Manual and automatic differential locker control system implemented in a Field Programmable Gate Array for a 1:10 scale RC off-road vehicle

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Abstract: ***A differential locker control systemis implemented in an FPGA (Field Programmable Gate Array) for anoff-road Radio-Controlled (RC) vehicle with front and rear differential lockers. The system could work in manual or automatic mode and is based on a detector that could differentiate between normal driving condition (vehicle turning) and driving conditions when a locking differential is needed, based on wheel and driveshaft angular speed. The system has simple visual indicators for the driver both in manual and automatic mode. The system also protects the lockers to engage if the vehicle is moving, a situation not recommended by the vehicle manufacturer.***

Keywords: differential locker control system, FPGA, detection system, off-road vehicle.

1. INTRODUCTION

Locking differentials allow both wheels to travel at the same speed, so when traction is lost for one wheel, both wheels will still keep spinning regardless of the amount of resistance. They can be added to either the front or rear axle, or even both axles. So, while that wheel is spinning freely, the wheel still maintaining contact with the ground will be stationary. That's not going to help the situation at all. With a locking differential, since equal power is transferred to both wheels, the one wheel with ground contact will be able to rotate along with the freewheel, propelling the vehicle forward to freedom. Brake lock differentials serve a similar purpose as diff locks but are not the same thing and cannot be substituted for a full-on locking differential [1].

2.1 Types of locking differentials

There are two main ways to categorize lockers:
-Selectable Lockers
-Auto-Lockers
Selectable lockers are lockers that are manually engaged or disengaged via a switch, button, lever, etc. Once the locker is engaged, it stays engaged until you manually disengageit.The benefit of selectable lockers is that you get to decide when they are engaged and disengaged. Some of the reasons you would want to manually disengage would be when you are in a tight situation and having the front or rear locked could cause difficult steering or binding. You also don't want to have lockers on when you are diving on the road in wet, snowy, or icy conditions, as this could cause loss of traction and potentially loss of control. Having a selectable gives you the benefit of choice. The disadvantages of selectable lockers are that they typically cost more money, they require external components to engage such as an air compressor, air line, and solenoid, electric motor, or cable attached to a lever. There are more potential points of failure due to the complexity.

Auto-Lockers are lockers that automatically engage using mechanical components that lock up the differential once a tire starts to lose traction. This is different than posi-track or limited-slip, because it locks the differential rather limit the amount of slip to a varying degree (auto-lockers are either on or off, nothing in between), but works similarly.The benefit of an auto-locker is that they are usually cheap, easy to install, and don't require any extra parts to engage since they engage on their own without the need for manual engagement from the driver.The disadvantage of auto-lockers is that they will lock when you don't always want them to, they can be noisy when turning due to the clicking nature of some of them, they typically aren't as strong as some of the selectable locker options [2].

The purpose of this project was focused on the following considerations:

a) To take the advantages of manual lockers associated with an automatic mode.
b) The importance of an automatic locker that detects and locks a specific axle when the vehicle is losing traction.

c) The automatic system is based on an easily implemented detector in a Programmable Logic Device (PLD), like the FPGA, andit is calculated using the wheel and driveshaft speed information, capable to be implemented in modern vehicles because they are already factory installed sensors.

d) The importance that the system has visual aids or indicators of the status of the detection system and the locker.

e) The importance that the locker is engaging only if the vehicle is stopped accordingly with the manufacturer specification, both in manual or automatic mode.

2. METHODOLOGY

2.1 Test vehicle and sensors

A Traxxas TRX-4 Defender 1:10 scale RC was used. It has off-road capability originally with T_Lock™ manual remote Locking Differentials and High/Low Transmission [3]. For measuring wheel and driveshaft speed, it was used Hall-Effect sensors from Traxxas [4] and ¼" diameter Neodymium magnets.
Each wheel has 6 magnets (Figure 1) and the driveshaft has 2 magnets (Figure 2).

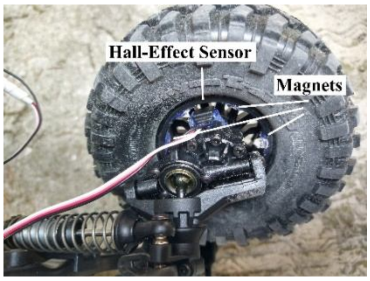


Figure 1 Right front wheel and suspension with Hall-Effect Sensor and Magnets

The sensors are: left front wheel (LF), right front wheel (RF), left rear wheel (LR), right rear wheel (RR), and driveshaft (DS). If the sensor detects one magnet, it goes from 3.3V to 0V.

