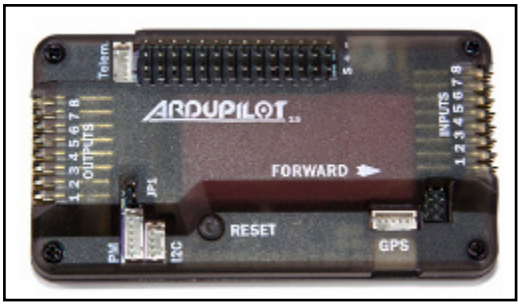
Kalman Filter for an Arduino IMU-GPS ArduPilot
Noel Zinn, www.hydrometronics.com, August 2018

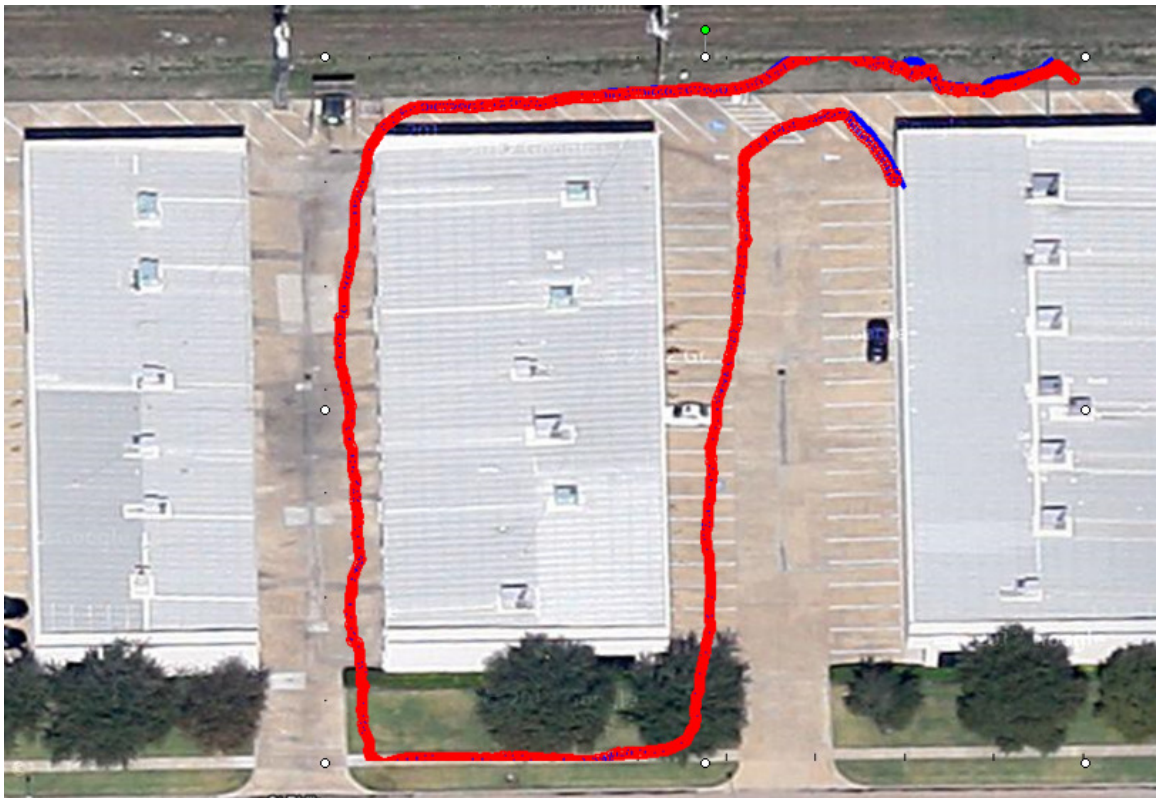
An ArduPilot APM 2.5 is the heart of a hobby drone's navigation system. Though currently superseded, it's still available on Amazon, DYI Drones and eBay. Its hardware consists of an Arduino Mega board with an Atmel microcontroller, a u-blox LEA-6 GPS receiver with a Taoglas GP 1575.25.4 antenna and an Invensense MPU 6000 IMU, the kind you might find in your iPhone. Purchased in its prime (2013) at $300, it ... or a successor model ... is available for half that much today . Combined with ArduCopter or ArduPlane firmware and software, the ArduPilot will navigate a hobby UAV (unmanned aerial vehicle) wherever permitted. Learn more at the open-source user community at DYI Drones <https://diydrones.com/>.



