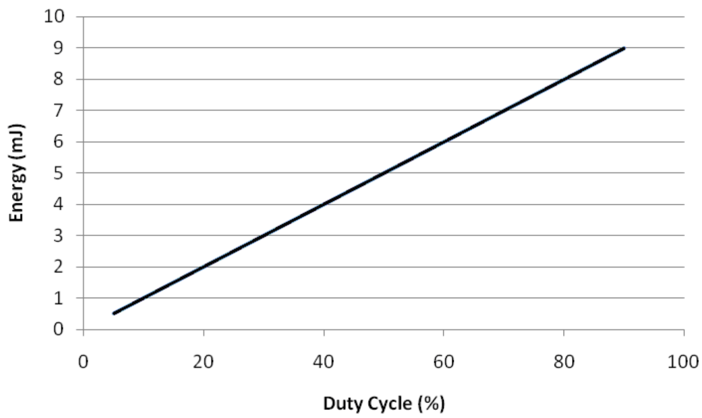

Fig. 2 – Theoretical energy variation *versus* the duty cycle.

2.3. ENERGY CORRECTION

A square wave of 5 V amplitude, with variable duty cycle, controls the high voltage which drives the Pockels cell. The laser energy provided at the output of the attenuator in function of the voltage differs for each attenuator. Fig. 3 shows the energy of the output of the system-laser, Pockels cell and polarizers, *versus* the voltage applied on the Pockels cell. The laser used for testing was a Solar TII LF117 Q-Switch with Nd:YAG as active medium and 1064 nm wavelength. The Pockels cell was a CIQS 8IM99 made by Linos. The energy was measured with a Coherent Field Max II energy meter. It can be observed that the energy dependence of high voltage is almost linear. However, for eye surgery, linearity and accuracy are very important. Because the high voltage is controlled by a square wave with variable duty cycle, we use a software correction based on adding or subtracting offsets from the duty cycle value, at each value of the energy in the range of 0.5 mJ to 9 mJ.

Only 85 steps from the available $2^{10} = 1024$ are used to modify the energy from the keyboard. To obtain a linear system, the intermediate steps are used for corrections determined experimentally for each laser and attenuator, and stored in the EEPROM. Each correction pair consists of two bytes, one for the sign of the offset and one for the value [5].

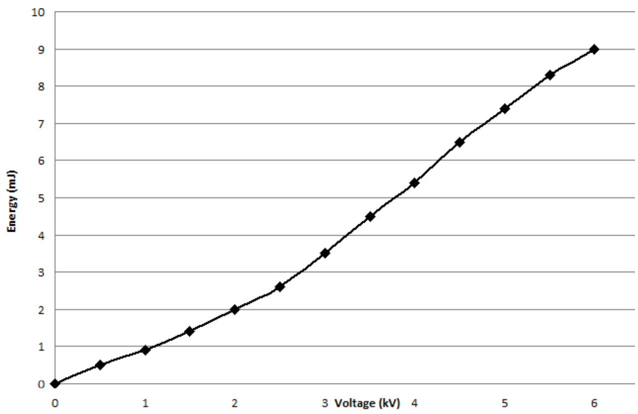

Fig. 3 – Continuous adjusting of output power *versus* the voltage.

2.4. SETTING THE POWER FOR THE POINTER IN THREE STEPS: LOW, MEDIUM AND HIGH POWER

The pointer used is a 655 nm, 1 mW laser diode module used to establish the target for the 1064 nm Nd:YAG laser beam into patient's eye. Pointer's output power should be variable in order to better see in patient's eye. For this neither variable voltage nor current control were chosen due to the reason of simplifying the electronic circuit. The solution chosen is to drive the visible laser diode module in PWM pulses of 2 kHz frequency with variable duty cycle in tree steps: 40 % filling of the duty cycle, 42 % filling of the duty cycle and 44 % filling of the duty cycle [3].

2.5. TRIGGERING THE LASER AFTER THE CONDITIONS ARE FULFILLED: THE CAPACITORS ARE FILLED, THE DESIRED ENERGY LEVEL IS ESTABLISHED

The laser shooting is triggered from a pedal, with a delay of one second, necessary to debounce the circuit and to prevent accidental multiple triggering. Before entering in the triggering mode, the software tests the energy level of the laser with an IR-sensitive photodiode assembly, for three laser shootings with closed shutter, for extra safety. Before each shooting, the software checks if the capacitors for supplying the flash lamp of the laser are charged enough. If one of the above requirements gives a mismatch with the data in the microcontroller's memory, an adequate error message is displayed.

2.6. INTERFACING THE USER WITH AN LCD DISPLAY AND A KEYBOARD

Interfacing the LCD. The chosen LCD is a 12×2 alphanumeric one with enlighten background. As communication interface were used only four data wires (D1, D2, D3 and D4). All communication was assigned to the port B of the microcontroller as follows in Table 1 [2].

Interfacing the keyboard. The keyboard is specially designed for this project and its structure together with the connections to the microcontroller are presented in Table 2. A reference 4.7 kΩ resistor is permanently pulled from each input key input to system ground. The keyboard is made from pushbuttons and their pressing goes to +5 V signal [2]. The software implemented de-bounce time is 20 ms.

Table 1

Connections of LCD to the microcontroller according to manufacturer's ports description
(According to manufacturer's ports description[2])

LCD port	**Microcontroller port**
Data1	B0
Data2	B1
Data3	B2
Data4	B3
RS (Reset)	B4
Enable	B6

Table 2

Connections of special keyboard to microcontroller ports
(Keyboard consists of a set of buttons necessary for the nagigation in the software menu)

Name	Up Arrow	Down Arrow	Left Arrow	Right Arrow	Enter	Info	Menu	Exit
Connection	D5	D3	D1	D7	D4	D0	D2	D6

The pinouts of the used microcontroller (PIC18F4550) can be found in [2].

