International Journal of Electrical and Computer Engineering (IJECE)
Vol. 13, No. 2, April 2023, pp. 1437~1448
ISSN: 2088-8708, DOI: 10.11591/ijece.v13i2.pp1437-1448

A microsystem design for controlling a DC motor by pulse width modulation using MicroBlaze soft-core

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Article Info

Article history:

Received Apr 16, 2022
Revised Sep 16, 2022
Accepted Oct 27, 2022

Keywords:

Digital pulse-width modulation
Direct current motor
Embedded C
Embedded system
MicroBlaze
Microsystem
VHDL

ABSTRACT

This paper proposes a microsystem based on the field programmable gate arrays (FPGA) electronic board. The preliminary objective is to manipulate a programming language to achieve a control part capable of controlling the speed of electric actuators, such as direct current (DC) motors. The method proposed in this work is to control the speed of the DC motor by a purely embedded architecture within the FPGA in order to reduce the space occupied by the circuit to a minimum and to ensure the reliability of the system. The implementation of this system allows the embedded MicroBlaze processor to be installed side by side with its memory blocks provided by Xilinx very high-speed integrated circuit (VHSIC) hardware description language (VHDL), Embedded C. The control signal of digital pulse-width modulation pulses is generated by an embedded block managed by the same processor. This potential application is demonstrated by experimental simulation on the Vertix5 FPGA chip.

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1. INTRODUCTION

Currently, the industrial sector 4.0, contains a lot of very advanced technologies. This development is characterized by the sharp increase in sales of electrical and electronic microsystems, to have a very high production rate. Even also in our daily life a rapid adoption by the general public with these technologies of home automation, as well as an autopilot for the whole house and electrical equipment [1]. Microsystems that control the speed of motors direct current (DC) have a lot of market demand [2], [3], provided that these systems are efficient, robust, and have a very high real-time response time. The major challenge for the developers of this type of control microsystem is the term security [4], [5]. The integration of this functionality is very important to keep the user safe in his environment. In modern life, we use a lot of control tools and accessories to simplify our control [6], so we will always try to focus as much as possible on control flexibility and control over a well-defined area of accessories. Today, electronics are increasingly being replaced by programmed electronics. We also speak of on-board systems or on-board computing [7].

Its purpose is to simplify the electronic diagrams and consequently reduce the use of electronic components [8], thus reducing the cost of manufacturing a product. This results in microsystems being more complex and efficient for a reduced space. Since electronics has existed, its growth has been meteoric and continues to this day. Electronics have become accessible to anyone who wants to: what we will learn. This work is a mixture of electronics and programming. We are indeed going to talk about embedded electronics which is a sub-field of electronics that can unite the power of programming with the power of electronics. Several works related to the use of a system or a control board (interface board) such as the Arduino [9], the Raspberry [10]. The use of the Arduino board with microcontroller ATmega328, either by wire connection or by Bluetooth, has been proposed for its performance how digital circuits of embedded implementation in applications and industrial fields [11], [12]. To respond to this major development, we have proposed a microsystem that allows controlling any device, vehicle [13]–[15], the machine through a field programmable gate arrays (FPGA) board. This electronic card made makes the command and control easy and flexible during piloting. MicroBlaze processor [16]–[19] is used to create many applications, precisely adopting hardware concepts, such as clock management, state machines, pipelining, and device-specific memory [19]. Many digital and transistor logic circuits (such as processors and microcontrollers) can develop microsystems on a chip system on chip (SOC), but what is interesting is to design the system on a programmable chip (SOPC) using the latest device programmable to use the functionalities of the FPGA [20]–[22].

2. RELATED WORK

Rotating machines have become one of the most requested resources in the industrial units as well as in domestic applications [23], and for this reason, all depth studies are done to improve the quality of response, safety, efficiency, and maximum control. The DC motor is one of these machines, its speed control by various methods allows it to reach a high level of satisfaction for the achievement of mechanical or electrical stains. Improved control is done by MATLAB/Simulink (system generator) [24] to determine the initial conditions and interest in the closed-loop operation of the brushless DC (BLDC) motor [25] so that the motor runs very close to the reference speed. Thus, the numerical control by microcontrollers such as the Arduino, which processes numerically the data, using the proportional-integral-derivative (PID) regulation blocks [26], [27] and other various platforms, such as conventional pulse-width modulation (PWM) to look for a linear relationship using the right frequency of the characterized DC motor [28], a novel data-driven sigmoid-based PI for angular velocity trajectory tracking of buck-converter powered dc motor [29], [30], is sent to control the motor. This command has an effect on the stator voltage in the case of induction motors [31]. The FPGA comes, in turn, to develop another digital method, by the very high-speed integrated circuit (VHSIC) hardware description language (VHDL) hardware language and the MATLAB system generator. This tool makes it possible to control the speed and the torque [32], [33] of the DC motor by PWM [34], [35] pulses through power circuits [36] in order to achieve the stability mechanical case of motor or stability electrical in case of alternator [37].

The optocoupler device is used to isolate the high current, which comes from the source to the metal–oxide–semiconductor field-effect transistor (MOSFET), and the low current of the unit control. It is mainly used to control the current in the DC motor. Electric motors are electromechanical energy conversion devices. Three electrical machines (DC, induction, and synchronous) are widely used for the conversion of electromechanical energy in Figure 1. The conversion of electromechanical energy for DC motors occurs, when there is a change in the magnetic flux connecting a coil, associated with a mechanical movement as shown in Figure 1.

