FPGA Implementation of a Satellite Attitude Control using Variable Structure Control

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***Abstract*— Satellite control systems are operating tens of thousands of kilometers from the earth where reliability, power consumption, and weight are very important factors in the design of such systems. In this paper, we present an FPGA implementation of a Variable Structure Controller (VSC) for a satellite. Our implementation uses fixed point representation instead of a floating point representation of numbers in order to save chip area and power consumption. We compare our implementation for different word-length vs. floating point implementation from the chip area and power consumption points of view as well as the performance (how fast the system stabilizes). We show that using a number of bits in the range of 9-15 bits with the model we used results in less energy and produce results that are very close to floating point numbers. We implement our design using Xilinx Nexys 3 board and Spartan-6 XC6SLX16 chip.**

I. Introduction

Control of position and attitude of a satellite is one of the most important aspects in the operation of satellites. On-board control system is assumed to control the satellite position and attitude with minimum interfering from ground control. Reliability is extremely important since there is no chance of bringing the system down to earth for repair. Also, power consumption and size are very important since the satellite on-board computer is responsible of controlling the satellite main mission and controlling the satellite position and attitude. A smaller attitude controller means that we can share the same chip among many tasks thus; reducing the weight and power consumption of the satellite.

Failure to properly control the satellite can lead to disastrous results. NASA's earth orbiting Lewis Spacecraft lost contact with ground control within few days after launch. It reentered atmosphere and was destroyed in less than a week after launch. NASA investigators concluded that the failure was mainly due to an error in the attitude control system [10], [11]. Another major failure is the loss of GPS BII-07 spacecraft due to stabilization problems [16]. For more information about major failures due to loss of control the reader is referred to [16]. In the following few sections, we briefly review the use of variable Control Structure (VCS) in satellite control. We also review the use of FPGA for on-board satellite control.

Inalhan, Tillerson, and How in [8] studied formation flying, and presented an algorithm for the initialization procedure for a large fleet of vehicles in an eccentric reference orbit.

The author in [4] developed a nonlinear uncertain Geostationary satellite model, then he simplified it using a linearized model with small angle deviations assumption. He also presented a robust VSC with sliding mode controller for attitude control. Simulation results show the effectiveness and reliability of the controller for damping out any deviations.

The authors in [7] presented a survey of VSC with sliding mode. They also discussed the advantage of using VSC for both linear and nonlinear systems such as its robustness and order reduction.

The authors in [20] derived an attitude-stabilizing control law in order to enforce the control authority of the system. Their controller could be viewed as a smooth analog implementation of the variable structure control technique. They also used simulation to show that attitude error can be reduced to zero with the proper choice of the design parameters. They also presented guidelines for the choice of the design parameters.

In [6], the authors presented a study of the attitude of a 3-degrees of freedom of a pico-satellite model incorporating uncertainties in both sensor data delay and actuator misplacement. They also used fuzzy variable structure controller (FVSC), that integrates the FC (fuzzy control) and VSC (variable structure control) techniques, and show its effectiveness and performance under model uncertainties that are mainly time delays in sensor systems and actuator misplacement. Additionally, three controllers are designed to compare performances with FVSC, these are: classic proportional-derivative (PD)-type controller, the second is a linear quadratic Gaussian (LQG) controller, and the third is a robust loop shaping controller (LSC).

In [14] the author studied the human operator modeling to explain the response characteristics of a dynamic system including manual controller. Then VSC techniques are used to model human operator behavior during acquisition tasks. They evaluated the performance of their strategy by considering several examples such as the longitudinal control of an aircraft during the visual landing task.

In [17] the authors presented an efficient design of an FPGA-based software defined radiation tolerant baseband module for a LEO satellite telecommand receiver. They used a combination of reduced precision redundancy and triple module redundancy in order to mitigate the effects of a single event upsets. Their approach uses 26% less power compared to triple modular redundancy.

A modular FPGA-based software defined radio is proposed in [12]. The author used FPGA to implement an adaptive digital communication system using the Universal Software Radio Peripheral (USRP) as a base. The author goal is to build a plug-and-play software defined radio to be used with CubeSat satellite.

In [1] the authors presented an FPGA implementation of a sine/cos calculator using CORDIC algorithm for use in the attitude determination calculation of a *femtosatellite*. They used a very small lockup table which translated into a very small memory requirements on the FPGA.

In [15] The authors presented an FPGA-based implementation for synchronization of data-aided as well as non-data-aided synchronization. They illustrated the use of their design by applying it to a satellite communication waveform DVB-S2.