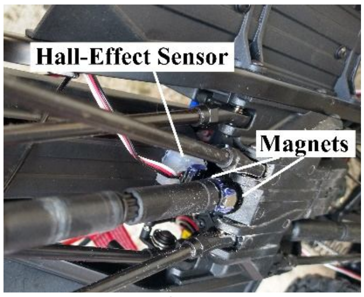


Figure 2 Bottom-view of vehicle showing driveshaft sensor and magnets

2.2 Differential Locker Control System

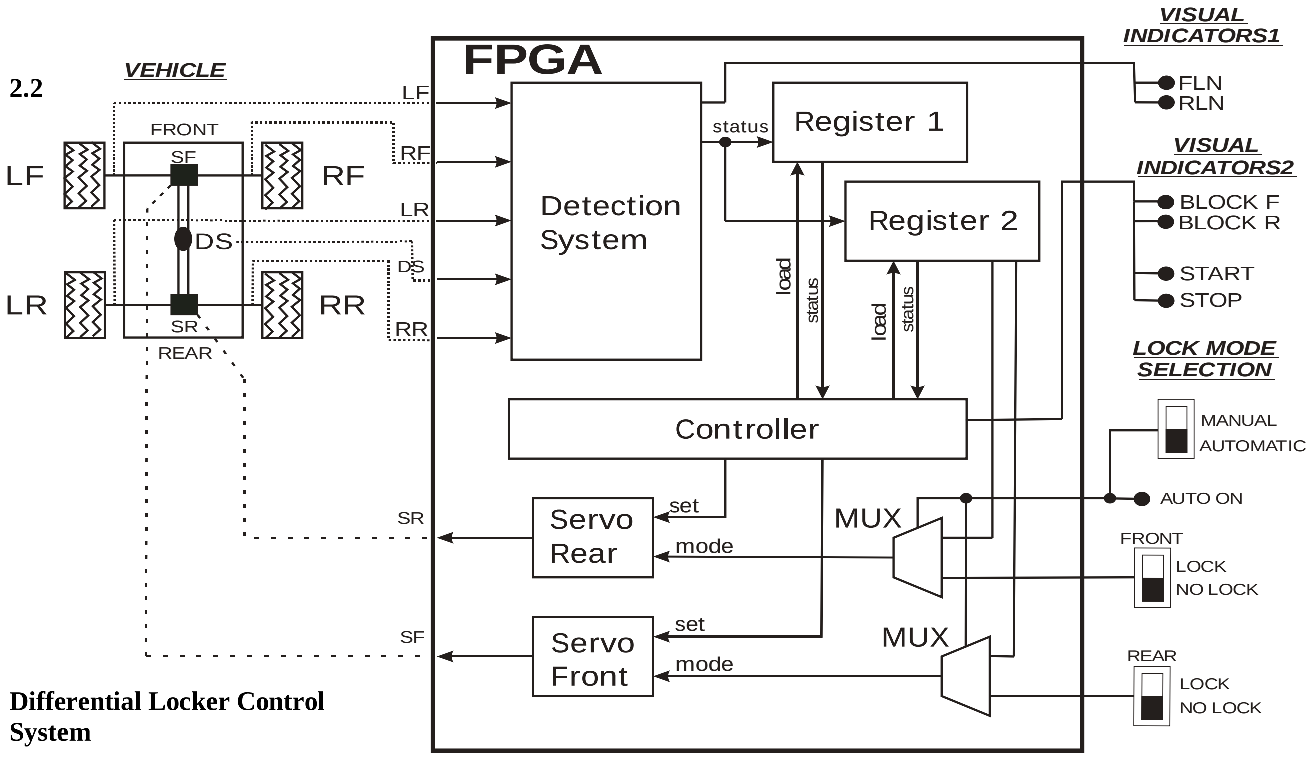


Figure 3 Block diagram of the Locker control system

Figure 3 shows the block diagram of the differential locker control system. On the left side, it is represented the vehicle with sensors (LF, RF, LR, RR, and DS) and the front and rear differential lockers servos for each axle (SF – servo front, and SR – servo rear). The FPGA system was described using VHDL (Very High-Speed Hardware Description Language) and implemented in a SPARTAN3 FPGA, using DigilentNexys 2 Development Board [5]. Register Transfer Level (RTL) methodology was used [6]. The systemhas six main blocks interconnected inside the FPGA. All were described using VHDL and each one will be explained further. On the right side of Figure3,it is the visual indicator area and the control switches.

