

# CprE 488 – Embedded Systems Design

## MP-1: Quad UAV Interfacing

**Assigned:** Monday of Week 4

**Due:** Monday of Week 6

**Points:** 100 + bonus for automated flight and advanced diagnostics

*[Note: the goal of this Machine Problem is for you to work with your group to increase your exposure to three different aspects of embedded system design:*

1. *Interfacing – you will reverse engineer an RC transmitter to gain an understanding of the trainer interface and format.*
2. *IP core design and integration – you will use the Xilinx tools to generate an AMBA AXI4-compliant IP core that you will integrate into an existing XPS project.*
3. *Finite State Machine design – you will design and implement an FSM-based hardware module to record and transmit PPM data.*

**1) Your Mission.** Jeff Bezos believes that within a few years' timeframe, Amazon will have Unmanned Aerial Vehicles (UAVs) deliver packages right to your doorstep. What could possibly go wrong with his vision, right? As a newly-hired engineering intern at a rival e-commerce company, you have been tasked with discovering spectacular answers to this question!

There are significant complexities involved in building a system for autonomous flight, as it requires solving challenges in multiple engineering domains, including image and signal processing, controls, and real-time embedded systems. Fortunately, as a fresh intern your only task (for now) is to design an interfacing and control platform for a simple quadcopter UAV and demonstrate its effectiveness.

**2) First Flight.** An RC quadcopter is a 4-rotor helicopter with motors that spin in counter-rotating pairs to create a downward thrust while canceling out rotational inertia, with two rotors spinning clockwise and two spinning counter-clockwise. We are using the Mini Fly QuadCopter ARF system which has a MultiWii Controller (MWC)



board and weighs only 325g. Quads of this scale are typically powered by a Lithium polymer (Lipo) battery and are controlled via a wireless transmitter / receiver pair.

Transmitters come in various configurations – ours is a Hobby King 2.4 Ghz 6 channel mode 2 transmitter. In mode 2, the left stick controls thrust (up-down) and yaw (left-right), and the right stick controls pitch (up-down) and roll (left-right). After a brief orientation from the TA, spend 5-10 minutes gaining some familiarity with quad flight. **In your writeup, describe your experiences in practicing controlling the quad.** Please keep the following considerations in mind when flying the quad:

- **Safety** should be your primary concern. Use the open space in the back of the lab to fly the quad, and make sure it is tethered safely to the ground at ALL times.
- The quads will only fly well when the **batteries** are completely charged. We have plenty of spare batteries and chargers, so just make sure you disconnect your battery from the quad and plug it into a charger when you're done. Note that these Lipo cells can produce a decent amount of current, so don't short-circuit or connect them to the chargers backwards.
- Did I mention **safety**? Do not fly the quad when students are walking nearby, do not hold them in your hand when they are activated, and in general respect the speed in which the propeller blades can spin. Learn from Frankie below!



*Figure: former CprE 488 student Frankie Four-Fingers after his unfortunate quadcopter incident*

- Start out **slowly**. We have spare blades and other parts, but our general rule is if you break it, you fix it.

**3) Trainer Port.** As is common in the RC world, our Hobby King transmitters have a trainer port on the back, which uses a 3-pin serial interface to transmit the Pulse Position Modulation (PPM) data that was described in the HW-1. A typical usage scenario of a trainer port is to have two people share control of an RC aircraft: the input (student) transmitter directly sends PPM data over the trainer port to a second output (instructor) transmitter, which copies this data over the RF link to the receiver on the aircraft.

See the illustration below – the intention behind this configuration is that the student can practice flying the aircraft while the instructor can take back control at any time.