In [3] the author applied VSC controller to attitude control of Geostationary satellite. MATLAB algorithm is developed to simulate the model and controller, then the derived SIMULINK model shows the same response of deviation damping and correction. Due to the geostationary satellite model type, its maneuvers, disturbances and its environment of launching and operation, all these factors lead to non-linearity and uncertainty of the model and its parameters. Satellite moment of inertia (MOI) Parameter estimation methodologies have been used to overcome this uncertainty problem.

The authors in [22] Implemented an FPGA-based controller for attitude control for a micro satellite. Their goal is to keep the satellite in a safe mode with reduced functionality in case of an anomaly in the software or hardware. The satellite is kept in a safe mode until the error is analyzed and fixed.

In [13], the author implemented a controller for maximum power point tracking in order to maximize power conversion on satellites using FPGA. Their design is more flexible and cheaper to implement than a comparable microcontroller or DSP-based design.

In [2] the authors implemented a flexible telemetry, tracking and command transponder for earth observation small satellite. Their system is capable of data transfer up to 40 Mbps. Their system consists of signal processor and a control processor with SpaceWire and CAN interface. They also implemented their design on a Xilinx Virtex chip.

In this paper, we concentrate on the efficient FPGA-based design and implementation of a variable structure controller for a geostationary satellite. We use fixed point implementation in order to minimize the chip area and power consumption. Fixed point implementation results in a loss of accuracy. We investigate the effect of word length on the stability of the controller compared to a standard IEEE754 single precision floating point representation. We also compare the power consumption and the chip area of floating point implementation vs. variable size fixed point implementation.

We summarize our contribution in this paper as follows

- We present a VSC controller for satellite attitude control.
- We characterize the effect of the word size on the performance of the VSC controller. We show that we can achieve almost identical results to a floating point implementation using fixed point representation.
- We present an efficient fixed point implementation of the Variable structure controller using FPGAs.

The organization of the paper is as follows: Section II presents the problem definition and how we choose to solve it. Section III describes the controller design. Section IV reviews the use of FPGA. Section V presents our implementation of the controller using fixed point representation on Xilinx Nexys-3 board using Spartan6 XC6LX16-CS324 FPGA chip. Section VI presents our results on the chip area, power consumption and performance metrics using both floating point implementation and fixed point representation. Section VII is a conclusion and future work.

II. Problem Definition

The problem stated as, the control of a geostationary satellite. the Nonlinear Geostationary Satellite model is uncertain model need to be controlled against any deviations, its dynamic equations are studied based on Euler's Momentum Equation, the sum of applied torques on satellite body = the rate of change of total angular momentum of the satellite (principle of angular momentum conservation).

Disturbances may cause changes in the satellite attitude. When that happens, the satellite maneuvers in order to correct and return to its prespecified attitude, that causes fuel and power consumption. The main job of the controller is to maintain the satellite in its correct orbit and attitude, and return back once it suffers any disturbance with minimum of time and energy.

The equations of motion are derived where the torque is used as an input and angles and angular velocities as outputs. Full nonlinear equations of motion for that satellite model will be linearized with respect to its equilibrium point [3], which is the normal operating point and with small angles maneuvers assumptions. Equations for roll and yaw motion are decoupled from those for pitch motion. Linearization of satellite model is performed based on small angles of deviations that leads to $\sin(\phi) = \phi$ and $\cos(\phi) = 1$ and assuming symmetry of moment of inertia, then the resultant re-arranged linear model is as follows [9]:

$$\dot{x} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{h_w n}{I_x} & 0 & 0 & -\frac{h_w}{I_x} \\ 0 & -\frac{h_w n}{I_y} & \frac{h_w}{I_y} & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ \frac{m_y b_z}{I_x} \\ \frac{m_x b_z}{I_y} \end{bmatrix} u \qquad (1)$$

Where u is the input, and x is the state vector x=[yaw angle, roll angle, yaw rate , roll rate]. The parameters and constants are defined in Table I.

TABLE I
SYSTEM CHARACTERISTICS PARAMETERS

Moment of Inertia	$I = diag[1989, 1876, 407]\ kgm^2$
Wheel angular momentum	$h_w = 53.66\ kgm^2\ /\ sec$
Magnetic moment vector	$m = [257.419, 154.062, 0]^T\ atm$
Magnetic field vector	$b = C[0, 0, 6.86157]^T\ tesla$

III. CONTROLLER DESIGN

In this paper, we apply VSC for satellite attitude control of a geostationary satellite. VSC systems comprise a collection of different, usually quite simple, feedback control laws and a decision rule that's designed to force the system states to reach a prespecified surface, and subsequently remain on, a predefined surface within the state-space, depending on the status of the system. The dynamic behavior of the system in order to reach the switching surface is called the *reaching mode*, while the dynamic behavior of the system when confined to the surface is named the *ideal sliding motion mode*.

