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FPGA Implementation of Closed Loop Control of Pan–Tilt Mechanism

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Abstract : In automated surveillance systems with cameras, the system must be able to position the cameras accurately. The camera must be able to pan and tilt such that an object detected in the scene is in a vantage position in the camera's image plane and subsequently capture images of that object for further analytics kind of information. This paper presents the details of a Field Programmable Gate Array (FPGA) implementation of closed loop control of pan and tilt angles of the camera mount using servo motors as actuators and compact RIO from National Instruments as the controller. The controller is programmed using the LabVIEW FPGA software. The paper presents the details of the mechanical design, hardware specifications, modelling information and control information details. The main objective is to perform position and velocity control of pan and tilt axis motion is to get accurate position and velocity.

Keywords : FPGA, Real Time Control, Pan-tilt, Servo motor control, Modelling, Simulation.

1. INTRODUCTION

Pan-tilt head is a 2-axis mechanism which is often used in imaging system to keep an object of interest in the field of view of the camera. The position and velocity of the pan tilt head are very important parameters since they determine the field of view in the scene and also match the velocity of any moving object in the real world. The pan-tilt head finds application in surveillance, automated video recording and video analytics in general. Videos captured by manual adjustment of pan and tilt angles are often accompanied by frame drops. Motorizing the pan-tilt head reduces the risk of the camera operator introducing any jerkiness or vibration to the shot during a pan or tilt. In automated cases motorizing the two axis is the norm. Numerous literature is available in the context of control of pan-tilt especially related to visual tracking systems, automated surveillance, solar tracking, video conferencing, live production, lecture capture and distance learning and when attached with a sensor it is used to detect objects and for measurement of distance at various points by controlling the pan and tilt angles in robots among many others. Automatically controlling the pan and tilt angles removes the need for a camera operator as it pans and tilts as the subject moves. Cameras with motorized pan tilt head over stationary cameras has its advantage in that the field of view can be changed whenever necessary instead of the need for manual adjustment of the mounting angle. Cameras attached to motorized pan tilt heads offer the ability to capture footage at multiple angles and perspectives while surveying a wide range of territory. This paper presents the details of implementation of closed loop position and velocity control of two degree of freedom pan-tilt mechanism in Field Programmable Gate Array using LabVIEW as a development platform. The motorized pan-tilt head generally consists of two servo motors for pan and tilt motion. They are controlled using compact RIO 9074 controller with two 9505 servo motor drive modules from National Instruments. These modules give full H-bridge control of the DC servo motor. The cRIO controller is programmed using LabVIEW using LabVIEW FPGA package which helps create the hardware definition language code for

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the Xilinx FPGA on board the cRIO controller. The motors are controlled by generating a PWM signal to the motion control module and it is then translated to an analog voltage to command the motor. High accuracy and precise speed control can be achieved when the pan and tilt operations are controlled through the servo motor. The paper is arranged in the following order which starts from mechanical design details of the pan-tilt mechanism, followed by the modelling and simulation of the DC motor used in the pan and tilt axis, hardware specifications of the various elements used and finally the FPGA implementation.

2. MECHANISM DESIGN

The pan and tilt mechanism requires a rigid base and a mount for pan motor. A C-clamp is used to mount the pan motor and provide a support for the rigid base. Along with the pan motor, the limit switches are placed on the top surface of the clamp. A flange is used to link the tilt mechanism to the pan motor shaft. The tilt motor is mounted on the flange using L-clamp. The camera mount is fixed to the tilt motor shaft through a flange. The initial model was designed using flat plates but actual implementation is done using channels. The pan axis motor mount is shown in Figure 1.

