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doi:10.15199/48.2023.03.42

Low-cost embedded intelligent system design for smart mobile robot controller

***Abstract**. The motion and sensing controllers are the main parts of any intelligent mobile robot. This paper has studied and tested the minimum possible hardware-consuming cost of motion and sensing controllers for mobile robot applications. The VHDL (Very high-speed integrated circuit Hardware Description Language) is used to design a counter-based architecture of motion and sensing controllers to gain the lowest possible implementation cost. Then a deep study of the designed architectures proved that it produces an economical use of hardware resources when implemented in XC3S1000 FPGA (Field Programmable Gate Array) device using ISE 14.1. The designed controllers worked successfully after implementation in XC3S1000 with 34 Slices cost only.*

***Streszczenie.** Kontrolery ruchu i czujników są głównymi częściami każdego inteligentnego robota mobilnego. W tym artykule zbadano i przetestowano minimalny możliwy koszt sprzętowy kontrolerów ruchu i czujników do zastosowań robotów mobilnych. Język VHDL (ang. Very high-speed Integrated Circuit Hardware Description Language) służy do projektowania opartej na licznikach architektury kontrolerów ruchu i czujników w celu uzyskania możliwie najniższych kosztów wdrożenia. Następnie dogłębne badanie zaprojektowanych architektur dowiodło, że zapewnia oszczędne wykorzystanie zasobów sprzętowych po zaimplementowaniu w urządzeniu XC3S1000 FPGA (Field Programmable Gate Array) przy użyciu ISE 14.1. Zaprojektowane kontrolery działały z powodzeniem po wdrożeniu w XC3S1000 przy kosztach tylko 34 Slices. (**Niedrogi projekt inteligentnego systemu wbudowanego dla inteligentnego kontrolera robota mobilnego**)*

Keywords: Mobile Robot Controller, FPGA, Ultrasonic sensor, Motion controller.
Słowa kluczowe: Kontroler robota mobilnego, FPGA, czujnik ultradźwiękowy, kontroler ruchu.

Introduction

Nowadays, mobile robotic systems require complex control procedures that occupy less space and less energy [1] [2]. As a result, robotic systems design in FPGA has become a fascinating field of study [3]. One of the most common systems in the mobile robot is the obstacle avoidance system of mobile robotics, which has three main parts: motion controller, environmental sensing controller, and obstacle avoidance algorithm. So, each part takes a great deal of research. Obstacles avoidance algorithm implementation in FPGA has a wide range of complexity starting from very simple, as in [4] [5], to complex like intelligent systems using Fuzzy control as in [6] [7] or Nero-Fuzzy control as in [8] [9]. Thus, no one can give a suitable hardware design for all levels of complexity. Motion controller implementation in FPGA has been tackled by [10]. However, they did not reach the lowest cost controller to be used as IP (Intellectual Property) core. Several studies have focused on environmental sensing controllers [11]. The research has studied the hardware design to interface the FPGA with IR sensor as an environmental sensor. Conversely, Jnaneshwar Das et al. [12] discovered that the ultrasonic range sensor is the most suitable environmental sensor due to its low cost and ranging capability when it works in mobile robot applications. Garcia and others [13] designed hardware suitable for FPGA implementation but did not give a low cost because they use 30% of the XC3S1600E FPGA device.

Fortunately, the obstacles avoidance system's motion controller and environmental sensing controller can be designed in hardware with a fixed design as IP core if the servo motors are used for motion and Ultrasonic sensors used for environmental sensing, representing a low-cost component [12]. So, in this paper, a deep study to design low-cost hardware of motion controller and Environmental sensing controller for FPGA implementation and to globally interface with servo motor and Ultrasonic sensor, respectively.

Methodology

The methodology of a pulse width modulation and ultrasonic sensor, the mobile robot, and the mechanical design were demonstrated in this section as follows.

1-Pulse Width Modulation and Ultrasonic Sensor

Switching power converters are used in most servo motor drives to deliver the required energy to the motor. The energy that a switching power converter provides to a servo motor is controlled by the Pulse Width Modulated (PWM) signal applied to the gate of a power transistor. PWM signals are pulse trains with a fixed frequency, magnitude, and variable pulse width. Every PWM period has one pulse of fixed magnitude [14]. However, the width of pulses (duty cycle) changes according to the required motor speed, as illustrated in Figure 1.