The required accuracy of a geostationary communication satellite may be achieved by torque due to thruster, momentum wheel, magnetic torquer and so on. Magnetic control is a favorable way to stabilize Satellite, despite of the fact that magnetic torque is weaker than that using thruster or control moment gyro. The magnetic control is clean and does not consume valuable fuel, in addition to simplicity and lightweight of its hardware. Another major advantage of the magnetic torque is that it does not change of mass of the satellite over time. The controller design [3] is as follows:

the switching service is defined as

$$s = c.x \tag{2}$$

The switching surface vector is

$$c = [10^{-7}\ \ 10^{-6}\ \ 8 \times 10^{-4}\ \ 10^{-3}] \tag{3}$$

and the conrntrol input is calculated as

$$u = \frac{-x * a * x}{c * b} - k * sign(s) \tag{4}$$

Figure 1 shows the yaw response input, roll rate, and yaw rate response

The deviation used in the simulation is $x = [0.5\ \ 0\ \ 0\ \ 0.002]$

IV. FPGA IMPLEMENTATION

FPGA (Field Programmable Gate Array) is a programmable logic device where the user can configure the hardware in the chip to perform many logical functions. The cost of FPGA-based design is much cheaper than ASIC design (provided we are not talking about large production in millions of units). The time to market is also much faster for FPGA-based design. These factors combined with the ease of reconfigurability made FPGA-based design a very attractive solution for design that are not manufactured in very large numbers, and that is certainly the case for satellite attitude control.

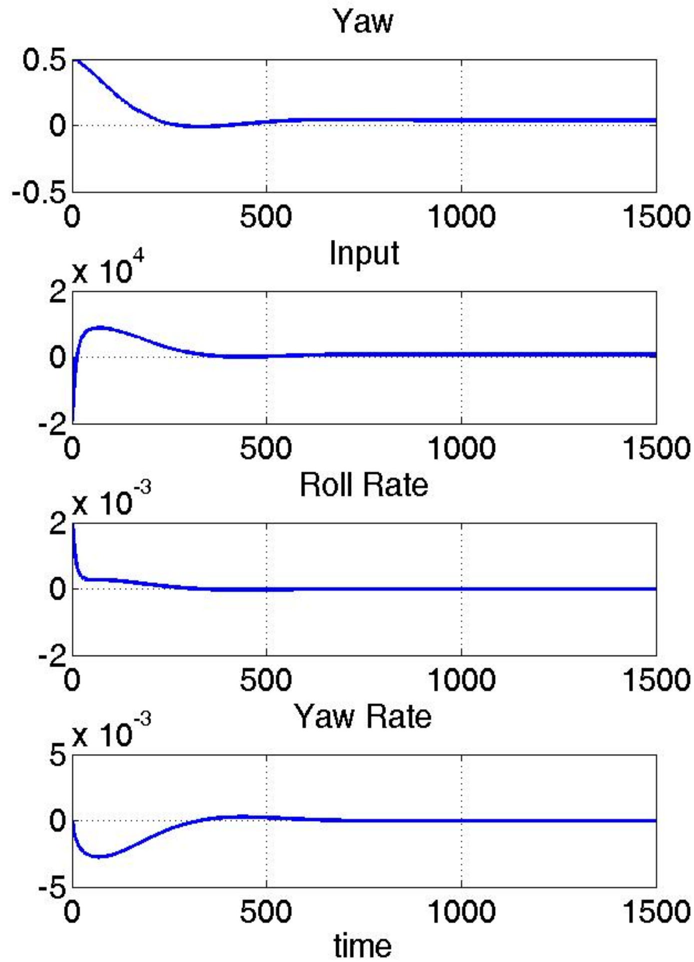


Fig. 1. System Response using floating point implementation

FPGA's are used in many areas such as communication devices, embedded systems, digital signal processing and many other areas for both prototyping and production. FPGA's have made huge strides in the field of reconfigurable computing especially with reconfigurability (reprogramming) being done in real time.

