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Research paper

FPGA Verification and ASIC Implementation of a Load Carrying Follower Cart

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Abstract

A Follower Cart system is designed using Verilog Hardware Description Language (HDL) and implemented in an Application Specific Integrated Circuit (ASIC). A prototype that is capable of carrying 0 kg load is developed with the use of Field Programmable Gate Array (FPGA) as its controller for debugging and verification. The study then acquired a chip level layout of the control system with an area of 498.94 µm that has a power consumption of 0.4981 mW and cell leakage power of 19.49 µW. The output of this study allows mass production of a dedicated IC for a Load Carrying Follower Cart control system which is more efficient in terms of unit cost and power consumption

Keywords: *Field Programmable Gate Array (FPGA); mobile robot; Unmanned Ground Vehicle (UGV); Ultrasonic Sensor; Verilog HDL*

1. Introduction

Looking back over history, it can be seen that technology is intended to make our lives easier. Machines such as robots have eased humans' efforts in doing a certain job. Such robots that increased person's capability and efficiency are mobile robots ---- an automatic machine that is capable of moving in any given environment. One type of mobile robot based on its application is a load-carrying robot. A load-carrying robot is an Unmanned Ground Vehicle (UGV) with large mounting surface that can carry a maximum specific load with wheels that made it possible to navigate from one place to another. Another type is a follower robot that has sensors to detect a user in order to follow it as it navigates a certain path [2].

The proponents designed a Follower Cart that can autonomously follow a user while carrying a maximum load of 20kg. The design is implemented in an ASIC to be able to mass produce a dedicated IC that can ease up transferring loads from one place to another. It can be used in factories in carrying equipment and loads, specifically in factories with harsh radiation environment since ASICs are more radiation tolerant compared to microcontrollers. Moreover, mass production will lessen the cost in manufacturing a follower cart controller. Also, ASIC controller is more efficient than other microcontrollers since it is custom-designed for a particular application. Thus, it optimizes the number of transistors and clock cycles (and therefore unit cost and power consumption). Furthermore, this study of designing a follower cart using Verilog HDL will be used as part of ongoing engineering research into mobile robots in FPGA controller and implemented in ASIC.

2. System Design

2.1. Follower Cart Prototype

The prototype was designed with a front swivel wheel and two rear wheels. Each rear wheel is coupled to a Direct Current (DC) motor, making it possible to maneuver and rotate up to 360 degrees. With the limitation of the DC motor's mechanical power, the researchers have come up with the design shown on Figure 1that is light weight and has a platform large and strong enough to support a load of 0kg. The Follower Cart's framework is mainly made of steel angle bar and the platform will be made up of plywood with allowable compression stress of 6.1 MPa. The following computation is done to assure that the platform will be able to carry the load of 0kg:

$$F = mg = (0kg)(9.81\ m/s^{\wedge}) = 196.\ N \qquad (1)$$

$$\sigma = F/A = (196.\ N)/(0.3344\ m^{\wedge}) = 586.7\ N/m^{\wedge} \qquad (2)$$

$$\sigma = 0.5\ MPa$$

where,
F = Force; m = Mass of the Load; g = Gravity
σ = Compressive Stress; A = area of the platform

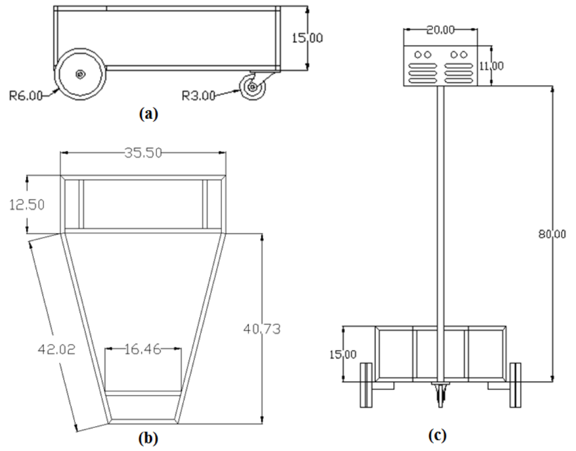


Fig. 1. (a) Side view, (b) Top view and (c) Front view of the cart

2.2. System Overview

The system consists of ultrasonic sonar modules, controller, H-bridge Motor Drivers, Transistors switches, DC motors and gears and its power will be supplied by 1V lead-acid battery. Two ultrasonic sensors are used for the distance measuring between the user and the cart and with the concept of triangulation, determining the position of the user will be possible. Using the feedback obtained from the distance sensors, the controller will analyze this information and then it will feed the motor drivers with instructions to control the dc motors so that the cart will follow the user while avoiding the cart from bumping the user. However, before the signal reached the motor driver, there is still a need for it to pass through transistor switches since the controller can only produce 3.3V and the driving voltage of the Motor drivers is 5V. Figure 2 shows the system block diagram of this research.