*Figure: your two TAs illustrating RC flight in a trainer configuration*

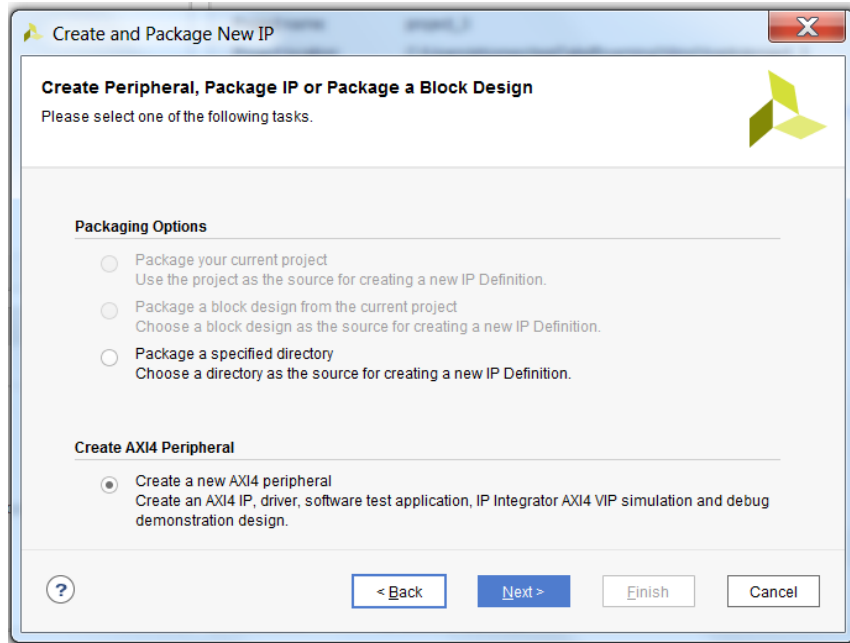
Using the supplied cable, connect the trainer port of your input transmitter to an oscilloscope, and in your writeup, describe the PPM signals. What do each of the channels correspond to, and what are their minimum and maximum ranges? What is the total length of the individual PPM frames, and what is the minimum length of the idle pulse?

For our purposes, we will be using the ZedBoard as an intermediate processing step between a pair of student and instructor transmitters, and will be connecting the trainer ports directly to PMOD pins on the ZedBoard. Based on the ZedBoard documentation and your oscilloscope measurement of the trainer port, what concerns do you have about making this connection? Be specific, and confirm with your TA before continuing.

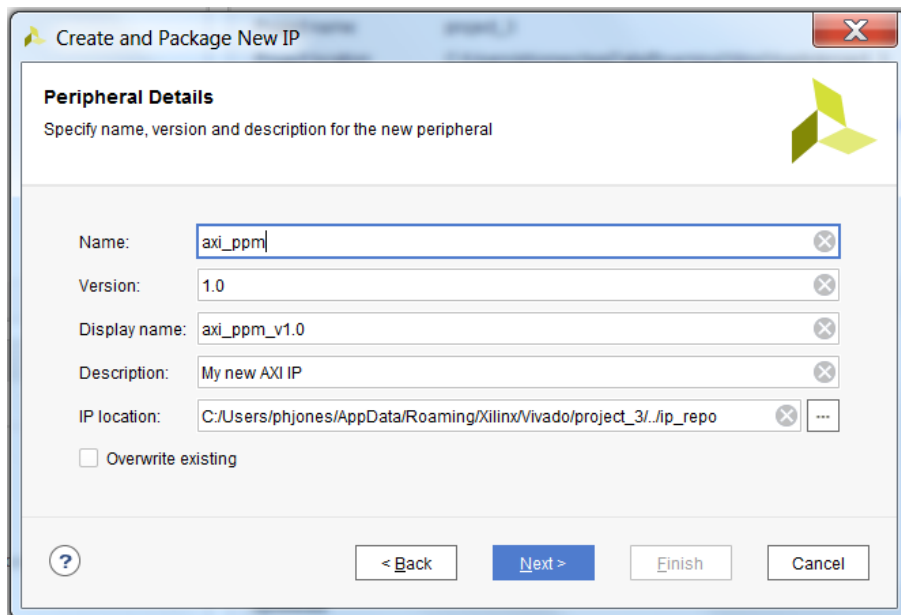
**4) Project Checkout.** Although we have not provided any source code or project files for this assignment, we do provide a zip file containing useful documentation. This includes documentation related to the RC controller, Quadcopter, voltage level adapter, and creating and packaging your own IP cores, and VHDL tutorials. This file is called MP-1.zip and is linked to the course website.