2.2 Detection System

One of the most important blocks is the detection system. The detection system is based on a previous project [7] and it was developed based on a real test with the vehicle in different conditions and implemented easily as a truth table and using wheel speed differences.
The locking differential need detector (F=1 indicate it is lock needed) works as follow:

Let A and B, be the wheels speeds for a specific axle then:

1)Determinate the maximum value (MAX) between A and B

$$MAX = MAX(A, B) \qquad (1)$$

2)Determinate the minimum value (MIN) between A and B

$$MIN = MIN(A, B) \qquad (2)$$

3)$If\ MAX = (0\ to\ 3)\ and\ MIN = 0\ then\ F = 0\ (no\ locking)$

$$else\ if\ MAX \geq 4\ and\ MIN = 0\ then\ F = 1\ (locking)$$

$$else\ if\ \frac{(MAX - MIN)}{MAX} < 0.6\ then\ F = 0\ (no\ locking)$$

$$else\ if\ \frac{(MAX - MIN)}{MAX} \geq 0.6\ then\ F = 1\ (locking) \qquad (3)$$

The simplified block diagram of the detection system is shown in Figure 4. The detector receives signals from the Hall-Effect sensors. The speed blocks calculate the speed of any wheel and the driveshaft in 0.9229s and give as output a binary number.

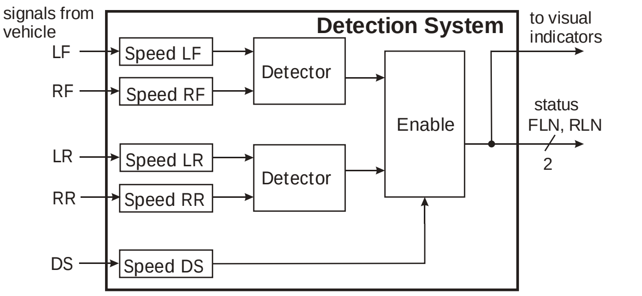


Figure 4 General block diagram of the detection system

The detector block was implemented as a true table and determinates if a differential locker is needed or not. The detection system used two detector blocks, one for each axle. The enable block controls the visual indicators LEDs (Light-Emitting Diode) and they are enabled only when the DS speed is below 1302 rpm and above195.3972 rpm. The status signals are Front Lock Need (FLN) and Rear Lock Need (RLN).If FLN=1 indicates that it is necessary to block the front differential, and RLN=1 indicates that it is necessary to block the rear differential. These are output status signals from the detector to the register blocks.

2.3 Register blocks

These are 2-bit temporal registers. Each register has input status signals (FLN and RLN), and each one is memorized (status_out) when the controller activatesthe load signal (load=1). The clock signal comes from a divider block and it is 2.98 Hz

Figure 5 Input and output signals of the register block

2.2.3 Controller block

The controller is a Moore typeFinite State Machine (FSM) and it controls most of the blocks and the logic sequence of al the automatic system. As it was said, the Traxxas TRX-4 Defender 1:10 scale RC has front and rear blockers, as it is recommended [8] the vehicle must be stopped before activating any blocker, this important condition is also verified by the controller.