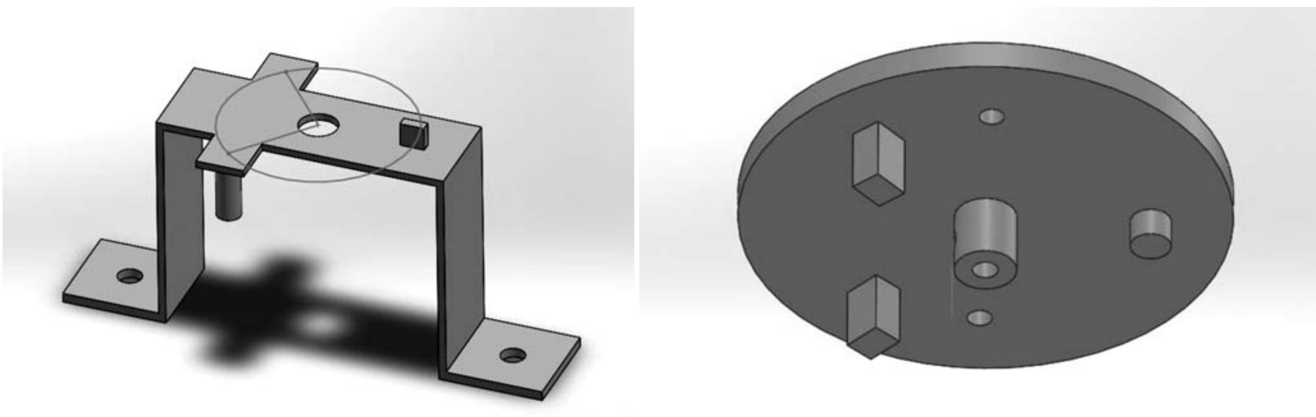

Figure 1: Pan Axis Motor Mount and Flange

The figure shows the support of the pan motor with the mechanical stoppage and extreme positions marked on it. It is attached to the structure base. The figure also shows the pan flange which is connected to the shaft of the pan motor. It shows the home position as well as the extreme positions extruded from it.

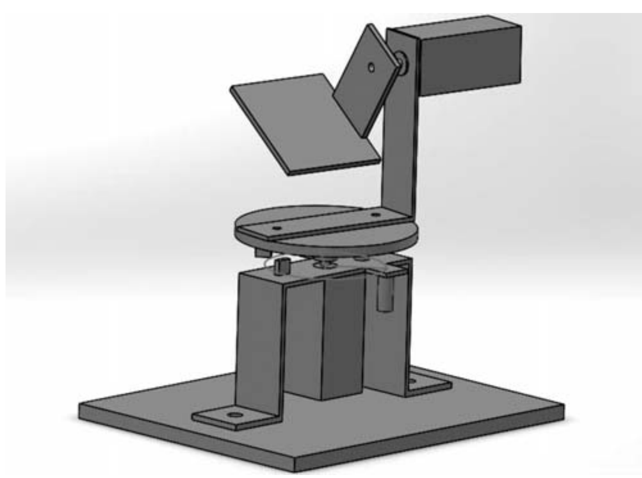

Figure 2: Complete Pan-tilt Mechanism

3. HARDWARE SPECIFICATIONS

The following section of the paper describes the various specifications of the pan-tilt setup developed.

3.1. DC Servo Motor

The pan and tilt axis are actuated by DC servo motors with quadrature encoders whose specifications are listed in Table 1. These motors feature extremely low inertia and zero cogging or preferred rotor position, as well as a uniquely high, power to volume ratio.

Table 1
Specifications of DC Servo Motors for Pan and Tilt Axis

Parameter	*Specification*
Type	Faulhaber 12V DC Coreless Motor
Gearbox Ratio	64: l Planetary 3 Stage Gear Box
Load Current	1400 mA
Power	17W
Speed	120Rpm
No Load Current	75mA
Encoder Type	Optical
Encoder Phase	AB
Encoder Resolution	768CPR of Output Shaft
Diameter	30mm
Length	42mm
Total Length	85mm
Diameter of the Shaft	6mm
Length of Shaft	35mm
Stall Torque	52 kg

3..2. cRIO 9074 Controller

The CompactRIO 9074 real-time controller consist eight-slot reconfigurable chassis into an integrated system. It has the ability to be synchronized on a network and also feature a built-in backup battery to maintain operation for the Real-Time Clock when external power is removed. The chassis can accept up to eight NI C Series I/O modules. A variety of I/O modules are available including voltage, current, thermocouple, RTD, accelerometer, and strain gauge inputs; up to ±60 V simultaneous sampling analog I/O; 12, 24, and 48 V industrial digital I/O; 5 V/TTL digital I/O; counter/timers; pulse generation; and high voltage/current relays. In the proposed system, a servo drive module and birectional digital modules are used in the chassis. The cRIO controller also have an Ethernet port that allows for programmatic communication over the network to a host PC or enterprise system and the other port for expansion I/O.

