

# OSVR: Sensics latency-testing hardware

The Sensics latency testing hardware is constructed using an Arduino, an Arduino gyro/accelerometer shield, and one or more photosensor inputs.

## Arduino

We built the prototype unit using an Arduino Uno board. The particular board we used was the SainSmart UNO ATmega328P, which was purchased through Amazon.com at [http://smile.amazon.com/SainSmart-ATmega328P-CABLE-Included-Arduino/dp/B006GX8IAY/ref=sr\\_1\\_5?s=electronics&ie=UTF8&qid=1422119284&sr=1-5&keywords=arduino+uno](http://smile.amazon.com/SainSmart-ATmega328P-CABLE-Included-Arduino/dp/B006GX8IAY/ref=sr_1_5?s=electronics&ie=UTF8&qid=1422119284&sr=1-5&keywords=arduino+uno) for \$17.69.



## Gyro/accelerometer

We built the prototype unit using a 6-axis accelerometer gyro Arduino shield module made by Robogaia.com. It was purchased through Amazon.com at [http://smile.amazon.com/Axis-Accelerometer-Gyro-Arduino-Shield/dp/B00GLCEXDG/ref=lm\\_ni\\_t?ie=UTF8&psc=1&smid=A3CCYN6649JF9L](http://smile.amazon.com/Axis-Accelerometer-Gyro-Arduino-Shield/dp/B00GLCEXDG/ref=lm_ni_t?ie=UTF8&psc=1&smid=A3CCYN6649JF9L) for \$39.99 plus \$4.49 shipping with an estimated delivery time of 6-25 days. It is designed to work directly with the Arduino Uno and can be adapted by adding wiring to work with the Arduino Mega 2560.

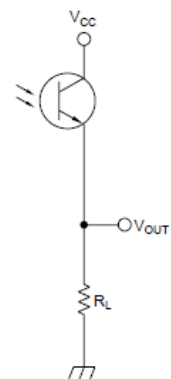


[Shield/dp/B00GLCEXDG/ref=lm\\_ni\\_t?ie=UTF8&psc=1&smid=A3CCYN6649JF9L](http://smile.amazon.com/Axis-Accelerometer-Gyro-Arduino-Shield/dp/B00GLCEXDG/ref=lm_ni_t?ie=UTF8&psc=1&smid=A3CCYN6649JF9L) for \$39.99 plus \$4.49 shipping with an estimated delivery time of 6-25 days. It is designed to work directly with the Arduino Uno and can be adapted by adding wiring to work with the Arduino Mega 2560.

**Installation:** The shield plugs directly into the top of the Uno board.

## Photosensor/Phototransistor

We built the second prototype using an IR phototransistor purchased at Radio Shack, which also operated in the visible-light range (part number 276-0145, \$1.99). We hooked the phototransistor up according to the SHARP Optoelectronics Photodiode/Phototransistor Application Circuit (see right). To produce voltages that changed over a range, we used a 10k $\Omega$  resistor ( $R_L$ ) in series with the phototransistor. To make the values larger for brighter light, we used a common-collector configuration with the resistor placed between the transistor output and ground.



**Installation:** Connect one side of resistor  $R_L$  to GND on the Arduino. Connect the collector on the phototransistor ( $V_{CC}$ ) to +5V on the Arduino. Connect the junction between the transistor collector and resistor ( $V_{OUT}$ ) to ANALOG IN A0 on the Arduino.

**Alternative:** We built the first prototype, which had slower response) using a wRobot light sensor through Amazon.com at [http://smile.amazon.com/Phantom-YoYo-Arduino-compatible-Sensor/dp/B00AF278A8/ref=sr\\_1\\_1?ie=UTF8&qid=1422394751&sr=8-1&keywords=arduino+light+sensor](http://smile.amazon.com/Phantom-YoYo-Arduino-compatible-Sensor/dp/B00AF278A8/ref=sr_1_1?ie=UTF8&qid=1422394751&sr=8-1&keywords=arduino+light+sensor) for \$6.99. These sensors had



You need to find some jumper cables to connect the pins on the photosensors to the pins on the Uno (actually on the shield's pass-through connectors). For the prototype, we bought some at Radio Shack, but you can also purchase them online. You want make-to-female jumpers like the ones at