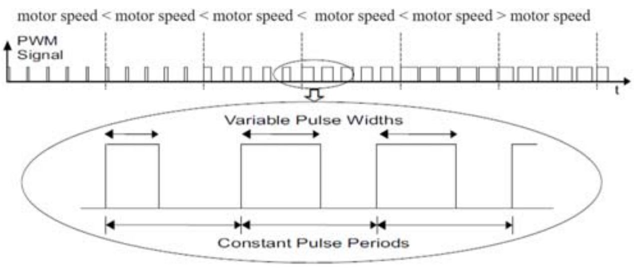

Fig.1. Pulse width modulation waveforms

The sound waves having a frequency higher than 20 kHz are called ultrasonic. In addition to the characteristics of sound waves (such as reflection, refraction, and diffraction), ultrasonic has the characteristics of centralized direction, good penetration, and small amplitude. Therefore, ultrasonic has a great advantage in real-time accuracy and non-destructiveness. The ultrasonic frequency is around 40 kHz and has the best transmission efficiency. So, the frequency of the driven signal for the ultrasonic emitter used in this design is 40 kHz. Currently, the time-of-flight (TOF) technique is the primary measuring procedure [15]. The TOF technique measures the time required by the ultrasonic wave to travel from a transmitter to a recipient. The distance between the middle of the obstacle and the sensor is calculated by

$$D = c * t / 2 \qquad (1)$$

where: D – distance, c – sound velocity, t – time-of-flight.

If the temperature is changed a little, the sound velocity of ultrasonic traveling in air is known, so it could be considered invariable [16]. However, Ultrasonic transducers can be used as distance measurement devices, giving relatively high accuracy, especially for short distance (1cm to 5m) measurement requirements [14].

2-Mobile Robot

There are many mobile robot-like wheeled, tracked, legged, flying, and underwater robots, but the wheeled robot is the lowest cost and most straightforward [17]. A wheeled robot can move on a surface only through the actuation of wheel constructions attached to the robot and in contact with the surface.

The robot design in Figure 2b is called "Ackermann Steering." Ackermann Steering is a car's standard drive and steering system with a rear-driven passenger. In this manner, it is handily controlled for driving bends yet can't turn on the spot since the determined wheel isn't situated in its middle. Figure 2c is classified as a "differential drive" and is one of the most regularly utilized versatile robot plans. The design provides static motors and wheels compared to the previous two designs. The blend of two driven wheels permits the robot to be driven straight, in a bend, or turn on the spot. The design simplifies the robot mechanics design considerably [17].

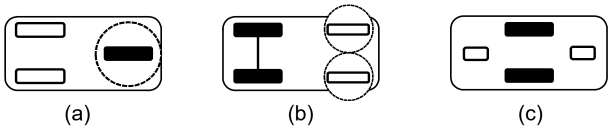

Fig.2. Wheeled robots

3-Mechanical Design

In Figure 2, the main wheeled mobile robot designs are shown. Each has its advantages; the differential drive seems to be the most suitable choice. This paper suggests a lower cost; one of the passive wheels of differential drive design can be deleted. This modification should be coupled with moving the robot's center of gravity to a suitable point. This design has the movement's ability to move in straight, in a curve, or to turn on the spot, as shown in Figure 3. The mechanical design of the mobile robot used is shown in Figure 4.

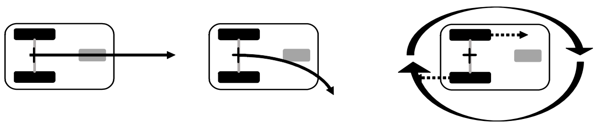

Fig. 3 The modified differential drive movement capabilities

Implementation Of The Designed Mobile Robot Architecture

The controller system of the designed mobile robot is shown in Figure 5, which represents the actual connections of the main parts. The FPGA used to implement the controllers is a 1,000,000-gate Xilinx Spartan-3 XC3S1000 in a 256- Fine-pitch, Thin Ball Grid Array package (XC3S1000-4FT256C). Spartan-3 devices contain a two-dimensional row and column-based architecture to implement custom logic. Its architecture consists of Input/Output Blocks (IOBs), Configurable Logic Block (CLB) and Slice Resources, Block RAM, Dedicated Multipliers, and Digital Clock Managers (DCMs). [18] The Spartan-3 FPGA used is on a Spartan-3 starter kit having a crystal of 50MHz. In contrast, the servo motor works at low frequencies. Servo motors are typical to be controlled by a PWM generator. Hence, the PWM generator controls the movement of the designed mobile robot. The question is: What is the suitable frequency needed for the servo motor used in the designed mobile robot. The lower frequency between 1Hz to 50Hz makes noticeable stops in motor rotation. High frequency (its value depends heavily on the internal coil of the servo motor) damages the motor. Thus, an empirical method with heat monitoring of the motor is used to decide the working frequency. It was discovered that the working frequency is between 50 Hz to 400 Hz.