3.3. DC Brushed Servo Drive NI-9505

The NI 9505 C Series module for NI Compact RIO is a full H-bridge servo motor drive for direct connectivity to actuators such as brushed DC servo motors. This module includes a built-in encoder interface for single-ended or differential inputs for position feedback from a quadrature encoder. It also includes a current sensor you can use to sample the current through the motor, or actuator, and read it through the FPGA in the CompactRIO chassis. With functions such as trajectory generation and proportional integral derivative (PID) control featured in the NI SoftMotion Development Module for LabVIEW, it is possible to develop a complete reconfigurable motion control and drive system in a compact form factor with CompactRIO and LabVIEW and accurately control velocity and position of DC Servo Motor. The module supports real-time data acquisition from the current sensor for flexible sampling time and motor current filtering to optimize the control loop. The nine-pin D-Sub connector on the NI 9505 offers encoder input for position and velocity feedback in addition to a +5 V connection for encoder power and an emergency stop input.

3.4. B-directional Digital I/O NI-9403

The NI 9403 is a 32-channel, 7 μs bidirectional digital I/O module for NI Compact DAQ or CompactRIO chassis. The direction of each digital line on the NI 9403 can be configured to be an input or an output. Each channel is compatible with 5 V/TTL signals and features 1,000 Vrms transient isolation between the I/O channels and the backplane. In this work the NI 9403 is programmed using LabVIEW FPGA for interfacing CompactRIO with sensors. Figure 3 shows the illustrative photograph of the cRIO chassis and the C-series modules used in the developed system.

Figure 3: Illustrative Photographs of cRIO Controllers and C-series Modules

3.5. Optical Limit Switches

A slotted opto-coupler is used as a limit sensor for homing and over-travel control. Since the servo motors used are incremental encoder type, mechanical homing becomes the norm. It measures the physical quantity of light and then converts it into a form that is readable by 9403 module. When the signal is interrupted, the light sensor operates as a photoelectric trigger and therefore gives the electrical output. The pan motor and the tilt motor is rotated to home position by reading the optical switches. The Figure 4 shows the photograph of the complete system indicated with the various sub-system elements.

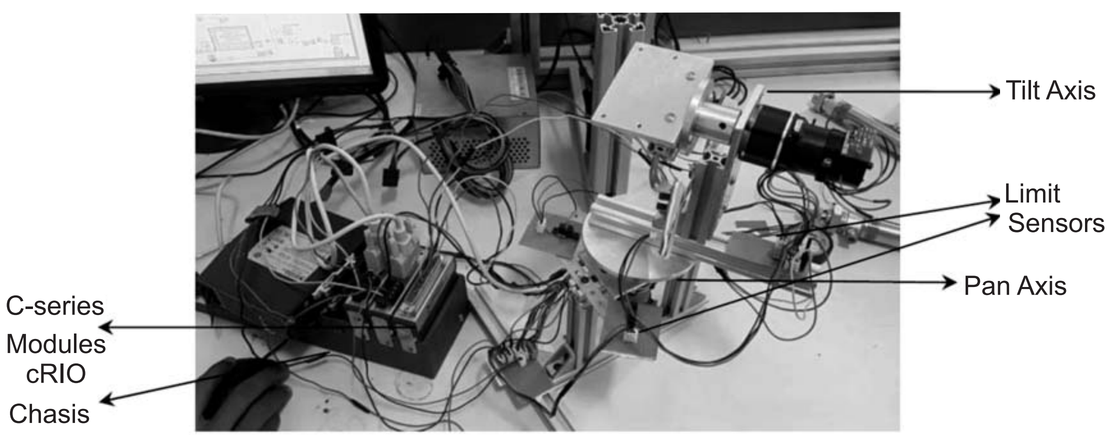

Figure 4: Photograph of the Complete System

The hardware connection diagram indicating the connection of the various sensors and actuators to the controllers and modules are shown in Figure 5.