**5) System and IP Creation.** Similar to the process we followed in MP-0, open VIVADO and create a new project that targets the Zedboard. Once the project opens, we will be creating a new hardware IP core to interface with the ARM-based Processing System via the AMBA Bus. VIVADO has a tool to aid you in creating IP cores with an AMBA interface. We will be specifically connecting our IP core as an AXI-Lite device.

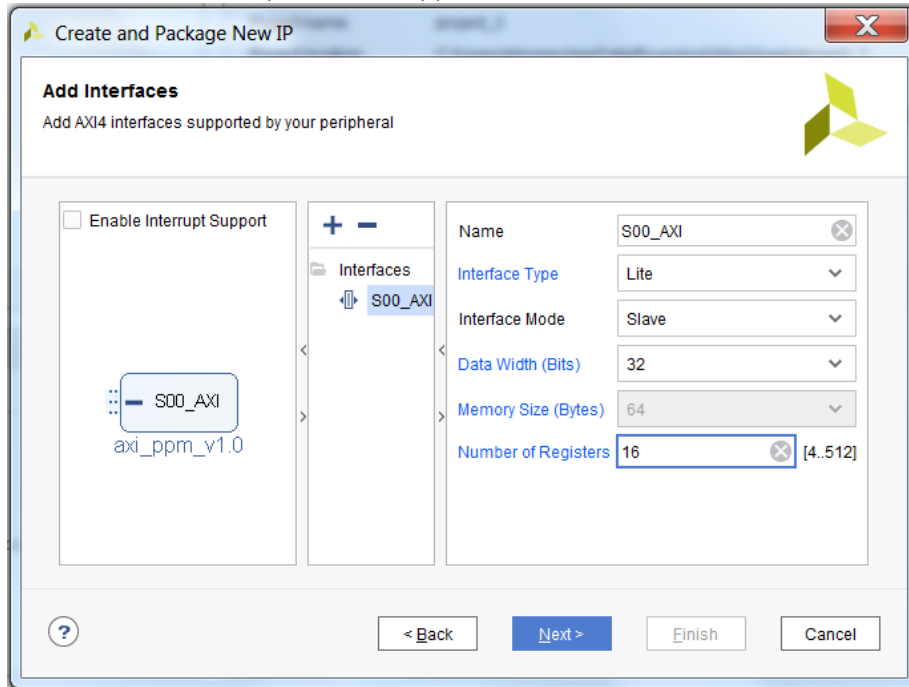
1. Select: Tools -> "Create and Package New IP ..."
2. On the next screen that opens, Click "Next".
3. The screen below when then open. Select "Create AXI4 peripheral", as shown, and then Click "Next"



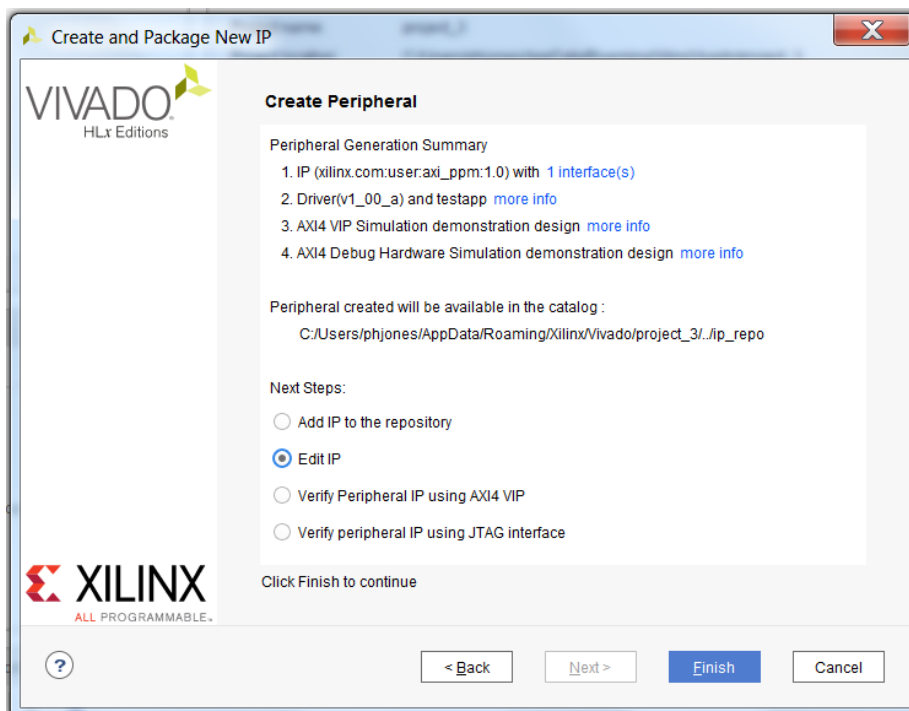
4. On the next window (see below), since we are creating an IP core to transmit PPM data over the AMBA AXI-light bus, name your component `axi_ppm`. Click "Next".