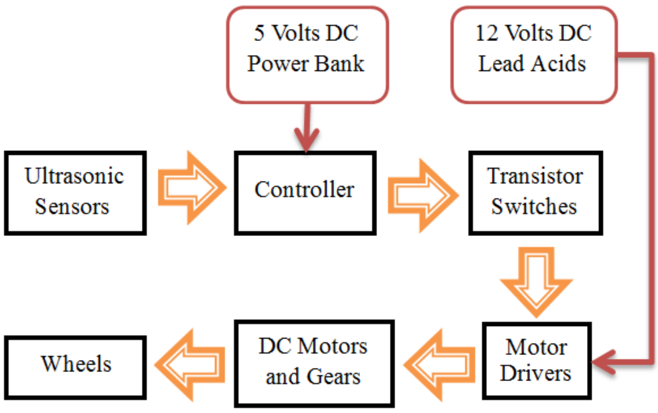
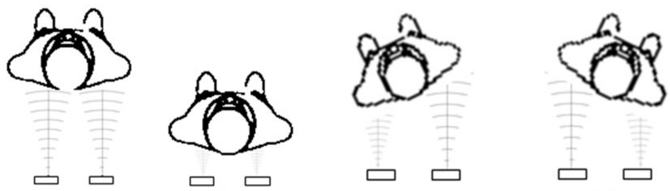


Fig. 2. System block diagram

2.3. Tracking System

In order to follow a user, a tracking system was designed with the use of two ultrasonic sensors and concept of triangulation. The following scenarios were taken to consideration in designing the algorithm of determining the position of the user in front of the cart:



(a) (b) (c) (d)

Fig. 3. Observed scenarios in tracking user's position

With the scenario projected on Figure 3 (a) and (b), the two ultrasonic will read distances wherein the difference between the two distances is less than 10 cm. Moreover, on Figure 3 (a), the distances should be greater than 45cm in order for the cart to undergo forward state. While on Figure 3 (b), the cart is in reverse state with distance readings of less than 30cm. Then if the system will encounter the scenarios showed on Figure 3 (c) and (d), the difference between the readings of the sensors should be more than 10cm. Then, the system will determine whether the cart should turn left or right. Specifically, on Figure 3 (c), the left sensor should acquire a distance lesser than the right sensor and if it is a reverse state the cart will move to the right side otherwise, left. Then if the acquired a distance of the left sensor is more than the right sensor which is projected on Figure 3 (d) and the cart is on reverse state, the cart will move to the left side otherwise, right.

2.4. Maneuvering System

To be able to maneuver the cart the two rear wheels are coupled independently with DC motors. In choosing the appropriate DC motor, there is a need to calculate the required mechanical power to be able to move the follower cart with a total weight of the cart together with the 20 kg load. Thus, the following calculations were done:

$$\text{friction} = \mu * N; \qquad \text{where: } \mu = \text{frictional coefficient} \tag{3}$$

friction = 0.6 (dead weight+ maximum weight)(gravity)
Force = friction = 0.6 (15 kg +20 kg)(9.81 m⁄s)
Force = 206.01 N

$$\text{Power} = \text{Force} * \text{velocity} \tag{4}$$

Power =206.01 N *1 m⁄s=206.01 W

$$\omega = \text{velocity/radius}; \qquad \text{where: } \omega = \text{angular velocity} \tag{5}$$

$$\omega = (1\ m/s)/(0.0762\ m); \qquad = 13.12\ rad/s = 125.29\ rpm$$

So, there is a need for a DC motor and gearing system that can produce more than 206.01 watts with angular velocity of greater than 125.29 rpm. And in this study, the DC Motor used is a Faulhaber Micromotor with a combination of planetary gearhead that in over-all the total mechanical power is 1122 watts. Therefore, the DC motor has more than enough power to move the cart. In order to control the direction of rotation and speed of the two DC motors, a motor driver was used in each DC motor. These motor drivers receive instructions from the controller to whether their respected dc motor should rotate clockwise or counter clockwise [14].