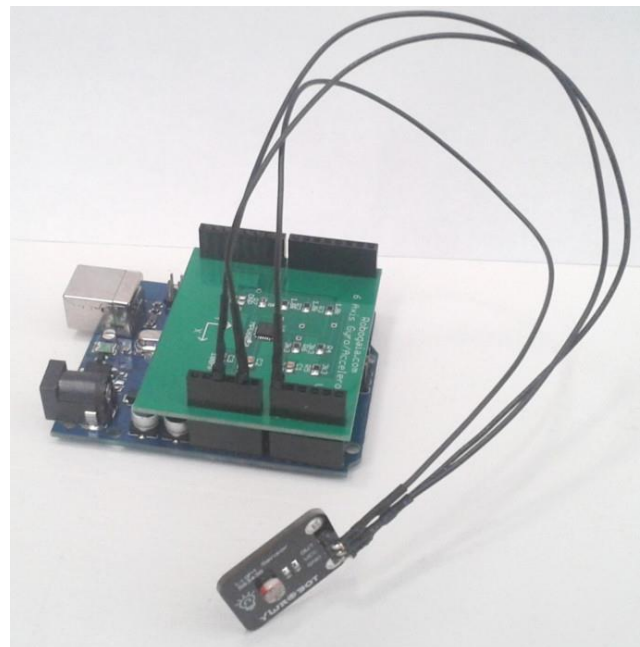
[http://smile.amazon.com/Male-Female-Jumper-Cable-Wires/dp/B00D7SDDLK/ref=sr\\_1\\_7?ie=UTF8&qid=1422653254&sr=8-7&keywords=jumper+wires+arduino](http://smile.amazon.com/Male-Female-Jumper-Cable-Wires/dp/B00D7SDDLK/ref=sr_1_7?ie=UTF8&qid=1422653254&sr=8-7&keywords=jumper+wires+arduino) from Amazon.

**Installation:** Connect the GND pin on the light sensor to GND on the Arduino (4<sup>th</sup> or 5<sup>th</sup> pin from the end on the first block). Connect the VCC pin on the light sensor to 5V on the Arduino (3<sup>rd</sup> pin from the end on the first block). Connect the OUT pin on the light sensor to ANALOG IN A0 on the Arduino (first pin on the second block).

## Hardware testing

The fully assembled unit (using the photosensor alternative) is shown to the right.

To enable use viewing a head-mounted display, you will want to attach the photosensor to the back of the unit (the bottom in the picture) with the sensor facing away from the unit. **Important:** Place a non-conductive element between the back of the sensor and the back of the unit, perhaps some sort of adhesive putty. To enable viewing the latency on the screen, you will want to use long jumper cables and put the sensor on a stand that keeps it fixed in space fairly close to the display screen.



You can test the analog sensor by running the ***print\_photosensor.ino*** program that comes in the source directory with the latency tester or using the ***File/Examples/01.Basics/ReadAnalogVoltage*** Sketch program in the Arduino interface, and watching the output on the ***Tools/Serial Monitor*** that comes built in. Move the photosensor in front of bright and dark locations on the screen and you should see a measurable difference in voltage (perhaps a range of 3V to 4.12V).

You can test the accelerometers and gyroscopes by running the ***print\_inertial.ino*** program that comes in the source directory with the latency tester or using the ***Accelerometer\_Gyro\_Shield\_test.ino*** program that you can download from the vendor site at <http://www.robogaia.com/6-axis-accelerometer-gyro-arduino-shield.html> in the **Example Code** section. Use the serial monitor to view output. As you flip the unit over, the accelerometer readings for the Z axis should change from negative several thousand to positive several thousand. As you rapidly rotate the unit, you should see the gyro values change.

**Note:** the Arduino resets itself when its USB port is plugged in, at least on a Mac and Linux. To avoid having command characters lost to the reset, any client code that wants to communicate directly with

the serial port must wait until it has been able to read the initial messages from the device before attempting to send the first command to it.

## Programming the Arduino

When you plug the Arduino into Linux, it is immediately recognized as a virtual serial device and will show up in `/dev/serial/by-id` as a device with the name `Arduino_Uno` in it (and may also appear as `/dev/ttyACM0`).