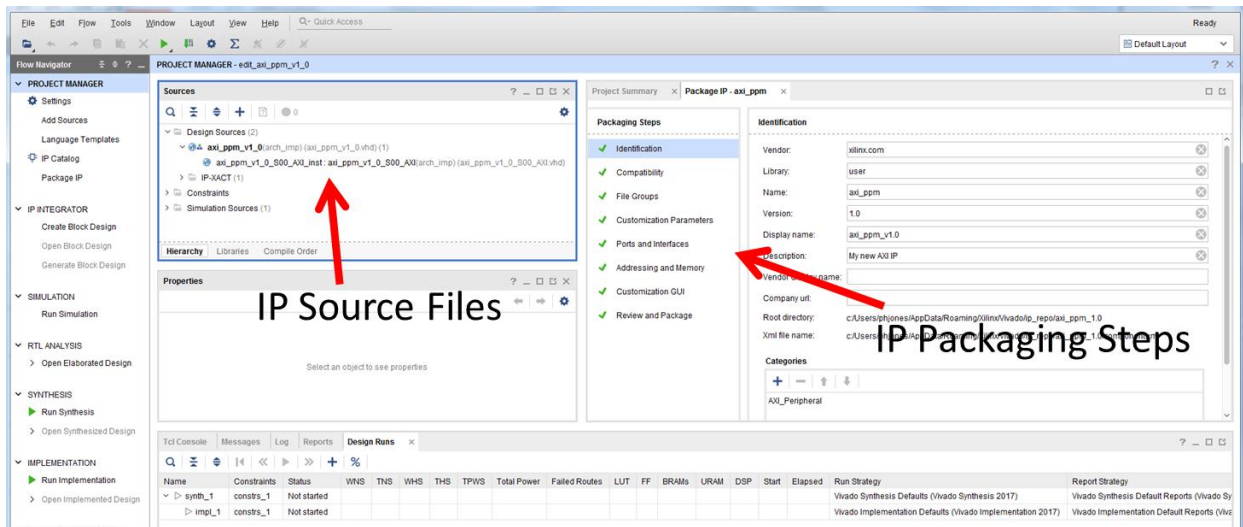
5. For the bus “Interface Type”, select “**Lite**” for AXI4-Lite. Since we will be reading and writing register values for this peripheral at a relatively low speed (~1KB/sec), there is no need for a higher throughput option. Make sure the Interface Mode is “**Slave**”, and increase the Number of Registers to **16**. These are Memory Mapped registers to be used to pass information between the ARM processor software and your hardware IP core. Explore the drop-down box options to get a feel for what other AXI4 interface options are supported. Click “Next”.