2.7. ACOUSTIC WARNING IN CASE OF ERRORS

A buzzer function is implemented on A1 microcontroller port. It is activated after the initialization of the software, releasing a short beep of 900 Hz. If an error occurs (capacitors not enough charged, checked energy not equal to preset energy, calibration offsets not found in EEPROM), it releases a long intermittent beep of the same frequency.

2.8. SHUTTER CONTROL

The shutter control function is transmitted on B7 and it is conditioned by the measured energy check and of entering in the shooting state. In the case that preset energy cannot be established, the shutter will not open and an error message will be displayed together with a long buzzer beep. If the energy measured at routine check is in the normal range, the shutter will open before laser turning on.

2.9. COUNTING THE NUMBER OF LASER SHOOTS

The counting of the number of laser shoots is achieved via the counting the pulses received at port A0, storing them in byte location number 3 of the microcontroller's EEPROM, and displaying the number in real time, while the physician is performing the surgery. The pulses are coming from a transducer connected to an inductive coil type sensor mounted on the laser's lamp supply wire. Pulse count can be accessed any time by pressing the button "Info". When a new laser shooting session is initialized, this position of the EEPROM is erased and written with the new value.

2.10. CAPACITORS MONITORING CIRCUIT

The capacitors monitoring circuit gives a signal between 4.5 V and 5 V when the capacitors are charged enough to supply the flash lamp. This signal is read on port C3. If the signal received is not in the desired range, an error message is displayed in the LCD and the laser triggering is stopped.

2.11. LASER ENERGY CHECK

A signal between zero and 5 V is read from the transducer of an IR photodiode. The checking routine is performed three times at the initialization of the microscope and each time after a new energy value is set from the keyboard.

2.12. OTHER FUNCTIONS

In addition, the following hardware blocks, not related to microscope functions, must be implemented:

– an HS oscillator (a 16 MHz quartz crystal [2]) chosen in order to have the maximum gain and frequency response, even if the power consumption is higher,

– a power supply based on a 5 Vcc voltage regulator of 1 A.

The block scheme of all software functions and additional hardware blocks that we obtained is shown in Fig. 4.

The firmware was designed based on logic diagrams in Flowcode® 4. The components (logic blocks from the diagrams) are C code blocks which code and variables had been customized which respect to the needs. Flowcode® 4 permits also the simulation of the firmware before burning into the microcontroller. A virtual panel was made which simulates the keyboard, LCD, pedal, analog inputs, digital I/O (and also the CCP modules), EEPROM. The simulation's results sharply respect all the points discussed in Experimental [5].

For the tests during the firmware design, a testing PCB it was prepared. It can easily emulate the microscope's components for the preliminary testing.

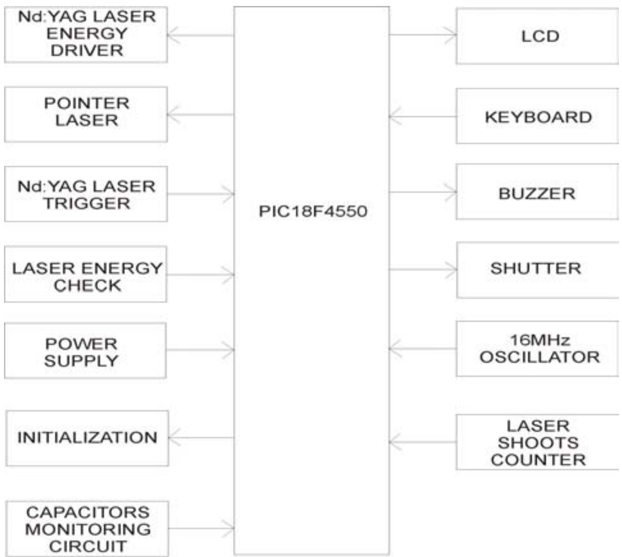

Fig. 4 – Block scheme of functions and hardware of the system.

At testing time, in order to increase the flexibility in calibrating the unit, a temporary recording of the offsets on a system consisting of a SD card reader made from a bidirectional MAX3002 driver and a voltage source was used. Therefore, the unit was designed to read external calibration data from an SD card, in addition to the normal EEPROM reading.

3. **CONCLUSIONS**

The compiled hexadecimal file has 17 KB out of 32 KB available from the program memory of microcontroller. It was burned in the PIC18f4550 using a Matrix Multimedia® PicMicro USB MultiProgrammer with PPP version 3 software.

Very good shielding of signal and supply wires was provided in order to avoid any parasitic interference from the laser's and Pockel's cell supply sources. The entire system is shielded with a metallic case such that it complies with the communitary reglementation stipulated in the second edition of EMC Directive 2004/108/EC which refers to the electromagnetic pollution problem approaches with implications mainly in biological effects [7].

The firmware developed was simulated and tested with all the necessary hardware.

The software modelling was done by using visual programming, which made the effort similar to the one necessary for code-write programming. Significant time was saved due to this approach, which – on our best knowledge, was applied here for the first time in designing a medical device.

We also used an optical attenuator based on a Pockels cell, for the first time in a laser surgical microscope. This allows a simple and efficient software control and a good calibration procedure and makes the object of a pending patent (A/00839/21.10.2009).

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