3. FPGA Verification

To verify the carts capabilities and the efficiency of the Verilog HDL code, the researchers developed a prototype of the Load Carrying Follower Cart with FPGA as its controller. Figure 4 and Figure 5 shows the constructed load carrying follower cart and the ultrasonic sensor transmitter/receiver simulation, respectively [15].

Fig. 4. Developed load carrying follower cart

Using Xilinx Integrated Software Environment, the researchers were able to acquire simulation waveforms of the follower cart. The following timing diagrams show that the designed Verilog code is efficiently working in response to simulated echo signals.

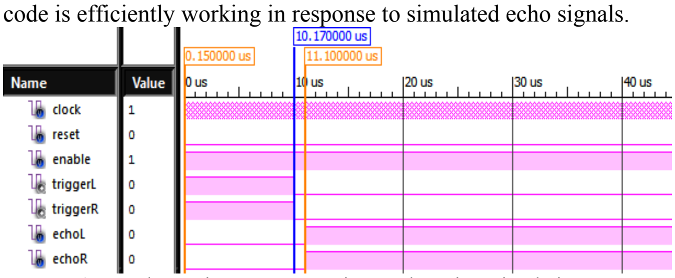


Fig. 5. Ultrasonic sensor transmitter and receiver simulation

In response to the logic levels of the direction indicators, the H-bridge Control module will produce corresponding signals of the watchdog pins, PWM pins and motor direction pins as displayed in Figure 6. The watchdog output signal has a period of 2.04ms with 3.92% duty cycle. And the PWM signals have a period of 1.02ms and the duty cycle is calibrated in proportion to the angular speed of the motor for a certain motion. For the motor direction pins, logic high causes the motor to rotate counterclockwise while logic low causes clockwise rotation.

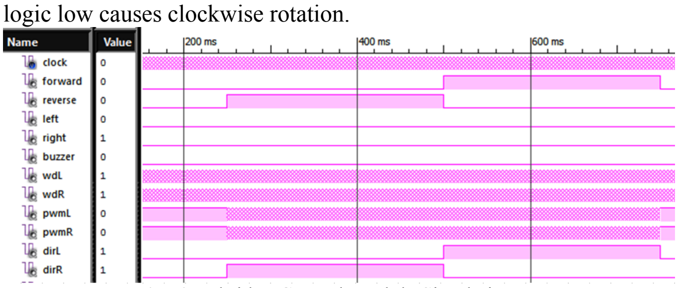


Fig. 6. H-bridge Control Module Simulation

4. ASIC implementation

Using Synopsys Design Vision, the researchers were able to compile and synthesize the over-all design of the system into gate-level HDL netlists. In synthesizing, the Synopsys Design Vision first checks the design files for syntax and save modules into the local folder in an intermediate format. The design is then mapped to a gate library or cell library.

After compiling and synthesizing, the top level external block model of the follower cart was obtained It can be seen in Figure 7 that the over-all control system has 5 inputs namely clock, reset, enable and the two inputs from the ultrasonic sensors and 13 outputs that is composed of 4 outputs for LED indicators of the direction of motion, 2 outputs for the ultrasonic transmitters, 6 for the H-bridge motor driver and 1 output for buzzer.

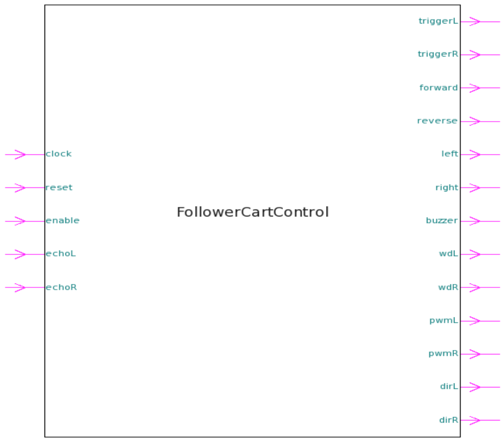


Fig. 7. Follower cart top level block model

Figure 8 shows the internal architecture of the Follower Cart system. Once this block diagram is synthesized, one congested module of the Follower Cart will be mapped into an over-all gate-level HDL netlists as shown in Figure 9.