6. Select “Edit IP”, and then Click “Finish”



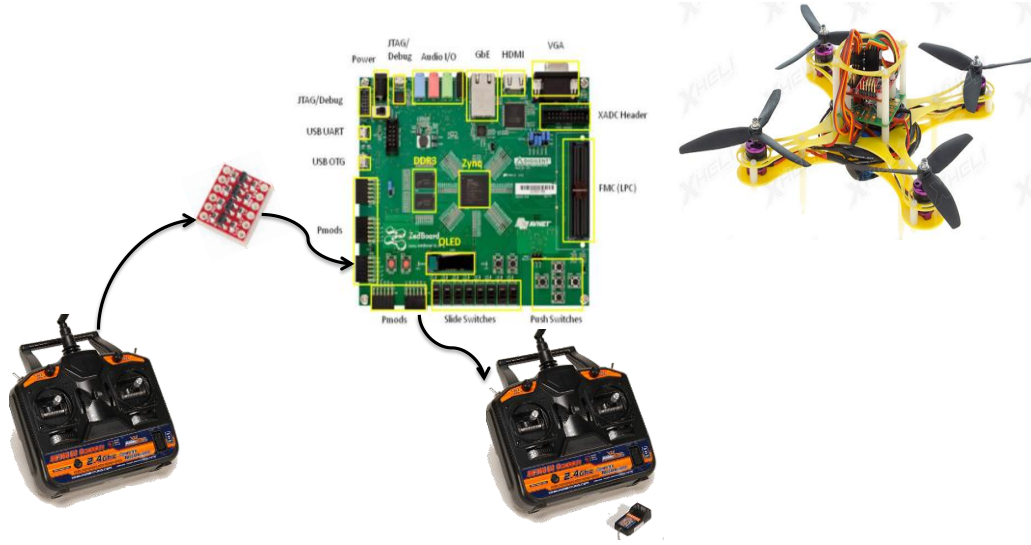
- A new project will open, as shown below, to allow you to Edit a skeleton of an AXI-Lite IP core. Notice the two VHDL source files in the “Sources” pane. You will be examining these two files to understand the structure for how the IP core connects to the AMBA bus, and for determining where to place your PPM logic for decoding and generating PPM signals. The “Packaging Steps” will be used to update your IP core before packaging it to be included in your MP-1 system as an IP component.



- Use the “Sources” pane to navigate the `axi_ppm` peripheral’s structure. 1) In your write up, provide a structural diagram of the `axi_ppm` design, from the top-level AMBA AXI interface down to where you user logic will reside. 2) How does an address on the AMBA bus generate a read or write enable signal for the slave registers in your design? 3) How will you PPM state machine get access to the IP core’s Memory Mapped registers.



As previously mentioned, we are using the ZedBoard as an intermediate PPM processing step between the pair of transmitters and the quad UAV. Specifically, we are connecting the trainer port of the “input” (student) transmitter to one of the PMOD data ports, and another PMOD data port to the trainer port of the “output” (instructor) transmitter.



Note the Sparkfun Logic Level converter sitting between the input transmitter and the PMOD interface! Based on this setup, modify your `axi_ppm` module to implement the following functionality:

1. At the top level, add an PPM\_Input and PPM\_Output port that will be used to bring into the FPGA and send out of it a PPM signal.
2. Use `slv_reg0` as a general configuration register. For now, when `slv_reg0(0)` is equal to '0', the core operates in a “hardware relay” mode. In this mode, pass PPM\_Input directly to PPM\_Output.
3. Create a Capture\_PPM Finite State Machine that samples PPM\_Input. When the PPM values for 6 channels have been detected, stores the corresponding cycle counts into `slv_reg10` through `slv_reg15`. These registers will only be readable (not writeable) via software, so you can sever their write connection to the AMBA AXI.
4. Once a new frame of PPM values has been captured (ch1 through ch6), increment a counter in `slv_reg1`. This register will be polled by software to easily determine when new PPM data is available.
5. Create a Generate\_PPM Finite State Machine that takes cycle counts stored in `slv_reg20` through `slv_reg25` and generates an appropriate signal for ch1 through ch6 on `sw_PPM_Output`. These registers will be writeable via software.
6. When `slv_reg0(0)` is equal to '1', we are in “software relay” mode. The `sw_PPM_Output` value should be connected to PPM\_Output.

Starting from the generic FSMs in your HW-1 write-up, update the User Logic module such that the design can appropriately capture and generate PPM values for the Hobby King 6ch transmitter as described above.

Note making these changes to you User Defined logic is not a trivial task. Some suggestions as you implement and test this module:

- a) While it might be tempting to looking for the rising or falling edge of the PPM\_Input port in order to store those values, FPGA synthesis tools treat all signals that trigger code on an edge (e.g. the `rising_edge` or `falling_edge` function in VHDL, `@posedge` and `@negedge` in Verilog) as a clock signal, which is not appropriate for this design. Instead, sample PPM\_Input and wait until a transition has been stable for multiple clock cycles.
- b) Create a testbench! There are a number of ways you can do this. See the VIVADO Logic Simulation Tutorial for one example (MP-1/docs/Tools/ug937-vivado-design-suite-simulation-tutorial).
- c) To minimize the chance of synthesis – simulation mismatches (in which a design that appears to work perfectly in behavioral simulation exhibits incorrect functionality once mapped to hardware), use the two process FSM style as described in chapter 7 of the *Free Range VHDL* tutorial, available under MP-1/docs/Tools/. In this style, one combinational process sets the next state and output values, and a second sequential process registers the current state. In the combinational process, make sure that every output signal is assigned a default value so as to avoid inferring latches.