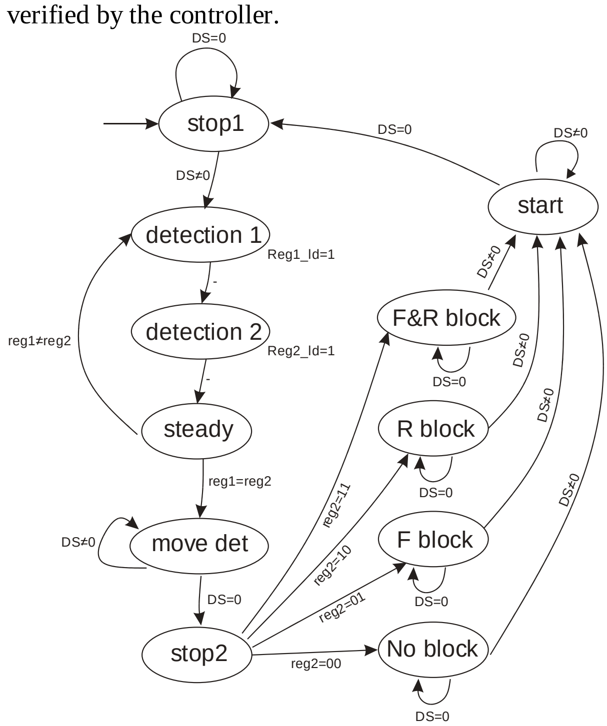


Figure 6 Finite-State Machine of the controller

The general FSM of the controller (Figure6) works as follows.If the vehicle is in Stop1 indicate that the vehicle is not moving, because DS=0, and it will stay in this state until DS≠0 because the vehicle start moving and it will jump to next state Detection1. When the car start moving the detector block detects if it is necessary to block the front and/or rear differential, and these status signals are stored in register1. Then the FSM jumps to the Detection2 state and stores again the status signals. The steady-state verifies if the status signals stored in Register1 and Register2 are the same, if they are, the configuration of the differentials is determined, if not, the FSM continues the process of Register1 and Register2 states. The vehicle must be stopped before configuring the block differentials, the move detection state verifies this, and until the car is stopped (DS=0) then jumps to stop2 state. Accordingto the need or not of the block differential stored, the following state is as shown in Table 1.

Table 1: Register2 value and status

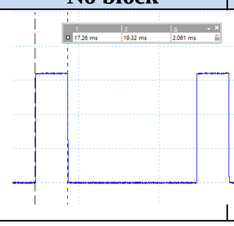
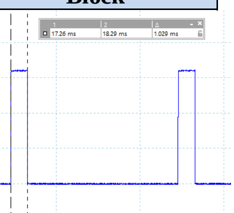
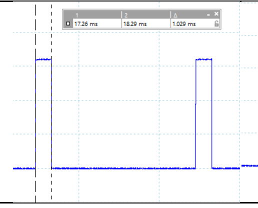
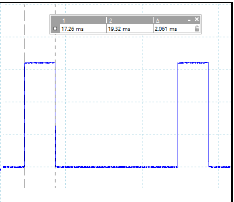
Register2 value	Status -> Next State
reg2=00	No block needed -> no block state
reg2=01	Front block needed -> F block state
reg2=10	Rear block needed. -> R block state
reg2=11	Front and rear block needed -> F&R state

The states verify that the vehicle continues in stop position (DS=0) and configure the servo blocks, and the block condition continues until the car stopped again, and the FSM returns to the initial state, to make a new measurement involving all the states described and if it is the case, free the blocking system, or change it. The controller uses a clock signal of 2.98Hz, the same as the registers.

2.2.4Servo Front and Servo Rear blocks

By factory, the Traxxas TRX-4 Defender 1:10 scale RC controls front and rear differential blocker manually using the RC Control. Both front and rear mechanical lockers are engaged using small RC servos, the control signals were measured using an Oscilloscope. These manual control cables were disconnected from the TraxxasControler and connected directly to the Nexys FPGA Board. The control signals use logic levels from 0 to 3.3V and with a period of 10ms. The control signals (Table 2) were described using VHDL for servo front and servo rear blocks.

Table 2: Servo signals

Mode	No block	Block
Front Servo		
Rear Servo		

2.2.5 Visual Indicators and selection switches

There are 7 LEDs (Light Emitter Diode) used as visual aids for the driver. The ON state of each LED represents:

a)From the detection system
FLN – Front differential needs to be locked
RBN- Rear differential needs to be Locked

b)From the controller
LOCK F – Front differential is locked
LOCK R – Rear differential is locked

START – The driver must start moving the vehicle
STOP – The driver must stop moving the vehicle

c)From the lock selection mode switches
AUTO ON – The locking differential system is in automatic mode and it is indicated by a LED. In manual mode, front and rear switches are used accordingly.

FRONT – The user lock or unlock the front differential blocker.

REAR - The user lock or unlock the rear differential blocker.

2.2.6 Clock signals

The system uses two clock signals. A 50 MHz based on the Nexys board crystal oscillator and a 2.98 Hz obtained using a VHDL counter as a clock divider. The clock signal used by each block is shown in Table 3.