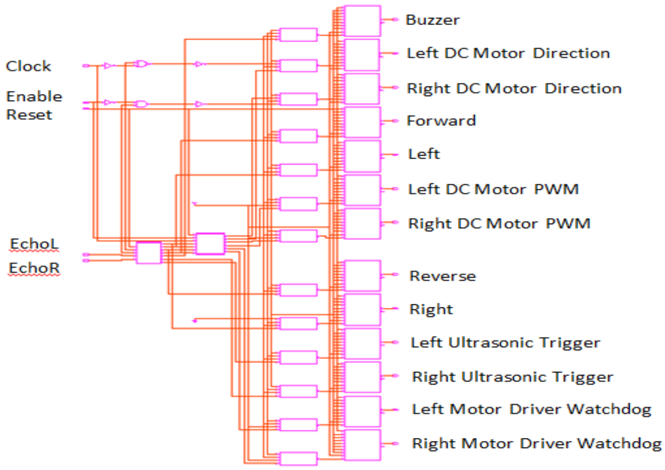


Fig. 8. Follower cart block diagram

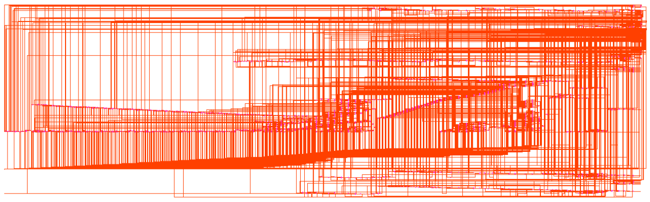


Fig. 9. Follower cart gate level schematic diagram

Figure 10 shows the acquired core layout of the Follower Cart Control System after the physical implementation using Synopsys IC Compiler cell libraries.

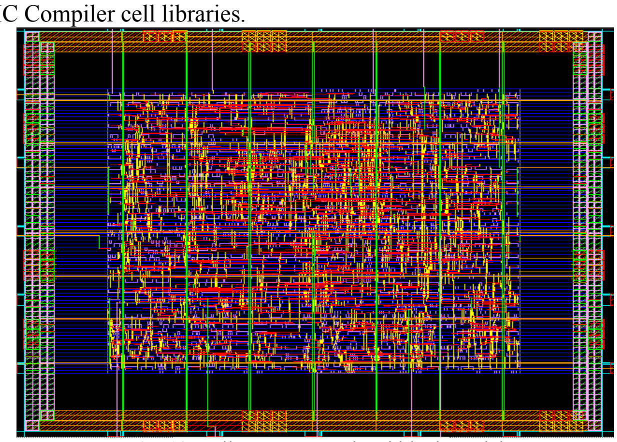


Fig. 10. Follower cart top level block model

Figure 11 shows the chip level layout of the Follower Cart Control System. This chip layout occupies an area of 4298.94 µm2.