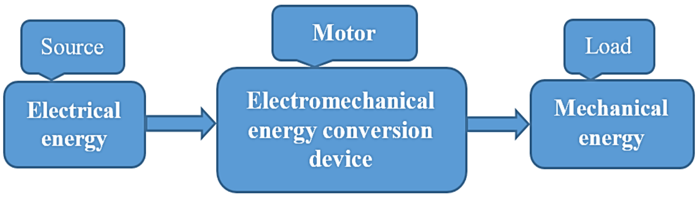


Figure 1. Energy conversion diagram of a DC motor

In addition, it is known by the electromagnetism laws that the electromotive force is proportional to the speed:

$$emf\ E = K.\omega_v \tag{1}$$

where *K* is constant *Emf*, the torque is proportional to the intensity.

$$torque\ T = K.I \tag{2}$$

So, the intensity *I* is constant:

$$\omega = \frac{E}{K} = \frac{U - rI}{K} \quad (3)$$

The rotation speed ω depends on the voltage *U* (controlled in voltage) and the intensity *I* (torque control).

3. METHOD

3.1. Description of the proposed microsystem

In this work, we will design a purely embedded control circuit for DC motor speed by the digital PWM [38] in the virtex5 FPGA by Xilinx platform studio (XPS) shown in Figure 2, while passing through the MicroBlaze processor and the power circuit. We will also do an in-depth study on studies the embedded digital PWM to control the speed of the motor and the choice of the frequency. Figure 3 shows the hardware kit of the proposed microsystem. This microsystem controls the speed of the DC motor in three parts. The first part represents the control part including the MicroBlaze processor; the second plays the role of an intermediary who converts power (high bridge). The last is the actuator as a motor.