With today technology, FPGA chips includes softcore and sometimes hardcore processor [21]. This makes it very attractive for System on Chip (SoC) design. In such a design, the work is divided between the on-chip processor, and the on-chip FPGA resources, This is very useful especially for applications that is not amenable to direct hardware implementation.

However, FPGA's are not a *panacea* for every design. FPGA-based systems consumes more chip area, and consume more power than equivalent ASIC design. But, with the cost of designing ASIC chips running in the millions of dollars, FPGA have proved itself to be a powerful player even in fields where there is market for millions of devices.

As mentioned before, FPGA-based design has found its way in many embedded control applications. In satellite control FPGA-based systems are widely used since the market is very small (compared to consumer electronics for example) and small reconfigurable systems saves a lot of weight and power consumptions which are very important criteria for satellite depending on solar panels for power and very limited space and weight requirement. We have already reviewed FPGA in satellite control applications in section I.

The FPGA is suitable for compute intensive application such as DSP application that require a huge computation power. This is not the case for satellite attitude control. The sampling rate here in the rang of hundreds of milliseconds. That does not require huge computation power. However, our goal is to use the FPGA chip that is most probably are there for other application for satellite attitude control. Thus performing the attitude control for free (from the hardware resources point of view) and with minimum energy consumption.

In this paper, we implemented the above controller using fixed point representation on a Xilinx Spartan6 XC6LX16-C324 chip on a Digilent Nexys 3 board [5]. Our design is compared to fixed point implementation in the next section.

V. Fixed Point Implementation

Most signal processing and control algorithms are implemented on MATLAB using double precision floating point arithmetic. Then, if the double precision is not needed, converted to single precision arithmetic and implemented on microcontrollers, DSP, or FPGA. The IEEE 754 standard floating point is represented by three parts s, e, b. A normalized standard representation of x is

$$x = (-1)^s \times 1.m \times 2^{e-b} \tag{5}$$

where s is the sign bit, m is the mantissa (23 bit for single precision numbers), e is the excess exponent (8 bits for single precision numbers), and b is a constant bias (127 for single precision numbers) for a total of 32 bits. this lead to a compact representation with a very large range.

The above standard representation is used almost exclusively in all desktops and laptops computers. The multiplication and addition of standard floating point numbers are rather complex operation. Especially for addition, where we have to convert the two numbers to a common exponent, perform the addition and then normalizing the number through shifting. For small embedded calculations, and when the accuracy of floating point number are not needed, we can use a simpler *fixed point representation* in **Qm.n** format.

The Qm.n format for N-bit binary number consists of 2 parts separate by an implied binary point. The left most m bits is the 2's complement representation of the whole number. The fraction part is represented by the n rightmost bits. An implied binary point separating the 2 parts (note that $m + n = N$). For example the Q2.3 number 01011 means 01.011 and is equal to 1 + 0.25 + 0.125 = 1.375.

The value of a the Qm.n number
$b_{m-1}\ b_{m-2}\ \ldots\ b_1\ b_0\ b_{-1}\ b_{-2}\ \ldots\ b_{-n}$ is

$$-b_{m-1}2^{m-1} + b_{m-2}2^{m-2} + \cdots + \\ b_1 2^1 + b_0 + b_{-1}2^{-1} + b_{-2}2^{-2} + \cdots + b_{-n}2^{-n} \tag{6}$$

The advantage of the fixed point format is although it represents real numbers but it is stored and operated on just like binary integer numbers which saves a lot of hardware and time in performing arithmetic operations. The disadvantage is the range and precision of the number to be represented is smaller than floating point representation with the same number of bits. For applications with limited range, and there is no requirements for the precision presented by the IEEE754, the fixed point representation is an ideal representation.

We simulated the same controller using Q3.12 in 15 bits format using Matlab. The following few Figures show the system response for both floating point and fixed point representation. Figure 2 shows the yaw response, Figure 3 shows the input, Figure 4 shows the yaw rate response, and Figure 5 shows the roll rate response using both floating point and fixed point representation.

Figure 3 shows the input u to the system. The input is completely different between floating point and fixed point representation. Since the input is not one of the system controllable states, it does not make any difference if the two inputs are identical or not. As a matter of fact, the input in the case of fixed point representation is much less then the input of the floating point representation That means saving fuel if fuel is used to correct the attitude. This is partially by design, since we allowed only three bits for the integer part of the response which limits the input to ± 4. However, even when we increase the number of bits representing the integer part, we still get much less input in case of fixed point compared to floating point numbers.