When you plug the Arduino into Windows 8, it does not immediately recognize it without a driver. You can download the Arduino software from the <http://Arduino.cc> web page. We used version 1.0.6 of the software to develop the latency-measuring prototype. Note that the software is GPL. Be sure to unplug your Arduino before installing the software (which includes a driver) and then plug it in again when the software has been installed. At this point, the device will show up as a COM port.

To load a program onto the Arduino, install the Arduino development environment and then open the `.ino` file. Press the run button (right arrow in version 1.0.6) to compile, load and run the program. There are two version of the latency tester, a motion-onset test and a motion-turnaround test.

### Motion onset test

**Warning:** Before running this test, either turn off all room lights or shield the sensor so that the lights are not visible. Even incandescent lights have enough ripple in their brightness to trigger the brightness-change test, so they can corrupt the measurements. Also, run the ***print\_photsensor.ino*** test and point the photodetector at a region on the screen with a constant brightness to ensure that the printed values don't change by more than maybe 1 count; some displays have a flashing backlight that can also corrupt the measurements.

Sensics first developed a ***motion\_onset\_test.ino*** program to be downloaded and run on the prototype system. This program waits for a period of no motion of the inertial measurement unit followed by a sudden motion (acceleration and/or rotation). It then looks for a change in brightness in the photodetector signal and reports the duration in microseconds between the onset of motion and the change of brightness.

To see the output from the program, open *Tools/Serial Monitor*. It should print a version number and give instructions. Rigidly attach the photosensor near a fixed location on the display screen or HMD. Rigidly attach the inertial measurement system (the body of the Arduino along with its shield) to the tracking device or mouse. Hold the tracking unit still and then move it suddenly in a way that will cause the part of the image in front of the photosensor to change its brightness dramatically in response to the motion. The program will report the number of microseconds between the detection of motion and the detection of a change in brightness. You probably want a situation where you can repeatedly rotate or move back and forth and have the brightness transition, so that you can get a number of measurements.

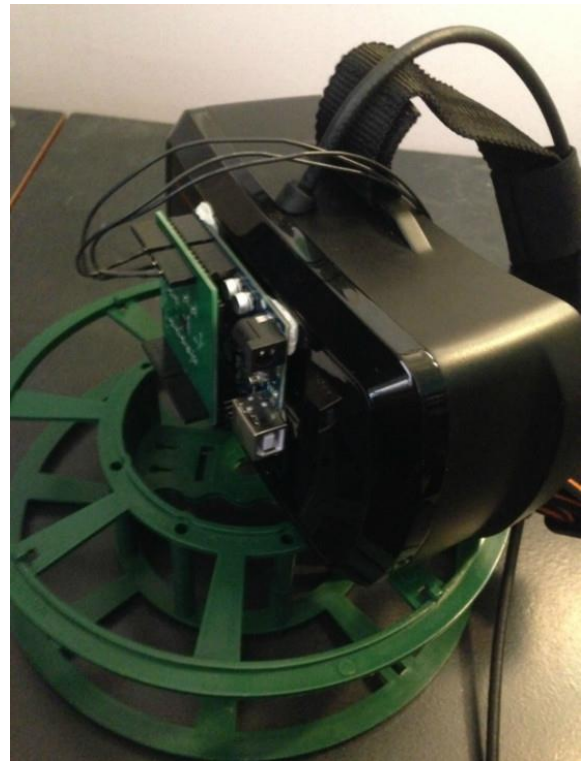
When the program runs, it first makes sure that the inertial measurement unit is held still for half a second; during the time it is waiting for the unit to become still, the LED will flash rapidly, looking like it is dim.

Once it has settled, it waits for a sudden motion. While it is waiting for this, the LED will be bright.

As soon as it detects the motion, the LED goes off while it waits for the brightness to change. If the brightness does not change for a second, it times out and goes back to looking for the unit to be held still. If it does detect a change, it reports the latency between the motion and the change in brightness and goes back for waiting for the unit to be held still.

Every 16 measurements, the program computes the average latency in microseconds for the previous 8 odd measurements, and also for the previous 8 even measurements (to support modes where there is an on/off or back/forth test being done). Timeouts are ignored when computing this average.