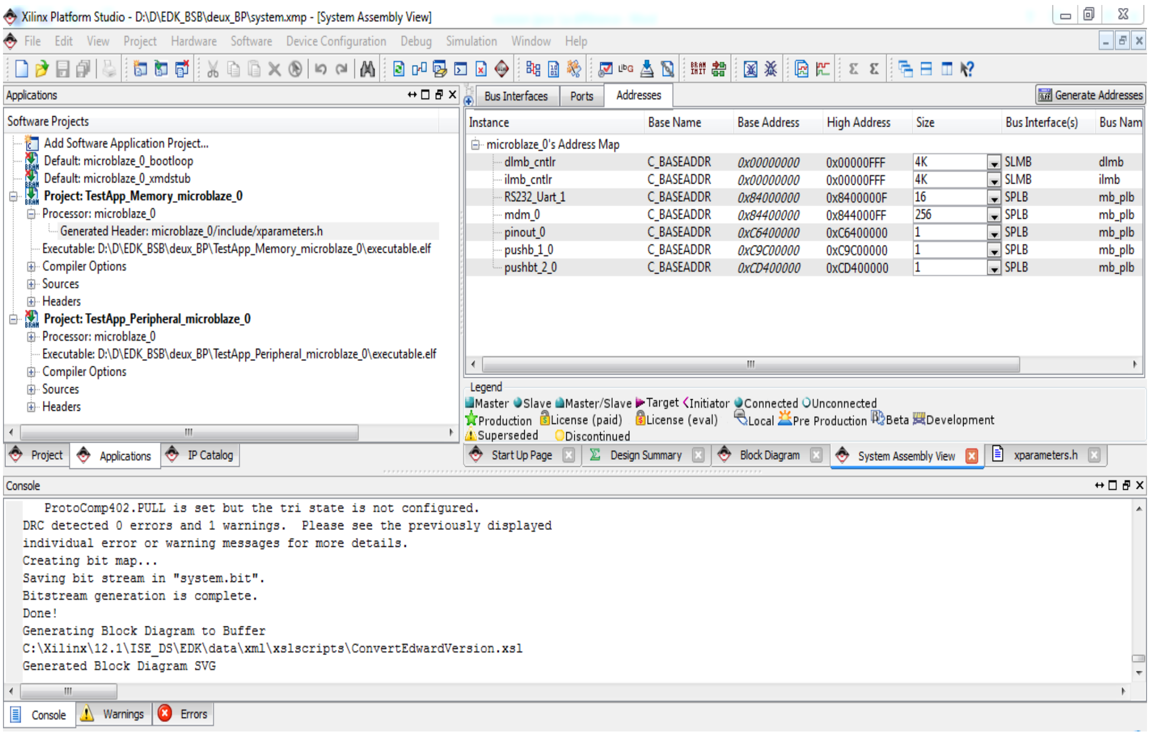


Figure 2. XPS windows

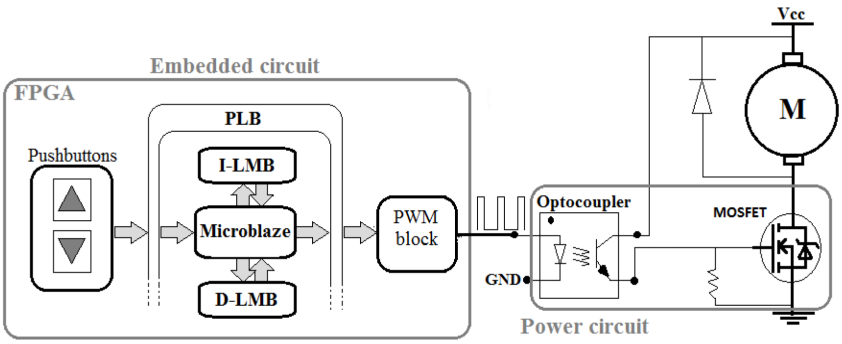


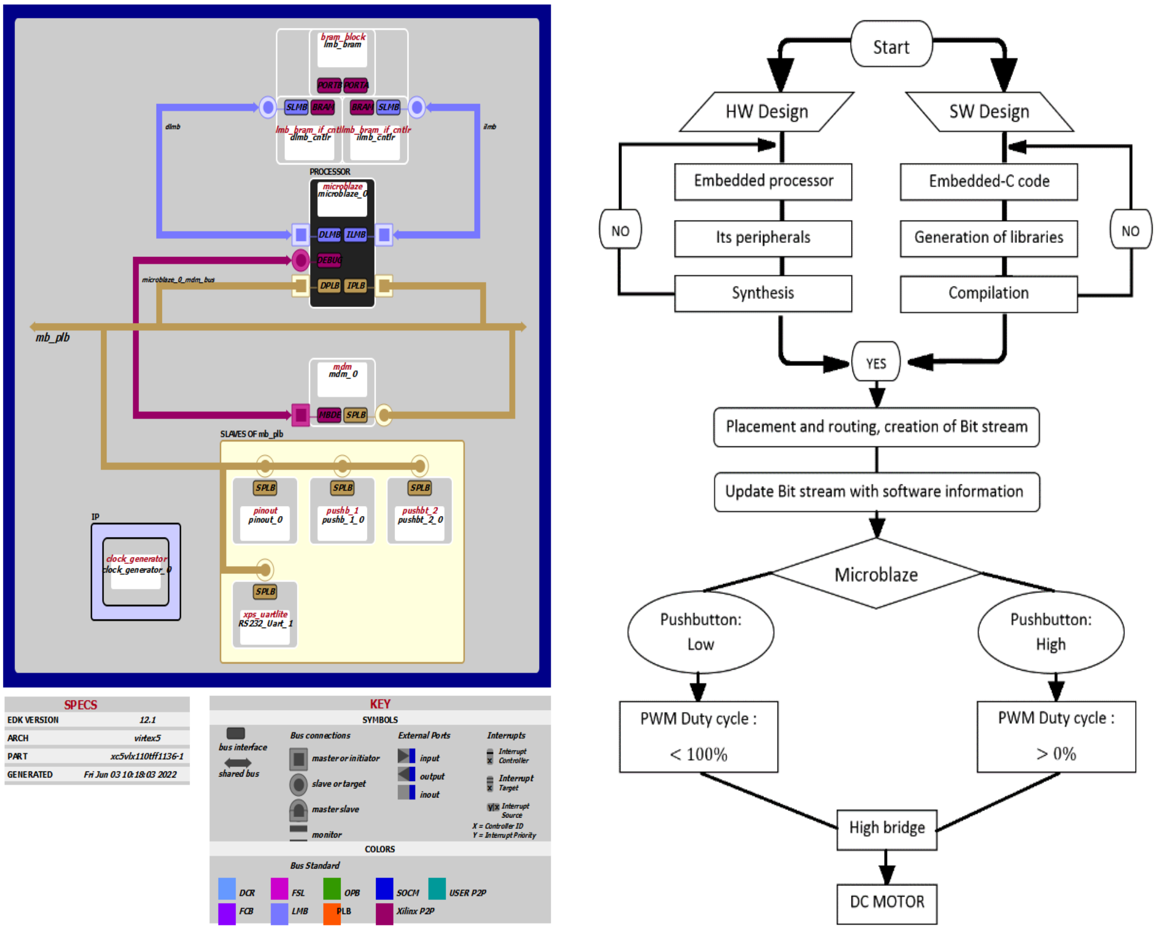
Figure 3. Functional architecture of the proposed microsystem

3.2. Description of the proposed microsystem

The FPGA devices integrate all the cells needed to form a standalone embedded hardware platform: logic, microprocessors (MicroBlaze), memory, speed I/O, and intellectual property (IP). After the generation of the bitstream, the XPS platform of Xilinx automatically generates a block diagram of all parameter systems and a different size of memory attached to the system, as shown in Figure 4(a).

An embedded system is a programmable electronic circuit dedicated to a specific task. It is a hardware and software package [36], which often applies the techniques of real-time. Depending on the application, the embedded system must meet certain constraints dictated by the specifications: low-cost price, small size, low energy consumption, satisfactory computing power, operating reliability, data security, and open (interfaces).

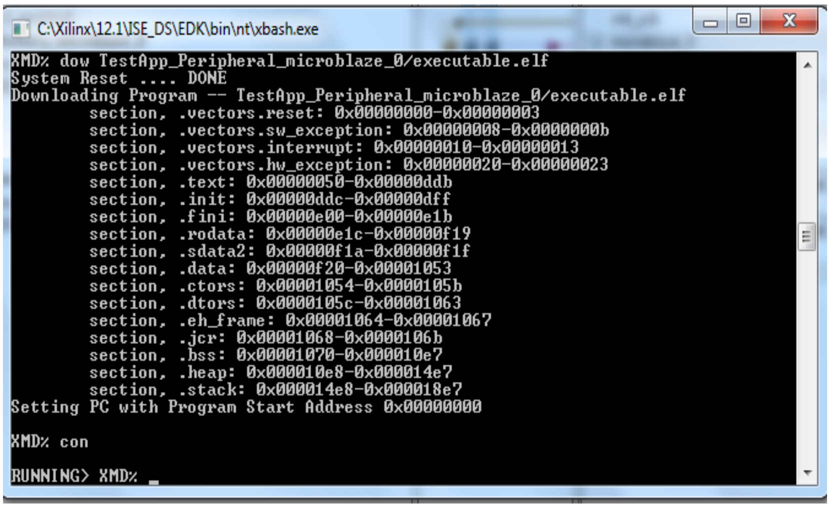
Now that the hardware platform is ready, it is time to make it live with a little soft as shown in Figure 4(b). We must export the application to a software development platform type "Eclipse Platform" which is a free tool. This tool makes it possible to identify the IP cores by their addresses, manipulate the byte, to exchange data with the outside world of the card (serial link and parallel port); to control each hardware device. The function read/write in registers (R/W) is done by a program C which runs indefinitely.