4. MODELLING AND SIMULATION OF MOTOR

The pan-tilt mechanism is actuated by two identical DC motors. In order to perform a flawless control of position and velocity, thorough understanding of the system is required. A complete model based understanding of the motor is performed in the Simulink platform. The details of the mathematical model developments and simulation results are presented in the following section of the paper. The torque equation of the DC motor is given by [1]

$$K_T I = J\frac{d^2\theta}{dt} + Bd\theta \tag{1}$$

This equation can be written as

$$\frac{d^2\theta}{dt^2} = \frac{k_T - Bd\theta}{J} \tag{2}$$

The current equation of the DC motor is given as

$$v = IR + L\frac{dI}{dt} + k_B\omega \tag{3}$$

This equation can be written as

$$\frac{dI}{dt} = \frac{1}{L}\left(v - k_B\frac{d\theta}{dt} - IR\right) \tag{4}$$

The differential equation can be simulated with armature voltage as input and position and velocity as output.

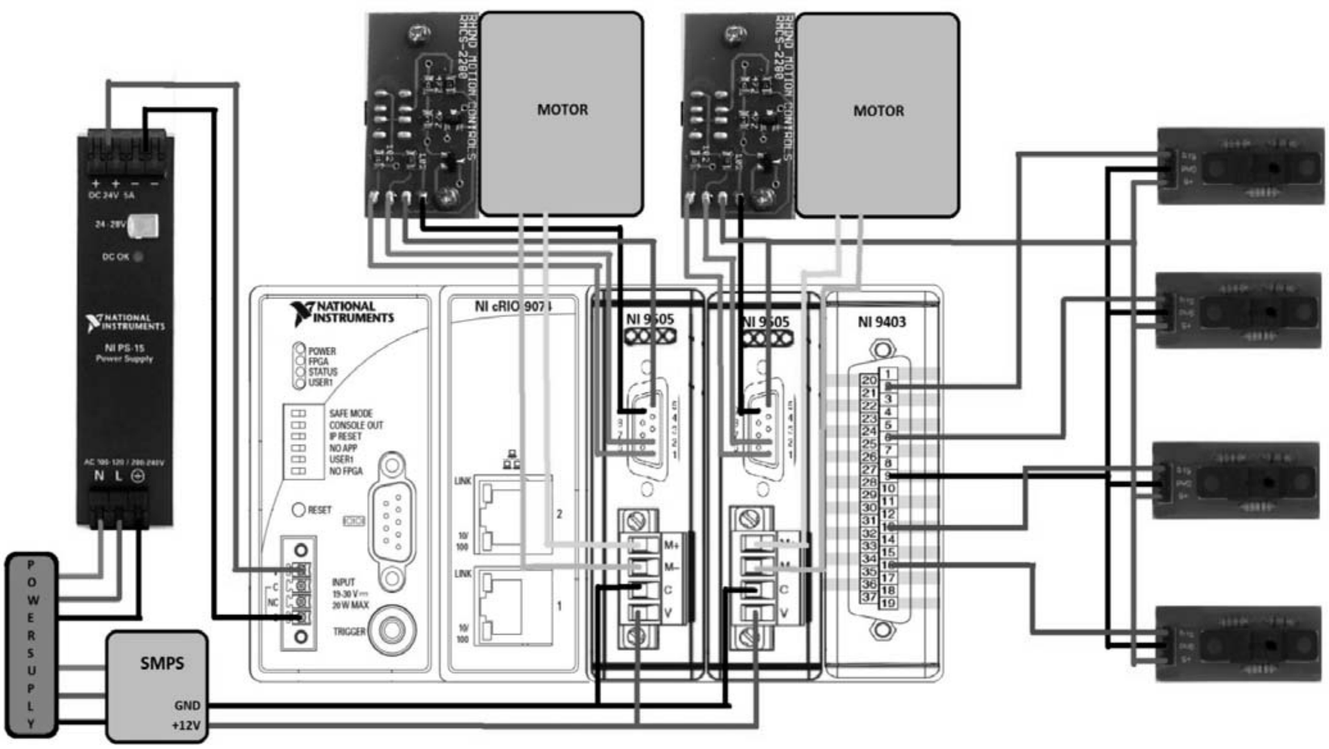

Figure 5: Hardware Connection Diagram of the Proposed System

The parameters of the Faulhaber DC motor acquired from the datasheet are as follows:

Table 1

Specifications of DC Servo Motors for Pan and Tilt Axis

Parameter	*Specification*
Resistance	1.9 Ω
Inductance	65 μH
Back-emf Constant	1.4 mV/rpm
Torque Constant	13.4 mNm/A
Rotor Inertia	5.7 gcm^2