**Test procedure:** There are some things to be careful of during the test procedure. First, **check the wiring** to make sure that it is routed such that it does not touch any surface that is moving relative to the head-mounted display. If the HMD is sitting on a surface, the wires should be routed above the display. This will keep them from being pulled and causing intermittent contact during motion. The image to the right is an example; if the unit is to be moved by hand, then be sure not to tug on the wiring during motion. The inertia of the wires themselves is not enough to cause problems. Second, **rotate as quickly as you can** without risking the HMD or causing the tester to fly off. Faster motion onset provides a tighter match between the inertial sensors' motion detection and the tracker's motion detection that drives the application to change its display. This means that the measured latency should depend less on the relative speed of rotation between runs, providing tighter bounds on the estimated latency. One approach is to hold the HMD in both hands and rapidly move it from one orientation to another and back again, pausing for a fraction of a second at each end of travel.



**Tweaks:** The motion and brightness thresholds are stored as constants in the program, with names `GYRO_THRESHOLD`, `ACCEL_CHANGE_THRESHOLD`, and `BRIGHTNESS_CHANGE_THRESHOLD`. You can adjust these as needed to provide additional sensitivity (or more robustness in the presence of noise) and then re-run the program. The number of delays to wait before averaging is stored in `NUM_DELAYS` and should be twice as many as will be averaged, since there is a separate even and odd measurement.

### Motion turn-around test

**Warning:** Before running this test, either turn off all room lights or shield the sensor so that the lights are not visible. Even incandescent lights have enough ripple in their brightness to trigger the brightness-change test, so they can corrupt the measurements. Also, run the *print\_photsensor.ino* test and point the photodetector at a region on the screen with a constant brightness to ensure that the printed values don't change by more than maybe 1 count; some displays have a flashing backlight that can also corrupt the measurements.

**Warning:** This test is still a work in progress and should be considered at best alpha software.

Sensics next developed a *motion\_turnaround\_test.ino* program to be downloaded and run on the prototype system. This program expects periodic rotation around one axis, where there is a brightness change correlated to motion such that the brightest image is present at the end of rotation in one direction and the darkest image is present at the end of rotation in the other.

To see the output from the program, open *Tools/Serial Monitor*. It should print a version number and give instructions.

To test latency, rigidly attach the Arduino base to the HMD whose latency is to be tested. Then rigidly attach the photosensor so that it is looking at an image that will get brighter as the HMD is rotated in one direction and darker as the HMD is rotated in the other direction. The image needs to continue getting dark and brighter over the whole range of rotation. The photodiode has a wide field of view, so it will probably integrate brightness over the whole scene.

Smoothly but rapidly rotate the HMD repeatedly from darker to lighter and back again. The program records the time when the axis (whichever is rotating the most) switches direction and then records the time when the photosensor's value reaches its extreme value (maximum or minimum). It computes the latency in microseconds between these two times and reports it (this report will not be accurate to more than 1ms). It running statistics for the latencies and reports the min, max, and mean when the HMD is held still for two seconds.

When the HMD is held still for more than two seconds, it resets its statistics. When its rotation is started again, it re-estimates which axis it will use. This lets you test the response for different orientation axes to see if the latency differs. Remember that the brightness needs to vary monotonically as you rotate around each axis that you want to test.

### Notes

The Arduino is programmed in a language called "Sketch", which is converted into C/C++ code and then sent to the board. When you compile and upload a program to the unit, it will continue to run that program even if the reset button is pushed or the USB power is removed and restored. The Sensics apps fill in the *setup()* and *loop()* functions with the Sketch code to be run at boot time and repeatedly. Any variables that need to persist between loop runs must be declared static.

The LED pin (pin 13) on the board is also used by the SPI communication protocol, so it is not available to be used for signaling when SPI communication is being used (to communicate to the gyro/accelerometer shield).

The `loop()` function is called about every 500 microseconds for the above two programs, so the granularity of measurements is on the order of half a microsecond.

## Client program

It is not necessary to run a separate client-side program to test the end-to-end latency of an application. The Arduino serial monitor can be used to report this latency as described above.