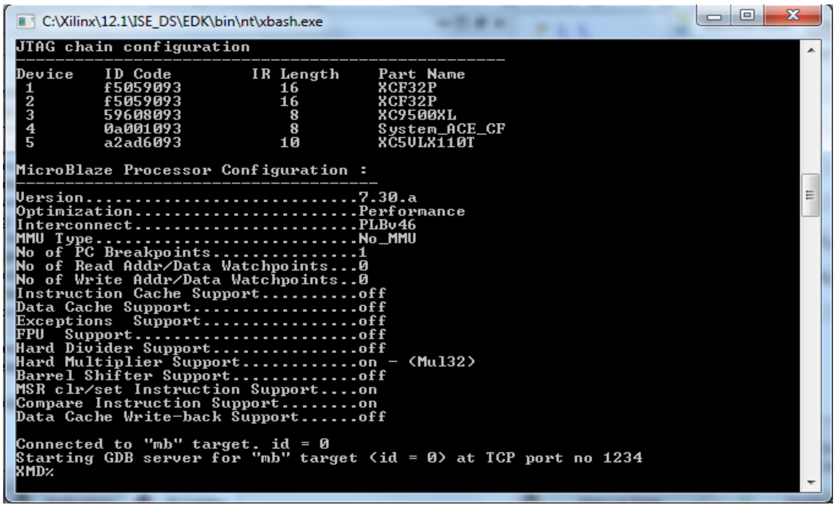
(a) (b)

Figure 4. The hardware and software part of the proposed system (a) generate flow diagram by Xilinx and (b) flow diagram of the proposed system

This will correspond to an infinite loop in competition possibly with an interruptions system called a super loop. After the implementation of custom peripherals and MicroBlaze processor on the FPGA through the software development kit (SDK), we charged a compiler C language in the memory of the FPGA to execute it by the micro blaze processor, as shown in Figure 5(a). Using the Xilinx® microprocessor debugger (XMD) to debug programs and verify systems using the MicroBlaze processor configuration as shown in Figures 5(b) [38].



(a)



(b)

Figure 5. Xilinx® microprocessor debugger (XMD) (a) downloads given ELF (with data option) on to memory of current target and continues from current PC and (b) TCP/IP connected with local host and targeted device

3.3. Controlling speed (PWM signal)

The control by the PWM is done with different tools (Arduino and FPGA). This project is based on FPGA as it offers a wide range of space to create treatment blocks and a purely embedded connection with low power consumption. PWM is used to vary the speed of motors without going through the variation of voltage at their terminals: one always feeds the motor under its maximum voltage (voltage full), and by varying the duty cycle. The speed varies according to the average voltage which is defined by (4).

$$Average\ Voltage = \frac{1}{P}\int_0^P u(t)dt = Voltage_{full} \times \frac{P_w}{P} = Voltage_{full} \times Duty\ Cycle \qquad (4)$$

3.4. The choice of the PWM frequency

The microcontroller PWM outputs use timers (or counters) with their options. For our case, the timers are embedded with the MicroBlaze in the FPGA chip by a C code and with the same options: the choice of the resolution, overflow value (or comparator) and prescale, as shown in Figure 6. The MicroBlaze has been configured on the XUPV5110T FPGA card, which uses a clock frequency of 100 MHz with 120 MHz amplification for software analysis.

– The frequency with prescale: The prescale can also be the number of instructions loops in the C code. It can have the following values:

1, 2, 4, 8, 16, 32, 64, 128, 256...1024, 2048….4194304, 8388608
So, with a prescale of 8: Clock Frequency/prescale=100 Mhz /8=12.5 Mhz

- Timer: The timer resolution depends on the frequency performance of the card. Choice of resolution on 23 bits (8,388,608)
- Overflow value: Determined according to the desired duty cycle (To/T).

*From the value=6291456 the duty cycle=(6291456/*8388608*)=0.75=>75%*

- PWM frequency: The frequency is given by (5).

$$F_{PWM} = \frac{F_{clock}}{2\times\text{prescale}\times\text{resolution}} \tag{5}$$

$FPWM = 100{,}000{,}000/(2 \times 8 \times 8{,}388{,}608) = 0.745$ Hz; $T = 1.34$ s.

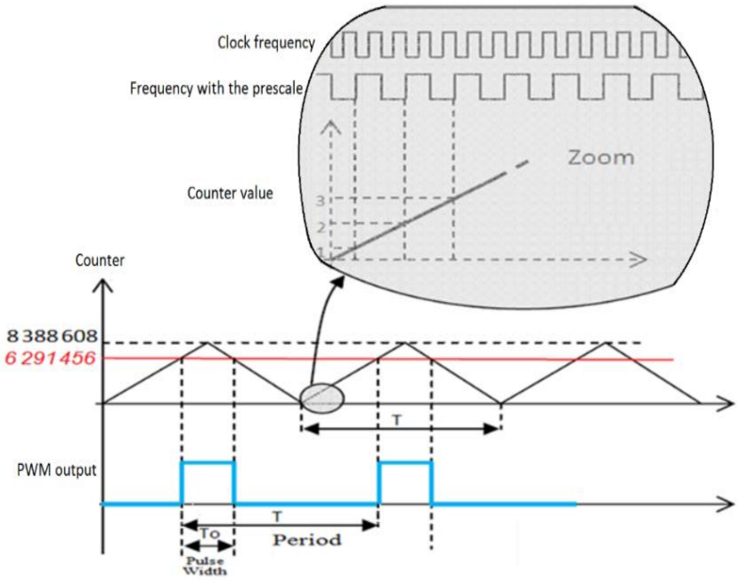


Figure 6. The curves of the PWM and counter

4. EXPERIMENTAL RESULTS AND DISCUSSION
4.1. Experimental results

The experimental simulation of Figure 7 is based on a DC motor 6 V controlled by a digital PWM signal. The control unit is the FPGA board Virtex5 XUPV5110T wherein it rests embedded processor MicroBlaze. The assembly consists of the control part, the energy conversion part, and the actuator part. The voltage U(t) of the generator relative to the PWM duty cycle of 75%.

Figure 8 shows the variation of the maximum voltage generated by the rotation of the rotor concerning the different duty cycles of the PWM. This variation is almost proportional, and it follows (6):

$$\Omega \approx U/(\Phi.k) \tag{6}$$

where Φ is the flux/pole in weber and *k* is the constant depending on coil geometry.

The experimental result was displayed in the oscilloscope. This method complies with the equations cited before which are described by the PWM as it indicates. In the case of two lines which gives a cyclic ratio of 75 %; the oscilloscope shows it well in Figure 8. Typical voltage ripple generated by a steady-state PWM frequency (75% duty cycle). The graph on the left shows a low voltage ripple, its effective value is close to the average value, which reserves a large part of the energy for the DC motor. This low ripple reflects the maximum stability of the DC motor at the level of its operation as well as a significant generation of the mechanical torque by the rotor part.