Now, the state variables are $x_1 = \dot{\theta};\ x_2 = \ddot{\theta};\ x_3 = \dot{I}$ (5)

The state equation is given by [2] $\dot{x} = Ax + Bu(t)$ (6)

when substituted with values
$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-B}{J} & 0 \\ 0 & \frac{-k_B}{L} & \frac{-R}{L} \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \\ I \end{bmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{V}{L} \end{pmatrix} u(t) \quad (7)$$

The Simulink model of the differential equation is shown in Figure 6:

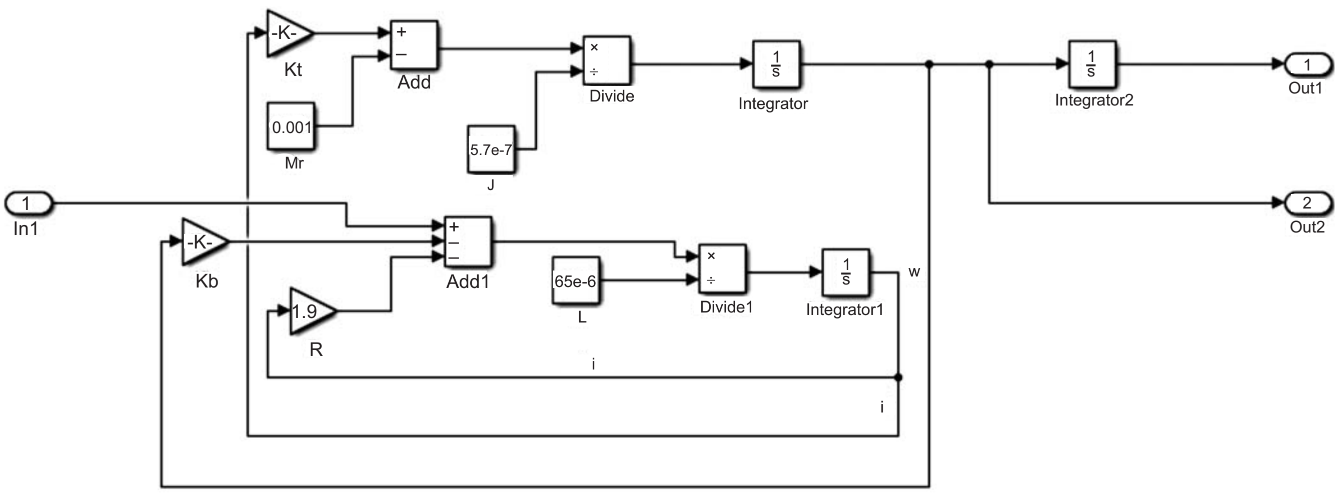

Figure 6: Simulink Model of the DC Motor

Thesimulation results shows the time plot of the shaft position and speed of the DC motor for a applied voltage is shown in Figure 7. The plot is basically a step response graph for the position and velocity.