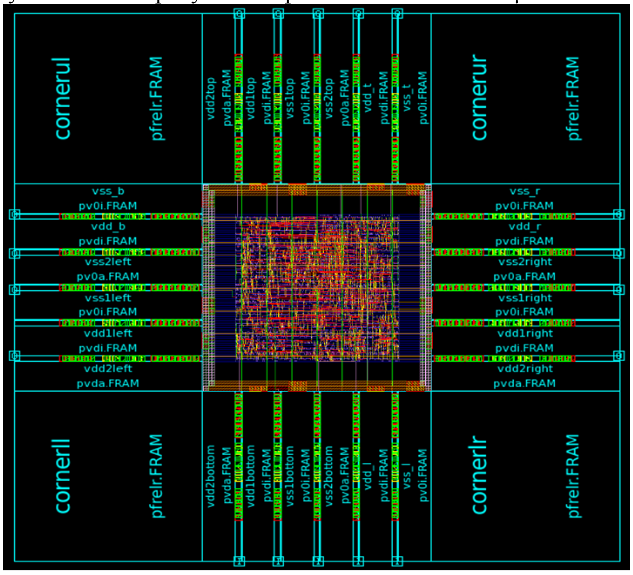


Fig. 11. Follower cart chip level layout

To test the performance of the ASIC layout, timing analysis was done and it resulted to a report shown on Figure 12. From this report, it can be implied that the design is good in terms of timing since the data arrived in the output path before the required time ended. The design was able to achieve a slack time of 14.17ns.

```
Startpoint: reset (input port clocked by clock)
Endpoint: Hbridge/dirL_reg
          (rising edge-triggered flip-flop clocked by clock)
Path Group: clock
Path Type: max

Des/Clust/Port     Wire Load Model      Library
------------------------------------------------
FollowerCartControl
                   ForQA                cb13fs120_tsmc_max

Point                                         Incr       Path
----------------------------------------------------------------
clock clock (rise edge)                       0.00       0.00
clock network delay (ideal)                   3.00       3.00
input external delay                          5.00       8.00 f
reset (in)                                    0.00       8.00 f
Hbridge/reset (HbridgeControl)                0.00       8.00 f
Hbridge/I_5/Z (GTECH_NOT)                     0.00       8.00 r
Hbridge/C443/Z (GTECH_AND2)                   0.00       8.00 r
Hbridge/B_3/Z (GTECH_BUF)                     0.03       8.03 r
Hbridge/C433/Z_0 (*SELECT_OP_2.1_2.1_1)       0.00       8.03 r
Hbridge/dirL_reg/next_state (**SEQGEN**)      0.00       8.03 r
data arrival time                                        8.03

clock clock (rise edge)                      20.00      20.00
clock network delay (ideal)                   3.00      23.00
clock uncertainty                            -0.80      22.20
Hbridge/dirL_reg/clocked_on (**SEQGEN**)      0.00      22.20 r
library setup time                            0.00      22.20
data required time                                      22.20
----------------------------------------------------------------
data required time                                      22.20
data arrival time                                       -8.03
----------------------------------------------------------------
slack (MET)                                             14.17
```

Fig. 12: Slack time report

Figure 13 shows the power consumption of the Follower Cart Control System. It can be observed from the figure below that the total dynamic power of the system is 0.4981 mW with cell leakage power of 19.49µW.

```
****************************************
Report : power
        -analysis_effort low
Design : FollowerCartControl
Version: E-2010.12-SP1
Date   : Mon Mar 24 05:05:16 2014
****************************************


Library(s) Used:

    cb13fs120_tsmc_max (File: /home/angel_sarmiento/ref/libs/mw_lib/sc/LM/sc_max.db)


Operating Conditions: cb13fs120_tsmc_max   Library: cb13fs120_tsmc_max
Wire Load Model Mode: Inactive.


Global Operating Voltage = 1.08
Power-specific unit information :
    Voltage Units = 1V
    Capacitance Units = 1.000000pf
    Time Units = 1ns
    Dynamic Power Units = 1mW    (derived from V,C,T units)
    Leakage Power Units = 1pW

Warning: Cannot report correlated power unless power prediction mode is set. (PWR-727)
Power Breakdown
---------------

                             Cell        Driven Net  Tot Dynamic       Cell
                             Internal    Switching   Power (mW)        Leakage
Cell                         Power (mW)  Power (mW)  (% Cell/Tot)      Power (pW)
----------------------------------------------------------------------------------
Netlist Power                   0.2268      0.2713   4.981e-01 (46%)   1.949e+07
Estimated Clock Tree Power   N/A         N/A           (N/A)           N/A
----------------------------------------------------------------------------------

***** End Of Report *****
```

Fig. 13. Power consumption report

5. Conclusion

The researchers were able to effectively design a Load Carrying Follower Cart that can follow the user by maintaining a 30-45cm distance range while carrying a load of 20kg using Verilog Hardware Description Language and it was verified to be efficiently working through simulation using Xilinx ISE and also through prototype test using Field Programmable Gate Array. Moreover, the working control system was successfully compiled and synthesized through Synopsys Design Vision. Through Synopsys Integrated Circuit Compiler (ICC), it was successfully implemented in an Application Specific Integrated Circuit. The layouted ASIC has acquired the specification shown in Table 1. With this paper, a dedicated IC for a Load Carrying Follower Cart can now be fabricated. Successful fabrication will allow for mass production of the IC, consequently lowering the Follower Cart Control System cost.

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