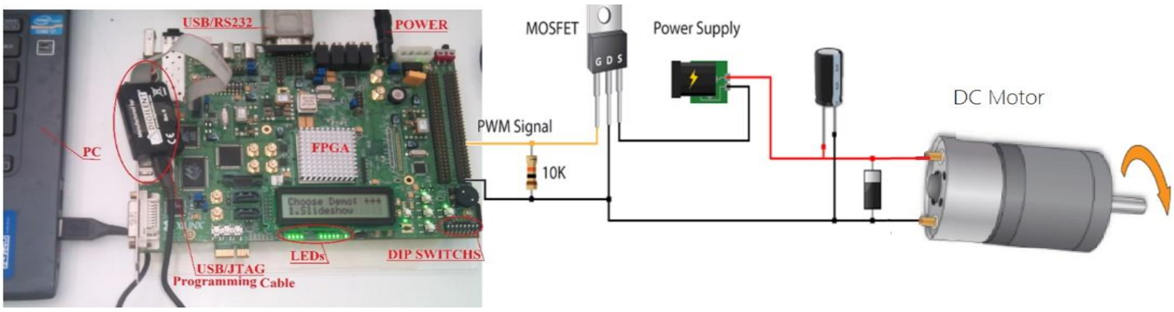
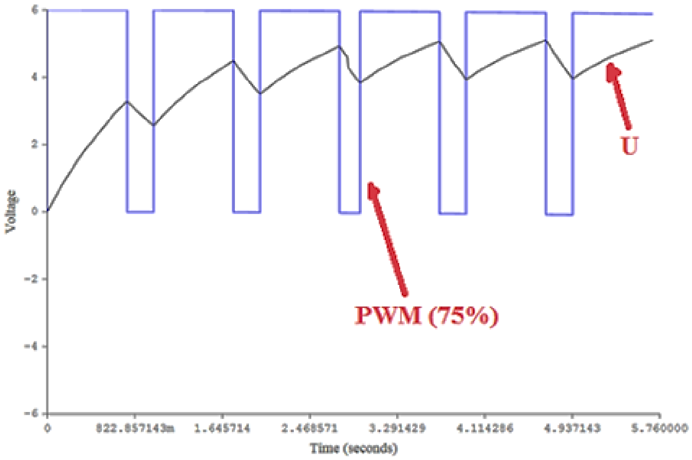


Figure 7. The low power MicroBlaze PWM signal switches on and off the gate at the MOSFET through which the high-power motor is driven



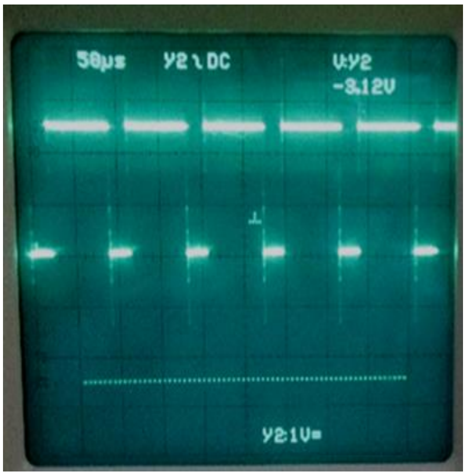
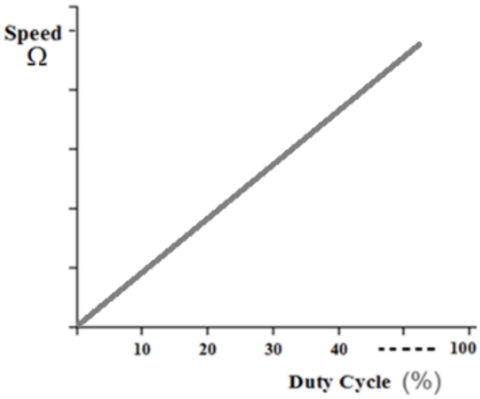
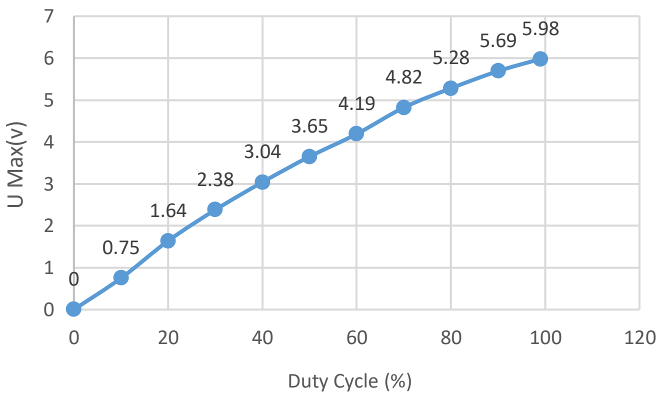


Figure 8. Variation of PWM (α=75%) with applied voltage

As a result, we can deduce tow things. The first one is the proportional variation of the rotation speed and the duty cycle, as shown in Figure 9(a). The second one is the proportional variation of the voltage and the duty cycle, as shown in Figure 9(b). The proposed microsystem developed using the components previously described in section 2 has been shown to behave according to the design criteria. The PWM signal provided by the FPGA was found to be of good quality, thus causing the motor speed output to be linear with the duty cycle of the PWM signal.





(a) (b)

Figure 9. Duty cycle variation (a) speed and (b) voltage

4.2. Discussion of the results

Embedded digital PWM control is interesting in the fields of treatments. The motor can be controlled by the on-board digital output of a MicroBlaze and the considerable improvement in energy efficiency. The embedded circuit based on the MicroBlaze allows us to gain enough space in the chip and therefore enough blocks of embedded processes to implement. This technique offers a reduction of energy consumed per control unit [39] in Table 1. The power part attacked by the embedded digital PWM creates a low thermal dissipation effect by the PWM. Indeed, all the energy is devoted to the motor rotation, which is interesting for embedded systems running on batteries.