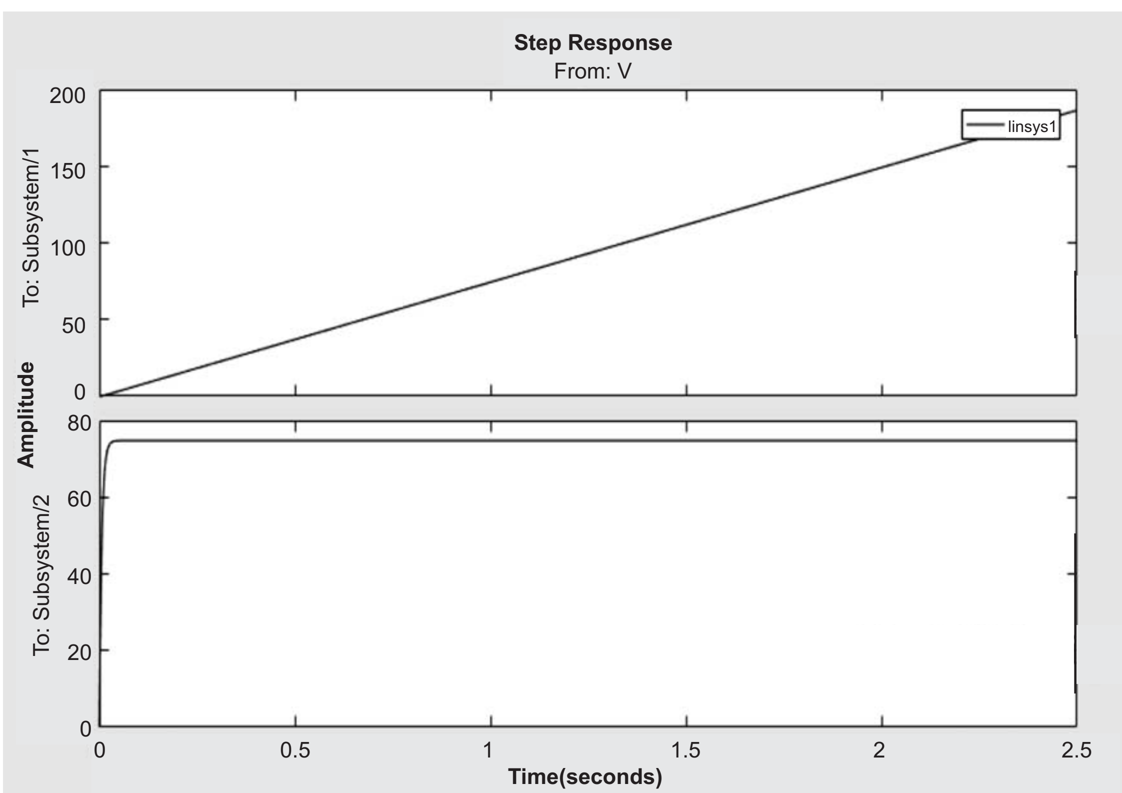

Figure 7: Time Plot of Position and Velocity

The output equation is given by $$y = Cx + D \tag{8}$$

The transfer function can be obtained by using

$$y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \\ I \end{bmatrix} \tag{9}$$

The obtained transfer function for velocity control is [3]

$$C \cdot [sI - A]^{-1}. B \tag{10}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-B}{J} & 0 \\ 0 & \frac{-k_B}{L} & \frac{-R}{L} \end{bmatrix} \quad B = \begin{pmatrix} O \\ O \\ \frac{V}{L} \end{pmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \tag{11}$$

The obtained transfer function for the position control is given by

$$TF = \frac{3 \cdot 8 * 10^8}{s^3 + 2 \cdot 9 * 10^4 s^2 + 4 \cdot 8 * 10^6 s} \tag{12}$$

The transfer function for the velocity control obtained from the model is given by

$$TF = \frac{3 \cdot 617 * 10^8}{s^2 + 2 \cdot 293 * 10^4 s + 4 \cdot 837 * 10^6} \tag{13}$$

The transfer function for the position control obtained from the model is given by

$$TF = \frac{3 \cdot 617 * 10^8}{s^3 + 2 \cdot 293 * 10^4 s^2 + 4 \cdot 837 * 10^6 s} \tag{14}$$

5. FPGA IMPLEMENTATION

Many PC based control of DC servo motors have been reported in the literature [4, 5]. In the current work, desired pan and tilt angles are kept as set points in the LabVIEW front panel. A proportional control is developed which uses the present error between the actual pan- tilt angles with the desired angles. Then the motors are rotated accordingly in order to obtain the desired pan and tilt angles. LabVIEW FPGA software module is used to read the quadrature signals and write drive signals to the 9505 C-series module for motor drive. Direct FPGA I/O read method is adopted since the algorithm is meant to run in the FPGA of the cRIO and not in the real time controller. The LabVIEW code is a graphical implementation of the control algorithm to control the inputs given to the pan and tilt motors. The encoder signals are received and converted into incremental values. Since a 12 CPR encoder is used and the speed reduction is ratio 64:1 there are 3072 pulses for each rotation of the output shaft. The desired angle is also converted to equivalent count value assuming a 12CPR encoder. This value will be compared with the encoder value obtained from the encoder feedback. And the position control is achieved. The direction of rotation is given by the sign of the input angles. For velocity control the power input given to the motor is given in the form of Pulse-Width Modulated (PWM) signals. The LabVIEW graphical code is developed for the position and velocity control are shown in Figure 8.