The environmental sensing controller also needs a lower frequency of less than 100 kHz. The cause will be discussed later. This study looks for lower implementation costs. Thus, one frequency divider is used to divide 50MHz by 12500 to obtain a clock of 4 kHz to synchronize all the systems. Efforts were set to minimize the implementation cost of frequency divider by developing the typical design, which uses up counter and integer comparator. Integer comparator uses 32 input AND gate when VHDL code modified to replace the integer comparator with binary comparator, FPGA implementation of the new frequency divider shows that the cost is decreased 29% in the number of Slices, 21% in the number of Slice Flip Flops, and 28% in the number of 4 input LUTs (Look Up Tables) this is because 14bit is needed to represent 12500 in binary. So, it uses 14 inputs AND gate instead of 32 inputs AND gate. The test and RTL schematic of the device shown in Figure 6 prove it works appropriately. The Implementation of the designed motion and environment sensing controllers was presented in this section as follows:

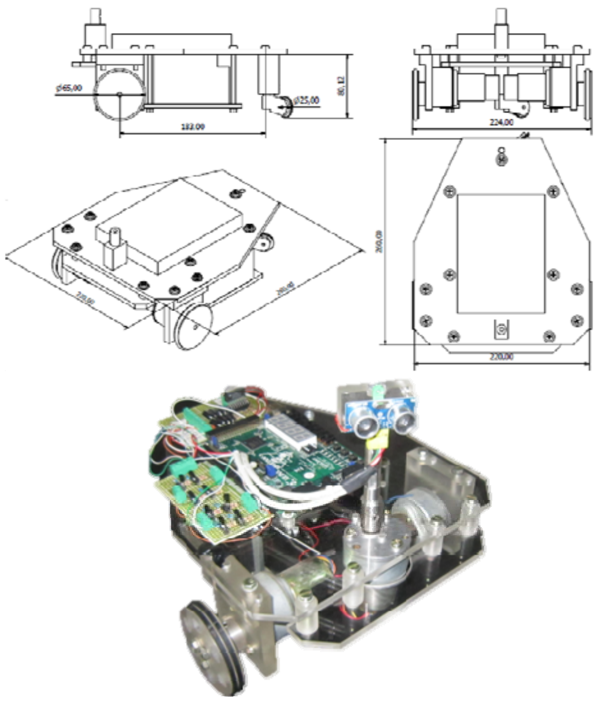

Fig.4. Mechanical design of the mobile robot

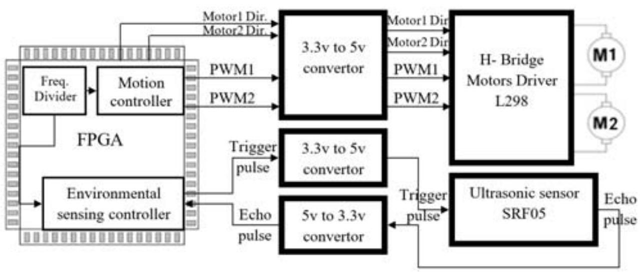

Fig. 5 Mobile robot controller main architecture

1-Motion Controller

Motion controller hardware depends heavily on the PWM generator since it costs at least two PWM generators, one for each servo motor. Hence, the efficient design implementation of the PWM generator must be studied intelligently. We built a hardware architecture for the PWM generator that contains a one-up counter and one binary comparator (shown in Figure 7), which gives '1' if the binary number from the counter is less than or equal to the input of the PWM generator (PWM_in) and '0' for a binary number that is more than the input until the counter reaches the final count. The number of bit (n) of PWM_in equals the number of bits of counter output numbers. So, the steps of changing the variable pulse width (shown in Figure 1) depend on (n) of PWM_in. For example, if n=8, variable pulse width steps=28 =256. However, if this PWM generator is used to control the speed of a servo motor, it will give 256 different speeds controlled by the PWM_in input signal. PWM_out has a frequency equal to clock frequency divided by 2n. The suggested architecture is implemented using VHDL code. The H- Bridge provides the required current to drive the servo motors and gives two control signals to control the direction control for the servo motor individually. We used L298, which can provide DC current up to 4A [19]