Table 1. Space occupied by the circuit elements

Device Utilization Summary (actual values)			
Slice Logic Utilization	Used	Available	Utilization
Number of Slice Registers	1799	69120	2%
Number of Slice LUTs	1776	69120	2%
Number used as Memory	130	17920	1%
Number of occupied Slices	968	17,280	5%
Number of bonded IOBs	7	640	1%
Number of Block RAM/FIFO	1	148	1%
Number of BUFG/BUFGCTRLs	2	32	6%
Number of BSCANs	1	4	25%
Number of DSP48Es	3	64	4%
Number of PLL_ADVs	1	6	16%
Total Memory used (KB)	**36**	**5328**	**1%**

Table 2 shows the power balance of the PWM circuit of each board. The FPGA has enough resources because Xilinx has offered two methods of creating an embedded system based on an FPGA board. First, use a MicroBlaze processor programmed in C or VHDL programmed in-circuit blocks. However, in the case of complex systems, including PWM, the FPGA must be used because it can support high-level algorithms through its memory capacity. The power dissipated by the output pin of the FPGA is of the order of 5,664 mW. The diversity of FPGAs and low power consumption help make PWM circuit implementation more reliable, flexible, and good quality for controlling external circuits in real-time. The increase and decrease of the speed of the motor are done by the push buttons of the FPGA card as much as a material part (XPS). The software part (SDK) is done by functions in command lines of an embedded C program, such as functions:

- «`PUSHB_1_mReadSlaveReg0(XPAR_PUSHB_1_0_BASEADDR, 0)` »,
- «`PUSHBT_2_mReadSlaveReg0(XPAR_PUSHBT_2_0_BASEADDR, 0)` »
- «`PINOUT_mWriteSlaveReg0(XPAR_PINOUT_0_BASEADDR, 0,1)` »

Table 2. The power dissipated by the pin outputs

Signal Name	IO Bank Number	Drive (mA)	Voltage (mv)	Power (mW)
PIN_OUT ARDUINO [40]	1	50	3300	165
External_clock_GPIO_IO_pin	11	12	472	5,664

These functions are respectively to increase, decrease and output digital PWM signal. The `mReadSlaveReg0` function provides slave reading for a data register. The `mWriteSlaveReg0` function provides slave writing to a data register.

4.3. Comparison between Arduino (ATmega328 controller) and FPGA (MicroBlaze controller)

This technique is proposed for its ability to exploit the on-board circuits in the control of DC motors as well as space-saving occupancy (at the chip level), also the gain in power consumption for the embedded control unit compared to the Arduino-based control. Finally, the execution time tends towards real-time. This system can be integrated into the most sensitive high power DC motor control units for the industrial field, as well as for the study and development side concerning the implementation of embedded processing and regulation blocks. The Table 3 shows a comparison of different parameters between two DC motor speed controllers, the first one using an ATmega328 microcontroller and the second one using a MicroBlaze controller from our system licensed by Xilinx (ATmega328 controller/MicroBlaze controller) [41].

Table 3. Different parameters between two types of commands DC motor's speed

Parameter	ATmega328 controller [42]	MicroBlaze controller
Operating Voltage	5 V	5 V
Input Voltage (Recommended)	7 to 12V	5 to 9 V
DC Current Per I/O PIN	20 mA	12 mA
DC Current Per 3.3V PIN	50 mA	12 mA
Flash Memory (ATmega328P)	32 KB (100%)	36 KB (1%)
SRAM (ATmega328)	2 KB	4 KB
EEPROM (ATmega328)	1 KB	0 B
Clock Speed	16 MHZ	120 MHz (converges in real time)
Cost	cheaper	expensive
Chip space	very limited	very large
Number of DC motors controlled directly by PWM pins	Max 15	Greater than 15 depending on card type
Consumption power by the control unit (mW)	165	5,664

5. CONCLUSION

The implementation of circuits on reconfigurable FPGA components is a topical subject, but one of great complexity in the field of research, because it requires not only a mastery of technologies relating to FPGAs but also a very good knowledge of applications. MicroBlaze processors have proven their efficiency with their power to create an embedded system, giving the best evaluation results. Very low consumption of memory resources. using MicroBlaze imports great flexibility which allows a reduction of the time by ensuring a parallel operation. While giving a dynamic of reconfiguration, which is advantageous compared to the other circuits. The proposed microsystem certainly presents many interesting prospects. In the industrial field, time is a very valuable parameter for machine control, which favors the use of reconfigurable FPGA circuits for the design of high-performance real-time devices (real-time controllers for different actuators). Using control circuits is a very vast field due to the variety of these circuits and their algorithms, which makes their implementation on reconfigurable circuits a very promising research axis. We can consider the hardware implementation of the algorithms and learn how to exploit the design of neural networks to have robust real-time controllers.

The digital PWM embedded circuit based on the FPGA provides a wide range of space to create purely embedded processing and recording blocks, as well as parallel data processing for large-scale applications with low power consumption. This type of control has advantages as we found in control unit, the integration in a digital system without using the analog (voltage control) and a low output resistance for drives. In actuator device, we found a compact speed drive, no or very little heat dissipation in the phase variation, motor torque higher at low rpm and a flexible control for multiple motors by a single control unit.

The prospects of this work are many and varied. The first concerns the control of power circuits for the servo, to make them more dynamic by adding embedded IP blocks to the Xilinx XPS environment. These IPs describe the operation of the digital PID control circuit (proportional integral derivative); to solve the performance (damping and response time) of a modeled process.

REFERENCES

[1] Y. Li and Y. Zheng, "Regional agricultural industry economic development based on embedded system and Internet of things," *Microprocessors and Microsystems*, vol. 82, Apr. 2021, doi: 10.1016/j.micpro.2021.103852.

[2] A. Narendran and R. Sureshkumar, "Hysteresis-controlled-landsman converter based multilevel inverter fed induction-motor system using PIC," *Microprocessors and Microsystems*, vol. 76, Jul. 2020, doi: 10.1016/j.micpro.2020.103099.