Sensics has also developed a specialized client-side program, named *Latency\_test*, to test the latency of various subsystems. Here is the output of its `-help` option:

```
Usage: C:\tmp\vs2013_64\Latency_test\Release\Latency_test.exe
    [-fullscreen]
    [-button vrpnDeviceName whichButton]
    [-analog vrpnDeviceName whichAnalog threshold]
    [-tracker vrpnDeviceName whichSensor translationThreshold rotationThreshold]
    [-trackerRotate vrpnDeviceName whichSensor whichAxis[0,1,2]]
    [-numquads num]
```

When it is run with the `'-button'`, `'-analog'`, or `'-tracker'` options, it will work with the motion-onset test for the hardware unit. Whenever it receives a large-enough motion, it triggers a transition from dark to bright. The `-tracker` option is given the VRPN device name (`"Tracker0@localhost"`), the sensor on the tracker to watch (0), the translation threshold to use for motion (0.01 works for a tracker like the YEI that does not report it) and the threshold for rotation (barely large enough not to be triggered by noise or inadvertent motion, 0.1 for the YEI tracker).

When it is run with the `'-trackerRotate'` option, it will adjust the brightness based on the angle of rotation one axis of a VRPN tracker. When used this way, you should first rotate the axis further than you will be using for the test itself, to set the maximum and minimum rotations such that the screen will not go completely dark or completely bright during the test. Then place the photosensor so that it can see at least a portion of the latency-test window and oscillate the tracker back and forth around that axis.

The *Latency\_test* program can also be used to measure the differential time to render a 2D mouse cursor vs. a simple 3D scene, and (with the `-numquads` option) to see the impact of polygon count (frame rate) on latency.

## Appendix A: Original photosensor latency testing

See Appendix D for testing done using the phototransistor.

There is a time constant associated with the photosensor that depends on the detector. To test this latency for the particular photosensor you are using, a *Photosensor\_latency\_test.ino* program has been



developed. To use this program, point the photosensor at the LED on the Arduino board and then run the program. Open **Tools/Serial Monitor** on the Arduino development environment after running the program to see what these values are.

The particular unit used in the first prototype had a fairly long time constant, so that operating the unit with a threshold halfway between the bright and dark value produced a latency of around 1-2ms for an LED-on event and of about 18-35ms for an LED-off event. This value depends on the ambient brightness and the difference between bright and dark levels for the photodiode. When operating with a threshold that is  $1/10^{\text{th}}$  of the way from the off value to the on value, the on latency was 0.4ms and the off latency 1.8ms for a fairly bright ambient; they were 0.5ms and 6ms for a dark ambient. When operating with a threshold that is  $1/20^{\text{th}}$  of the way from on to off, the latencies were 0.4ms and 3ms for a dark ambient; 0.28 and 0.7ms for a bright ambient. All of these values include a 0.14ms loop delay (how long it takes for the Arduino to read the analog value and go once more through its loop function).

The algorithm used for latency testing uses the  $1/20^{\text{th}}$  of the full-scale threshold so that the photodiode latency will be a small fraction of the total system latency. **Note:** This photosensor should not be used for the brightness-ramp testing due to variable delays depending on the brightness levels being used and the speed of brightness change. For the on/off testing with large brightness changes and sensitive thresholds, it is fine.

## Appendix B: End-to-end latency testing of `motion_onset_test`

We tested version 1.0.0 on the prototype by holding the alternate photosensor and the system board together in one hand and rapidly moving the entire unit so that the photosensor was moving out from behind an occluder and viewing a light. When moving as suddenly as possible by hand, latencies of as low as 1ms were observed. Latencies of as low as 2ms were observed when moving towards darker regions. As expected from by-hand testing, the measurements were variable and were sometimes much larger (as much as 30ms).

Adhesive putty was used to attach the photo sensor to the body of the unit and the unit was placed on a table top near the edge of an overhang that blocked the light. It was repeatedly tapped sharply with a fingernail to move it into the darkness, resulting in reliably low measurements (2.8ms, 3.1ms, 1.7ms, 2.4ms, 3.7ms). The variability in the measurements may still be attributable to variations in initial starting position and strength of tap.

When holding the unit and rotating it so that the photo sensor went into and out of the light, slightly higher latencies (3-6ms) were observed, probably due to the rotational inertial of the hand/Arduino/cord system being higher relative to muscle strength than the translational inertia.