The Figures show that for a 15 bit fixed point representation, the response is almost identical to the floating point representation. One important aspect here that is worth of discussion is the point by point comparison of the 2 responses yields considerable differences. We argue that this is not important from the control point of view. For example, consider these two responses of a controller that takes an error value of 1 to the value 0, the first is
$R1 = [1\ 0.9\ 0.5\ 0.3\ 0.1\ 0\ 0.1\ 0\ 0.1\ 0\ 0.1\ 0]$ The second is , $R2 = [1\ 0.9\ 0.6\ 0.4\ 0\ 0.1\ 0\ 0.1\ 0\ 0.1\ 0\ 0.1]$.
A point by point comparison to calculate the difference between these 2 sequences leads to a considerable difference. However from the control point of view, these 2 controllers are identical. In both cases the system state changes from 1 to the range [0.0 0.1] in 4 clock cycles, and stays in the range [0.0 0.1] for a very long time after that.

VI. Comparison

Now, we investigate the effect of word length in fixed point implementation on the system response. Because of the space limitation, we show only the yaw response as a function of total number of bits. However, the rest of the states have a

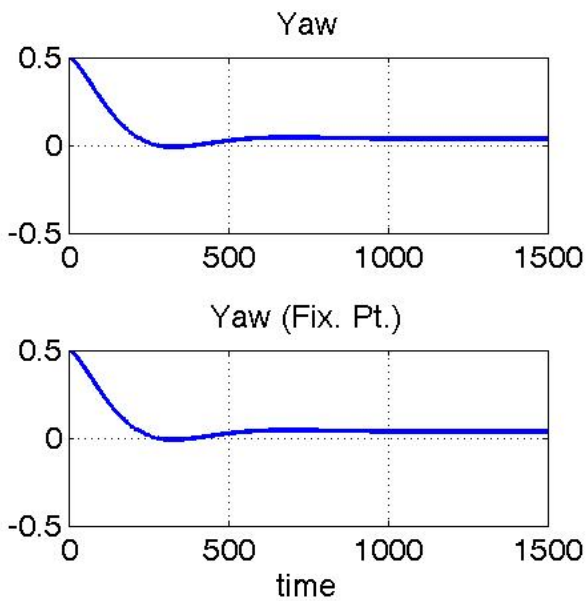


Fig. 2. Yaw Response

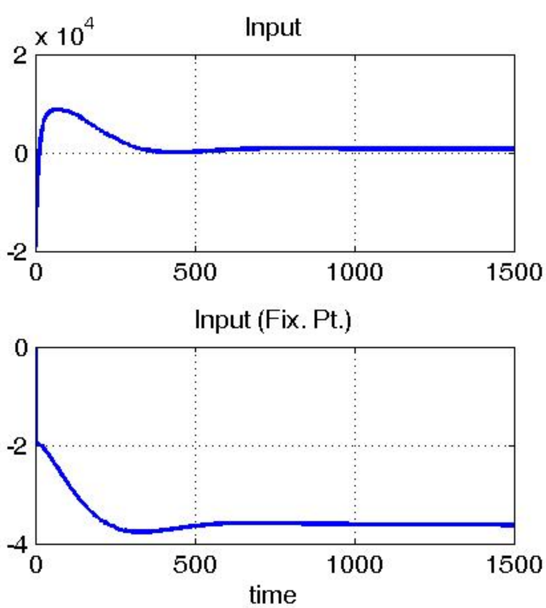


Fig. 3. Input

similar behavior. Figure 6 shows the Yaw response for Q3.9, Q3.6, and Q3.3. We note that the response is identical for these three values. We are not sure if that is because of the particular problem we are solving, or because of the VSC, but that is a topic for further investigation.

The proposed controller is implemented in FPGA using Xilinx Spartan-6 FPGA (XC6SLX16) [21] and implemented on Nexys-3 board [5]. In our implementation we implemented only the controller on Spartan-6 chip FPGA. Our objective is to compare between a standard floating point implementation using Xilinx IP and our proposed implementation from the power consumption and chip area point of views.