[3] S. Suresh and B. Karthik, "Discrete switching strategy for direct torque control of induction motor using adaptive pulse width modulator," *Microprocessors and Microsystems*, Oct. 2020, doi: 10.1016/j.micpro.2020.103313.

[4] J. Zhou, "Real-time task scheduling and network device security for complex embedded systems based on deep learning networks," *Microprocessors and Microsystems*, vol. 79, Nov. 2020, doi: 10.1016/j.micpro.2020.103282.

[5] D. Levshun, I. Kotenko, and A. Chechulin, "The application of the methodology for secure cyber-physical systems design to improve the semi-natural model of the railway infrastructure," *Microprocessors and Microsystems*, vol. 87, Nov. 2021, doi: 10.1016/j.micpro.2020.103482.

[6] W. Leilei and C. Huina, "Physical education image analysis based on virtual crowd simulation and FPGA," *Microprocessors and Microsystems*, vol. 79, Nov. 2020, doi: 10.1016/j.micpro.2020.103319.

[7] E. Torti *et al.*, "Embedding recurrent neural networks in wearable systems for real-time fall detection," *Microprocessors and Microsystems*, vol. 71, Nov. 2019, doi: 10.1016/j.micpro.2019.102895.

[8] M. Madani and C. Tanougast, "FPGA implementation of an optimized A5/3 encryption algorithm," *Microprocessors and Microsystems*, vol. 78, Oct. 2020, doi: 10.1016/j.micpro.2020.103212.

[9] C. E. Castañeda *et al.*, "Electronic locking devices based on microcontrollers and chaotic maps using model-matching control," *Microprocessors and Microsystems*, vol. 86, Oct. 2021, doi: 10.1016/j.micpro.2021.104338.

[10] A. Barodi, A. Bajit, T. El Harrouti, A. Tamtaoui, and M. Benbrahim, "An enhanced artificial intelligence-based approach applied to vehicular traffic signs detection and road safety enhancement," *Advances in Science, Technology and Engineering Systems Journal*, vol. 6, no. 1, pp. 672–683, Feb. 2021, doi: 10.25046/aj060173.

[11] S. Chaouch *et al.*, "DC-motor control using Arduino-Uno board for wire-feed system," in *2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM)*, Oct. 2018, pp. 1–6, doi: 10.1109/CISTEM.2018.8613492.