Table 3: Clock signals

Clock signal frequency	Block
50 MHz	Detection system Servo front Servo rear
2.98 Hz	Register 1 Register 2 Controller

2.2.7 Synthesis and implementation

The VHDL code was synthesized using Xilinx ISE and then the programing file was generated for the spartan 3 FPGA. The system developed (Figure 7) uses 199 slices, 280 Flip-Flops, 374 four-input LUTs (Look-up Table), 7 input pins, 8 output pins, and 1 global clock. The maximum propagation time is 8.622ns.

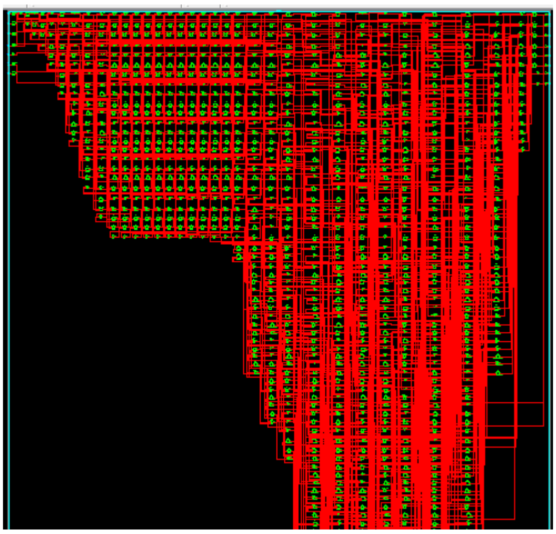


Figure 7 FPGA Technology Schematic of the

Figure 8shows the Traxxas TRX-4 without his cover and the Nexys FPGA Board.

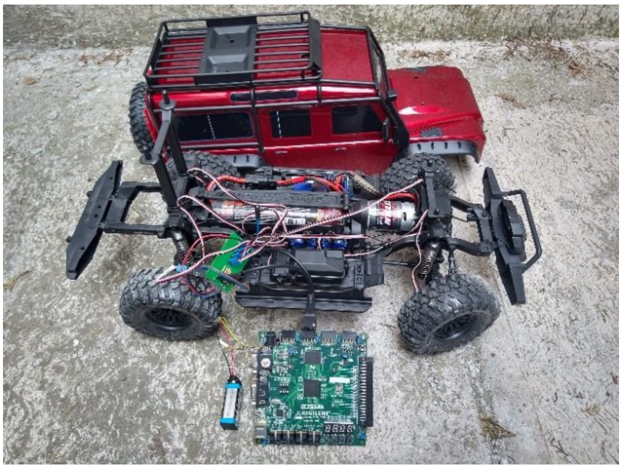


Figure 8 Traxxas TRX-4 and FPGA Board

Figure 9 shows the Traxxas vehicle with the FPGA and differential control system programmed during the test of the implemented system.

Figure 9 Traxxas TRX-4 with differential control system

3. RESULTS, CONCLUSIONS, AND FUTURE WORK

a)The automatic system was developed to configure the front and rear differential lockers based on a detection system considering differences if wheel speed conditions. Some vehicles have already sensors for sensing wheel and driveshaft speed, and if the vehicle has a manual locker installed, the automatic system could be used to help drivers in a difficult driving situation when the locking system is needed.

b)Some vehicles have only a rear differential manual locker, the system developed could be used without modification and just leaving unconnected de front differential actuator signal.

c)The system has simple but important visual aids (LEDs) for the detection system, the status of the front and rear locker actuator, and help the driver to know if he must stop or start the vehicle. Now it is a simple interface, but it could be a very sophisticated and impact view interface with more specific and detailed information.

d)The system is based on the detection system used in [7], using wheel speeds and in different test conditions. The detector should be verified and modified accordingly with the specific vehicle wheel and driveshaft speed sensing characteristics. It does not have the problem of some lockers that assume a locking situation from normal driving in corners.

e)The use of a Programmable Logic Device (PLD) as it is the FPGA, has the following advantages: i) the detection system works in parallel, ii) the system was developed using blocks, this methodology helps the designer in modifying only some blocks of the system accordingly with the vehicle intended to use.

f)The system includes protection to the mechanical locking parts, as it verifies and only makes the lock when the vehicle is in a stop condition, as the manufacturer established.

g)With the actual system, the driver must start and stop the pedal accelerator (in RC is a trigger) to let the system configure the locker accordingly with the road conditions, in the future, it is possible that the system control also the regulation of the accelerator to manage the interaction between the controller states.

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