With the system sitting above the photosensor between it and the light, when we tapped the system slightly so that the amount of shading increased a bit, we saw the following latencies (ms): 23, 20, 16, 14, 23, 11, 17, 11, 12, 6 (for varying-strength taps). For a series of strong taps with the unit positioned to partly shadow the sensor (ms): 8.5, 9.4, 8.4, 6.9, 8.8, 7.9, 8.3.

Switching the photosensor threshold from 5 down to 3 (version 2.1.0 of the software) produced latencies in the unit positioned to partly shadow the sensor of (ms): 6.8, 6.2, 8.3, 7.3, 6.9, 6.9. For the fingernail-tap into the darkness under an overhang test, the latencies were (ms): 1.0, 1.0, 1.2, 1.2, 1.1, 1.1, 0.9, 1.3, 0.8, 0.8.

### Appendix C: End-to-end latency testing of motion\_turnaround\_test

We tested version 1.0.0 of this program on the prototype by rigidly attaching the alternate photosensor to the inertial unit and rotating back and forth such the photosensor faced towards and away from a bright window.

Over 50 measurements, the minimum latency was 496 microseconds and the maximum was 504. This latency is half of the sampling rate of the inertial sensors, and is probably close to the iteration speed of the loop that is doing the testing. The same results were obtained when rotating around the X and Y axis of the unit.

### Appendix D: Phototransistor latency testing

To test this latency for the particular photosensor you are using, a *Photosensor\_latency\_test.ino* program has been developed. To use this program, point the photosensor at the LED on the Arduino board and then run the program. Open **Tools/Serial Monitor** on the Arduino development environment after running the program to see what these values are.

The phototransistor was tested with a 10k $\Omega$  resistor as  $R_L$ .

#### Latency tester

Using the *Photosensor\_latency\_test* program with on and off thresholds both set at halfway between the brightest and darkest value, we find the on delay to be 280-390 microseconds (0.3ms) and the off delay to be around 400 microseconds (0.4ms).

#### Screen observations

Observations made using an oscilloscope, placing the scope probe across  $V_{OUT}$  and GND with the circuit attached to the Arduino, which was operating the *print\_photosensor* program to indicate the levels it was reading. The response time was fast enough to capture changes in display brightness that happened over less than 2 milliseconds (details below), indicating a response time under 2ms. This is consistent with the results above, which indicate that the voltage is passing the halfway mark in under half a millisecond.

**External display:** With the phototransistor attached to an LCD display operating at 60Hz using adhesive putty looking at the display turned off, the Arduino reported values between 6 and 7, and the scope showed around 0.1V. When looking at a dark patch (black send to the display) with the display on, values ranged from 5 to 39 and the scope showed an exponential-approach square-wave from 0.1-0.4V. When looking at a bright-white patch of an LCD display with room lights off, the Arduino was reporting values between 56 and 135. The oscilloscope showed from 0.4-0.8V.



In the two cases with the display turned on, the oscilloscope showed an exponential approach to a higher value that lasted about 3ms, followed by an exponential decay back down towards a lower value that took about 1.8ms. This is consistent with the display using an illuminator that cycles on and off at about 500 Hz.

When the brightness changes on the display, there is an envelope of brightness that goes exponentially from the first brightness level to the second, with a time constant of around 10ms. This is consistent with a display response time of around 10ms.

**Laptop display:** With the phototransistor pointed at a bright patch on the laptop display (also operating at 60Hz), the Arduino reported a steady value of 180 and the oscilloscope showed a steady 0.9V. When toggling the brightness on the screen from full black to full bright, the oscilloscope shows an exponential approach to the bright value or dark value with a time constant of approximately 10ms. This is consistent with a display response time of around 10ms.

### Appendix E: End-to-end latency testing of motion\_turnaround\_test

We tested version 1.1.0 of this program on the prototype by rigidly attaching the phototransistor to the inertial unit and rotating back and forth such the photosensor faced towards and away from a bright patch on the screen (and onto the black laptop bevel).

Over 50 measurements, the minimum latency was 496 microseconds and the maximum was 504. This latency is half of the sampling rate of the inertial sensors, and is probably close to the iteration speed of the loop that is doing the testing. The same results were obtained when rotating around the X and Y axis of the unit.

Sometimes the unit reports latencies of 4-6ms during these tests. Runs where this occurs should be discounted, but it is disconcerting because this might presumably also happen during an actual run.