[12] V. K. Singh, A. Sahu, A. Beg, B. Khan, and S. Kumar, “Speed and direction control of DC motor through Bluetooth HC-05 using Arduino,” in *2018 International Conference on Advanced Computation and Telecommunication (ICACAT)*, Dec. 2018, pp. 1–3, doi: 10.1109/ICACAT.2018.8933698.
[13] A. Barodi, A. Bajit, M. Benbrahim, and A. Tamtaoui, “Improving the transfer learning performances in the classification of the automotive traffic roads signs,” *E3S Web of Conferences*, vol. 234, Feb. 2021, doi: 10.1051/e3sconf/202123400064.
[14] A. Barodi, A. Bajit, S. El Aidi, M. Benbrahim, and A. Tamtaoui, “Applying real-time object shapes detection to automotive traffic roads signs,” in *2020 International Symposium on Advanced Electrical and Communication Technologies (ISAECT)*, Nov. 2020, pp. 1–6, doi: 10.1109/ISAECT50560.2020.9523673.
[15] A. Barodi, A. Bajit, M. Benbrahim, and A. Tamtaoui, “An enhanced approach in detecting object applied to automotive traffic roads signs,” in *2020 IEEE 6th International Conference on Optimization and Applications (ICOA)*, Apr. 2020, pp. 1–6, doi: 10.1109/ICOA49421.2020.9094457.
[16] M. A. Çavuşlu, S. Tuğaç, and M. Öner, “FPGA implementation of bearing tracking using passive array for underwater acoustics,” *Microprocessors and Microsystems*, vol. 87, Nov. 2021, doi: 10.1016/j.micpro.2021.104366.
[17] K. R. S. Chandran and P. V. Chandramani, “Hardware-software co-design framework for sum of absolute difference based block matching in motion estimation,” *Microprocessors and Microsystems*, vol. 74, Apr. 2020, doi: 10.1016/j.micpro.2020.103012.
[18] S. N. Shahrouzi and D. G. Perera, “Optimized hardware accelerators for data mining applications on embedded platforms: Case study principal component analysis,” *Microprocessors and Microsystems*, vol. 65, pp. 79–96, Mar. 2019, doi: 10.1016/j.micpro.2019.01.001.
[19] M. Lin, S. Chen, R. F. DeMara, and J. Wawrzynek, “ASTRO: Synthesizing application-specific reconfigurable hardware traces to exploit memory-level parallelism,” *Microprocessors and Microsystems*, vol. 39, no. 7, pp. 553–564, Oct. 2015, doi: 10.1016/j.micpro.2015.03.005.
[20] I. Damaj, M. Elshafei, M. El-Abd, and M. E. Aydin, “An analytical framework for high-speed hardware particle swarm optimization,” *Microprocessors and Microsystems*, vol. 72, Feb. 2020, doi: 10.1016/j.micpro.2019.102949.
[21] A. Barodi, A. Bajit, A. Zemmouri, M. Benbrahim, and A. Tamtaoui, “Improved deep learning performance for real-time traffic sign detection and recognition applicable to intelligent transportation systems,” *International Journal of Advanced Computer Science and Applications*, vol. 13, no. 5, pp. 712–723, 2022, doi: 10.14569/IJACSA.2022.0130582.
[22] F. Smith and J. Omolo, “Experimental verification of the effectiveness of a new circuit to mitigate single event upsets in a Xilinx Artix-7 field programmable gate array,” *Microprocessors and Microsystems*, vol. 79, 2020, doi: 10.1016/j.micpro.2020.103327.
[23] A. Sathyan, M. Krishnamurthy, N. Milivojevic, and A. Emadi, “A low-cost digital control scheme for brushless DC motor drives in domestic applications,” in *2009 IEEE International Electric Machines and Drives Conference*, May 2009, pp. 76–82, doi: 10.1109/IEMDC.2009.5075186.
[24] M. Yaich and M. Ghariani, “Control strategy for switched reluctance motor based on embedded system,” *Journal of Electrical Systems*, vol. 14, no. 1, pp. 156–173, 2018.
[25] K. Prathibanandhi, C. Yaashuwanth, and A. R. Basha, “Improved torque performance in BLDC-motor-drive through Jaya optimization implemented on Xilinx platform,” *Microprocessors and Microsystems*, vol. 81, Mar. 2021, doi: 10.1016/j.micpro.2020.103681.
[26] M. E. El-Shimy and S. A. Zaid, “Fuzzy PID controller for fast direct torque control of induction motor drives,” *Journal Electrical Systems*, vol. 12, no. 4, pp. 687–700, 2016.
[27] R. Neerparaj and R. Bijay, “Neural network based closed loop speed control of DC motor using Arduino Uno,” *International Journal of Engineering Trends and Technology*, vol. 4, no. 2, pp. 137–140, 2013.
[28] J. Lopez-Gomez *et al.*, “Influence of PWM torque control frequency in DC motors by means of an optimum design method,” *IEEE Access*, vol. 8, pp. 80691–80706, 2020, doi: 10.1109/ACCESS.2020.2990158.
[29] M. I. F. M. Hanif, M. H. Suid, and M. A. Ahmad, “A piecewise affine PI controller for buck converter generated DC motor,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 10, no. 3, pp. 1419–1426, Sep. 2019, doi: 10.11591/ijpeds.v10.i3.pp1419-1426.
[30] M. A. Ahmad and R. M. T. R. Ismail, “A data-driven sigmoid-based PI controller for buck-converter powered DC motor,” in *2017 IEEE Symposium on Computer Applications and Industrial Electronics (ISCAIE)*, Apr. 2017, pp. 81–86, doi: 10.1109/ISCAIE.2017.8074954.
[31] Y. V. N. Kumar, P. H. Bindu, A. D. Sneha, and A. Sravani, “A novel implementation of phase control technique for speed control of induction motor using Arduino,” *International Journal of Emerging Technology and Advanced Engineering*, vol. 3, no. 4, pp. 469–473, 2013.
[32] S. Kang and S.-K. Sul, “Direct torque control of brushless DC motor with nonideal trapezoidal back EMF,” *IEEE Transactions on Power Electronics*, vol. 10, no. 6, pp. 796–802, Nov. 1995, doi: 10.1109/63.471301.
[33] A. Sathyan, N. Milivojevic, Y. Lee, M. Krishnamurthy, and A. Emadi, “An FPGA-based novel digital PWM control scheme for BLDC motor drives,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 8, pp. 3040–3049, Aug. 2009, doi: 10.1109/TIE.2009.2022067.
[34] M. Venkatesan, B. Adhavan, K. Suresh, K. Balachander, and M. L. C. Prabakar, “Research on FPGA controlled three phase PV inverter using multi carrier PWM control schemes,” *Microprocessors and Microsystems*, vol. 76, Jul. 2020, doi: 10.1016/j.micpro.2020.103089.
[35] R. Sarker, A. Datta, and S. Debnath, “FPGA-based variable modulation-indexed-SPWM generator architecture for constant-output-voltage inverter applications,” *Microprocessors and Microsystems*, vol. 77, Sep. 2020, doi: 10.1016/j.micpro.2020.103123.
[36] N. Milivojevic, M. Krishnamurthy, Y. Gurkaynak, A. Sathyan, Y.-J. Lee, and A. Emadi, “Stability analysis of FPGA-based control of brushless DC motors and generators using digital PWM technique,” *IEEE Transactions on Industrial Electronics*, vol. 59, no. 1, pp. 343–351, Jan. 2012, doi: 10.1109/TIE.2011.2146220.
[37] A. Zemmouri, R. Elgouri, M. Alareqi, M. Benbrahim, and L. Hlou, “Design and implementation of pulse width modulation using hardware/software MicroBlaze soft-core,” *International Journal of Power Electronics and Drive Systems*, vol. 8, no. 1, pp. 167–175, 2017, doi: 10.11591/ijpeds.v8i1.pp167-175.
[38] A. Zemmouri, M. Alareqi, R. Elgouri, M. Benbrahim, and L. Hlou, “Integration and implimentation system-on-a-programmable-chip (SOPC) in FPGA,” *Journal of Theoretical and Applied Information Technology*, vol. 76, no. 1, 2015.
[39] A. Zemmouri, R. Elgouri, M. Alareqi, H. Dahou, M. Benbrahim, and L. Hlou, “A comparison analysis of PWM circuit with Arduino and FPGA,” *ARPN Journal of Engineering and Applied Sciences*, vol. 12, no. 16, pp. 4679–4683, 2017.
[40] P. Teikari *et al.*, “An inexpensive Arduino-based LED stimulator system for vision research,” *Journal of Neuroscience Methods*, vol. 211, no. 2, pp. 227–236, Nov. 2012, doi: 10.1016/j.jneumeth.2012.09.012.
[41] A. Zemmouri *et al.*, “Proposal of a reliable embedded circuit to control a stepper motor using MicroBlaze soft-core processor,”

International Journal of Reconfigurable and Embedded Systems (IJRES), vol. 11, no. 3, pp. 215-225, 2022, doi: 10.11591/ijres.v11.i3.pp215-225

[42] S. Angalaeswari, A. Kumar, D. Kumar, and S. Bhadoriya, "Speed control of permanent magnet (PM) DC motor using Arduino and LabVIEW," in *2016 IEEE International Conference on Computational Intelligence and Computing Research (ICCIC)*, Dec. 2016, pp. 1–6, doi: 10.1109/ICCIC.2016.7919599.

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