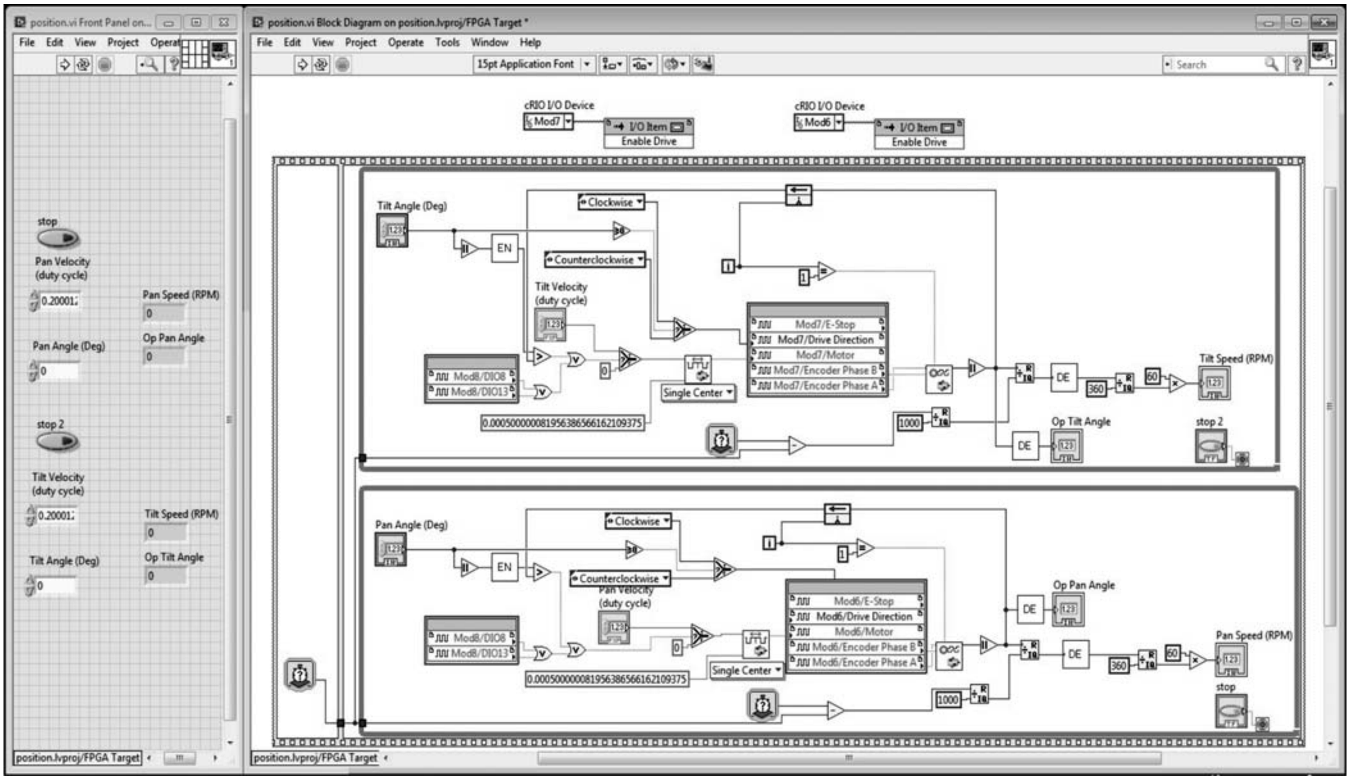

Figure 8: LabVIEW code for position and velocity control

6. CONCLUSION

The developed setup can be further used in the field of visual tracking, which is the original intent for the development of the proposed work. It is the field which combines results from many fields like imaging, high speed image processing, real time computing. The performance of the visual tracking system relies the effectiveness of he motion control system. The FPGA implementation exhibited highly consistent results in terms of the time performance, though from accuracy standpoint lapses were noticed due to the asymmetry in the encoder wheels used in the motors. The FPGA implementation has one of the significant advantage of zero computational overheads ensuring a true real time performance. This is mainly attributed to the no software used in the control such as operating systems or assembly codes. The future work in the project is to integrate a vision system with motion control for performing a visual tracking of moving objects in the field of the camera attached to the pan-tilt system developed.

7. REFERENCES

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