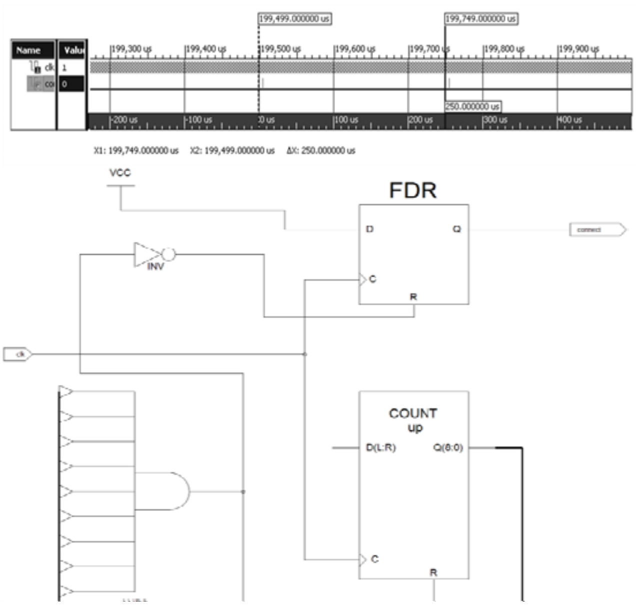

Fig. 6 Frequency divider test and RTL schematic

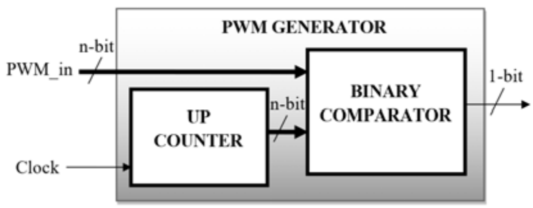

Fig. 7 PWM generator architecture

2-Environmental Sensing Controller

The environmental sensing controller is used to interface with the Ultrasonic sensor (SRF05), so it should be able to send, receive, and process the signals shown in Figure 8. The controller can deal with each signal separately. Trigger pulse can be generated using the frequency divider and PWM generator. From Figure 8, the Trigger pulse has a minimum time of 10µs of '1' and a minimum period of 50ms [20]. So 250µs, more than10µs, (4 kHz) is selected to use the same frequency divider, which divides by12500, used in the motion controller to minimize the cost. The period can result from using the PWM generator of 8bit input (PWM_in) and giving it a constant value of (00000001)B.

Consequently, the period of PWM_out will be equal to 250µ×28 = 64ms, more than 50ms. The sensor receives the echo pulse from the controller and processes it to get the distance. It is challenging because the counter should reset when the rising edge of the Echo pulse is reached, then it counts up when the Echo pulse is '1' and keeps its output unchanged during the counting state. Later, when the falling edge of the Echo pulse is reached, the counter should output the last counted number. Hardware is designed using VHDL code with the minimum possible cost to meet these requirements.

Finally, it is worth mentioning that FPGA has an input and output of 3.3v standard. However, H-Bridge and the ultrasonic sensor use 5v standards. So, it is essential to interface them with a 5v to 3.3v converter and vice versa. Accordingly, the voltage converter uses two cheap 2N3904 transistors with four resistors.

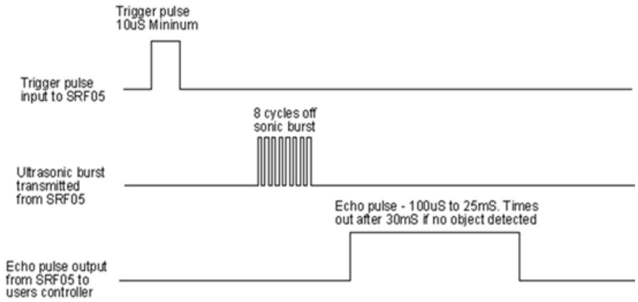

Fig. 8 Ultrasonic (SRF05) signals [20]

Results And Discussion

The final hardware design contains two main parts: the motion controller and the environmental sensing controller. Each part's test and implementation results are discussed separately and assembled in single hardware to check the total cost.

1-Motion Controller Hardware

The hardware test in ISE 14.1 of its VHDL code is shown in Figure 9, and it proved to give different widths of '1' duration depending on PWM_in.

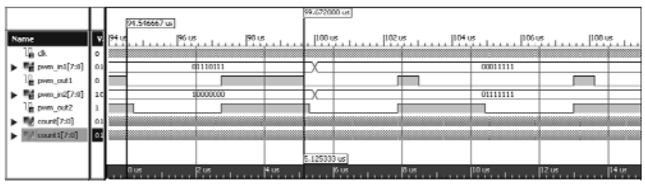

Fig. 9 Hardware test of Motion controller

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Device utilization summary:
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Selected Device : 3s1000ft256-4

 Number of Slices:                 14  out of   7680     0%
 Number of Slice Flip Flops:       10  out of  15360     0%
 Number of 4 input LUTs:           24  out of  15360     0%
 Number of IOs:                    19
 Number of bonded IOBs:            19  out of    173    10%
 Number of GCLKs:                   1  out of      8    12%
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Fig. 10 Hardware resources cost of Motion controller implementation

The motion controller of two servo motors contains two PWM generators, costing 14 slices only after implementation. The results and RTL schematic are shown in Figures 10 and 11.