**6) System Completion.** After you are fairly confident in your `axi_ppm` module, add it to your MP-1 system project as an IP core. Note that while the core will be automatically connected to the AXI bus, you will need to connect the PPM\_Input and PPM\_Output ports to external ports on the design, and constrain these external ports to the appropriate PMOD pins on the FPGA.

After correctly integrating the core into your system project, you are ready to export the design to SDK by clicking the “Export Design” button. As before, the default directory for this option should be. Then run ok – click “Launch SDK”.

**7) Control Software.** In SDK, create a new Application Project named `rc_control`.

Your `rc_control` project should demonstrate the following modes:

- 1) When SW0 is set to 0 put the system in *hardware relay* mode. Otherwise, set it to *software relay* mode. As previously mentioned, in hardware relay mode the `axi_ppm` module directly passes PPM\_Input to PPM\_Output. In software relay mode, the CPU reads the most recent PPM frame (stored in slave registers 10 through 15) and copies the values to slave registers 20 through 25, which are read by the `axi_ppm` module to generate PPM\_Output. Quadcopter flight should not be appear any different in these two modes.
- 2) If the middle button (BTNC) is pressed, exit the application. This is in general a good idea for all apps that feature an infinite control loop, as the Processing System occasionally locks (requiring a ZedBoard power cycle) up even when the application terminate button is pressed.
- 3) When SW1 is set to 1, put the system in *software debug* mode. In this mode the software outputs (over UART) the current value of the PPM channels stored in the slave registers in `axi_ppm`.
- 4) SW2 turns on *software record* mode. In this mode, the down button (BTND) stores the next PPM frame in an array and increments the array index, and the up button (BTNU) rewinds the recording by decrementing the index to this array.
- 5) SW3 turns on *software play* mode. In this mode, the right button (BTNR) transmits any stored PPM values over the `axi_ppm`, while the left button (BTNL) decrements the current play index.



- 6) SW4 turns on *software filter* mode. In this mode, any values to be transmitted (via) software to the `axi_ppm` are first analyzed to determine if the quad will be put in an unstable position.

Note that VIVADO/SDK does create a software driver for the `axi_ppm` module, which can be found in in your list of devices for the BSP. You may use this driver by copying it into your `rc_control` software project, although this isn't necessary since the `axi_ppm` module is a simple memory-mapped peripheral.

**What to submit:** a .zip file containing your modified source files (modifications to the two AXI vhd1 files, and any other VHDL file you created, MP-1.xdc, and `rc_control.c`) and your writeup in PDF format containing the highlighted sections of this document. In the Blackboard submission, list each team member with a percentage of their overall effort on MP-1 (with percentages summing to 100%).

**What to demo:** at least one group member must be available to demo the current state of your implementation. A full demo score requires a system that can fly using the various hardware and software modes, but partial credit will be given for effort. Be prepared to briefly discuss your source code.

**BONUS credit.** MP-1 has two separate bonus point criteria. The first is for the group with the best automated flight *longevity*. Using a combination of software record, software play, and software filter modes, how long can you keep your quad in the air without using the input transmitter? To be eligible for these bonus points, the quad has to land safely after its automated flight. (25 bonus points).

The second criterion is advanced *diagnostics*. In your software debug mode, the ZedBoard transmits over UART the current PPM values for the six RC channels. While this is useful for debugging the system, it does not provide much in terms of any useful diagnostics for the flight itself. Upgrade the diagnostic capability of the system, through some combination of software running on the ZedBoard and your host workstation. The teams with the most useful data diagnostics visualization as determined by the TAs will be eligible for this bonus. (25 bonus points).

Each group is limited to 100 bonus points for the entire semester.