The resources and energy used by the two implementations

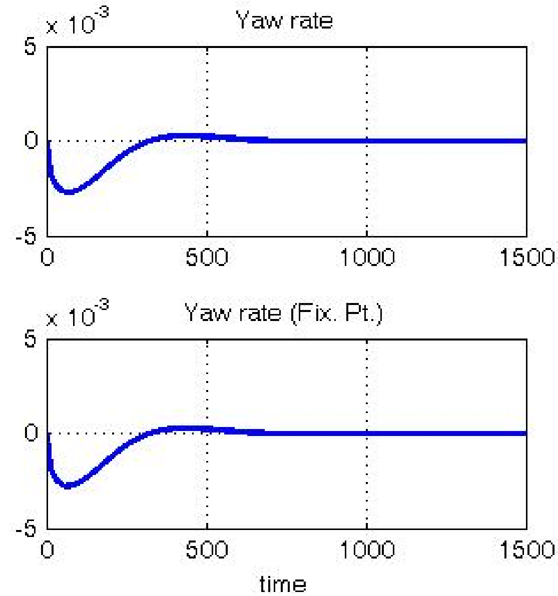


Fig. 4. Yaw Rate Response

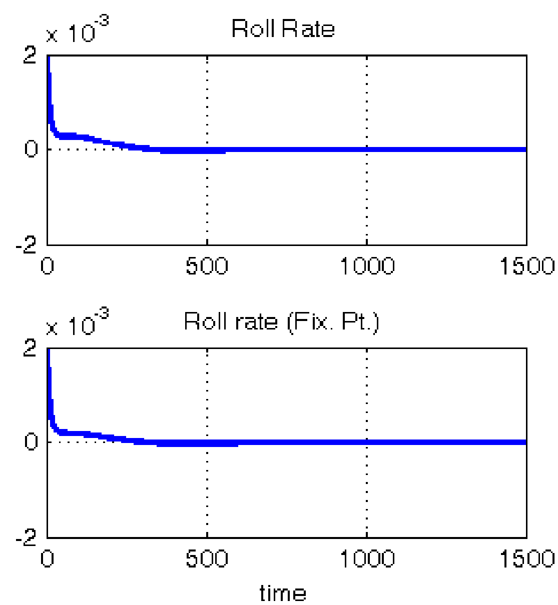
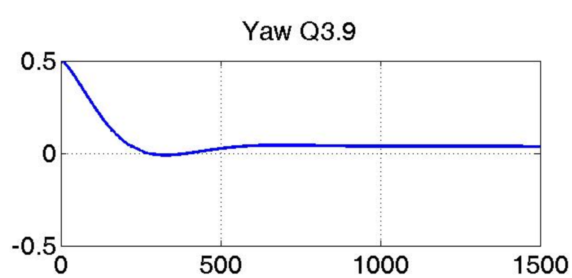


Fig. 5. Roll Rate Response



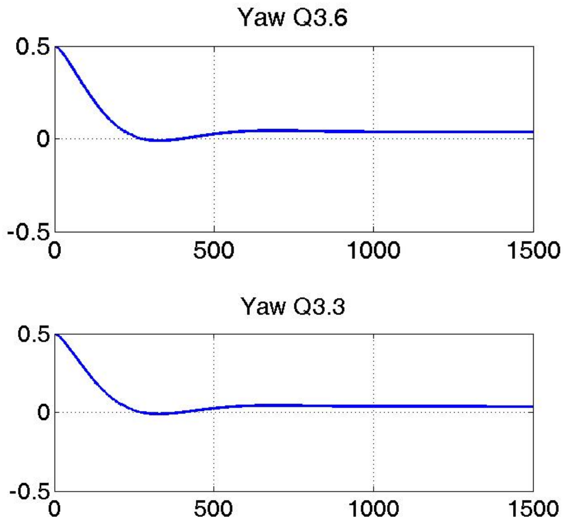


Fig. 6. Yaw for different vallues of Qm.n

are shown in Table II. While there is a slight advantage in energy consumption, There is a huge difference in the hardware resources. For example the number of slice LUTs vary by more than one order of magnitude between floating point implementation and Q3.6.

For the power consumption, we used Xilinx Power Analyzer (XPA) after place and route (ISE 14.4). The input is a random sequence of numbers. We generated vcd file from the simulation and used it as an input for XPA.

VII. Conclusion and Future Work

In this paper we presented an implementation of a VSC controller for satellite attitude control. We show that by using fixed point representation instead of floating point representation we can use much less resources in the chip and slightly less energy consumption without sacrificing performance.

We plan to extend our work to implement a hardware emulator for the satellite. That will allow us to implement the emulator and controller on the same chip and also allow us to study the delay and jitter effect on the performance of the controller.

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TABLE II
Comparison between Floating point and fixed point implementation of the controller

Metric	Q3.12	Q3.9	3.6	Floating Point
Slice registers	44	36	30	79
Slice LUTs	111	84	57	1088
Occupied slices	34	28	20	366
MUXCYs	116	92	60	688
Power (mW)	27	26	24	32

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