As seen in Figure 9, the controller can treat every motor separately. Consequently, this controller improves the movement to move in a curve produced from the ratio from dividing pwm_in1 by pwm_in2. This result is the lowest cost reached as compared to the cost in related studies [11] [21] [22].

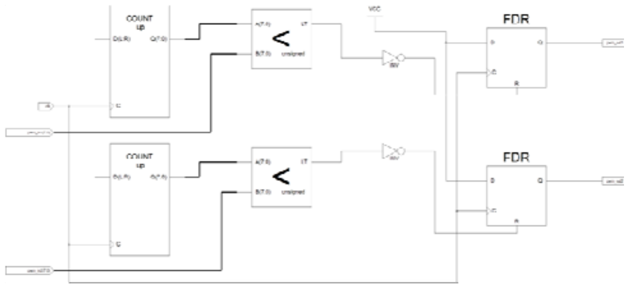

Fig. 11 RTL schematic of Motion controller

2-Motion Controller Hardware

The controller's hardware is tested in ISE 14.1, shown in Figure 12, and the signals start with a trigger pulse generated from the PWM generator. After a while, the ultrasonic sensor answered by its echo pulse for a duration represents the distance discovered by the sensor, then a bus of signals called distance (9:0) shown in Figure 12, which represents distance as a binary number is obtained after processing.

The implementation of this controller is the lowest in cost among related studies [11] [13] [16] [22] [23]. The cost is shown in Figure 13.

The RTL schematic of the echo pulse processor (the RTL of the trigger generator is the same as the PWM generator) is shown in Figure 14.

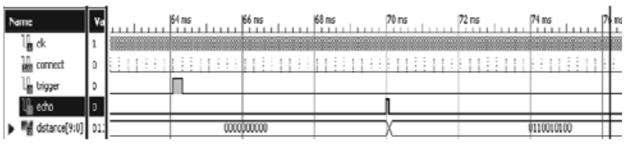

Fig. 12 Hardware test of environmental sensing controller

Device utilization summary:

Selected Device : 3s1000ft256-4

Number of Slices:	24	out of	7680	0%
Number of Slice Flip Flops:	34	out of	15360	0%
Number of 4 input LUTs:	44	out of	15360	0%
Number of IOs:	14			
Number of bonded IOBs:	14	out of	173	8%
IOB Flip Flops:	10			
Number of GCLKs:	2	out of	8	25%

Fig. 13 Hardware resources cost of Environmental sensing controller implementation

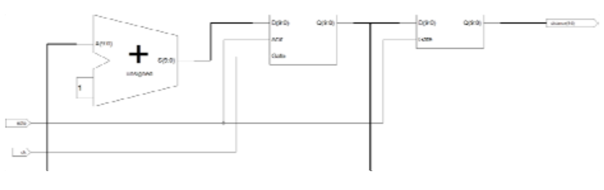

Fig. 14 RTL schematic of echo pulse processor in Environmental sensing controller

Device utilization summary:

Selected Device : 3s1000ft256-4

Number of Slices:	34	out of	7680	0%
Number of Slice Flip Flops:	36	out of	15360	0%
Number of 4 input LUTs:	60	out of	15360	0%
Number of IOs:	32			
Number of bonded IOBs:	32	out of	173	18%
IOB Flip Flops:	10			
Number of GCLKs:	2	out of	8	25%

Fig. 15 The final hardware design implementation cost

3-Final Hardware Design

The goal of the final hardware is to make a hardware controller that provides the obstacles avoidance algorithm with all its requirements at the lowest possible cost so that the rest of the FPGA resources can be dealt with the algorithm. So, the motion and Environmental sensing controllers with their standard frequency dividers are assembled in one VHDL code and implemented in the FPGA to obtain the final hardware design cost. The implementation results shown in Figure 15 prove that the design has the lowest cost as compared with [4], [11], and [22].

Conclusion

The design and execution of a mobile robot controller in a Spartan-3 FPGA device have been presented. It is based on designing each part alone and counter-based design because counters have low FPGA implementation costs and assemble all design components. The controller worked well. The signals needed to control and interact with the mobile robot are simulated and tested in ISE 14.1. The final design was implemented with less than 1% (34 Slices) of Spartan-3 FPGA resources. It has been found that the counter-depending robot Motion and Environmental sensing controller design gives the lowest possible FPGA implementation cost.

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