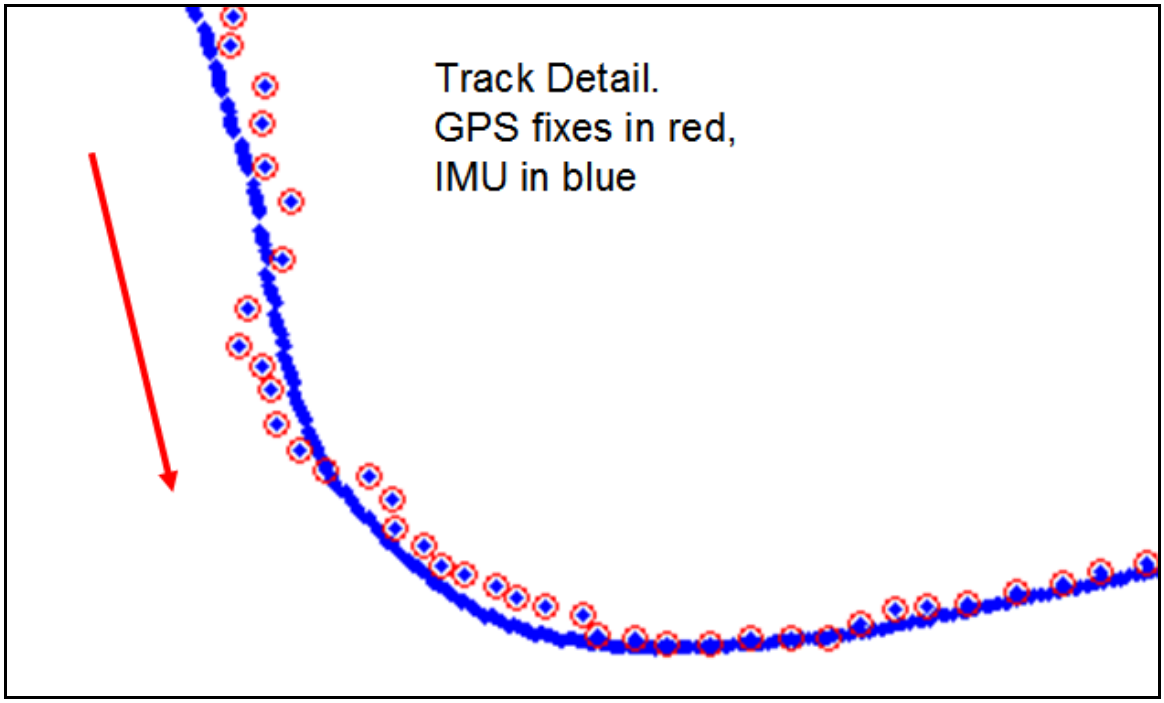
The ArduPilot's onboard sensors alone are totally adequate to control a UAV in real time. Nevertheless, having a 25Hz IMU relative sensor and a 5Hz GPS absolute sensor in the same "box" provides an opportunity to improve them both in post processing with a Kalman filter ... despite the hobby quality of the sensors themselves. The GPS absolute coordinates (latitude, longitude and height) will discipline the relative accelerations and rotations of the IMU. The higher frequency of the IMU will fill the gaps in the lower-frequency GPS coordinates ... and filter (improve) them as well. It's the best of both worlds.

Hydrometronics developed a 15-state Kalman filter (Kf) for this purpose: 3 position states (X, Y, Z), 3 velocity states (dX, dY, dZ) , 3 attitude states (roll, pitch and yaw), 3 gyro bias states and 3 accelerometer bias states. The Kf was largely based upon a text by Paul D. Groves, *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*, Second Edition, April 2013. This is an excellent book with excellent, well-documented Matlab code (on an accompanying CD-ROM) that required modification for our purpose, but was a great place to start. To be clear, the Kf does not run in the Atmel microcontroller of the Arduino Mega board, but in a separate computer. Having said that, this Kf was translated from Matlab to C-code and compiled by GCC (GNU Compiler Collection) in a Raspberry Pi with a more capable ARM CPU than an Arduino microcontroller. So, it is possible to fit all into a UAV in real time ... possible, but not necessary.

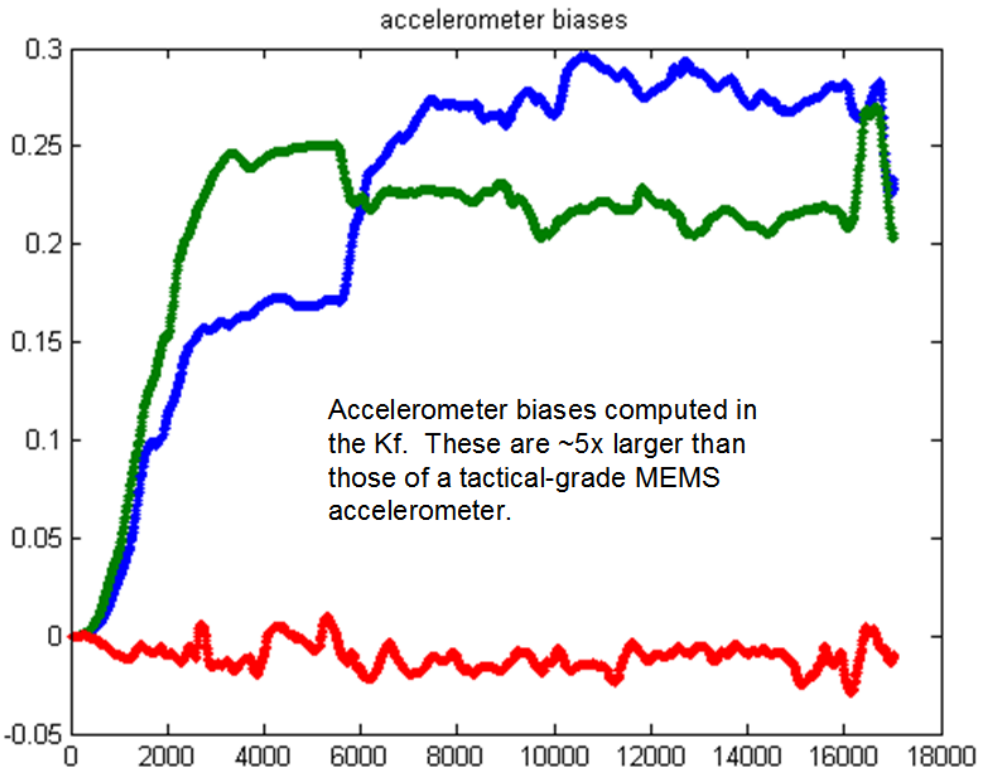
For this exercise, the ArduPilot was hand mounted and walked between and around some buildings near a client's facility, and its data post processed in Matlab. The following graphic shows the entire path ...

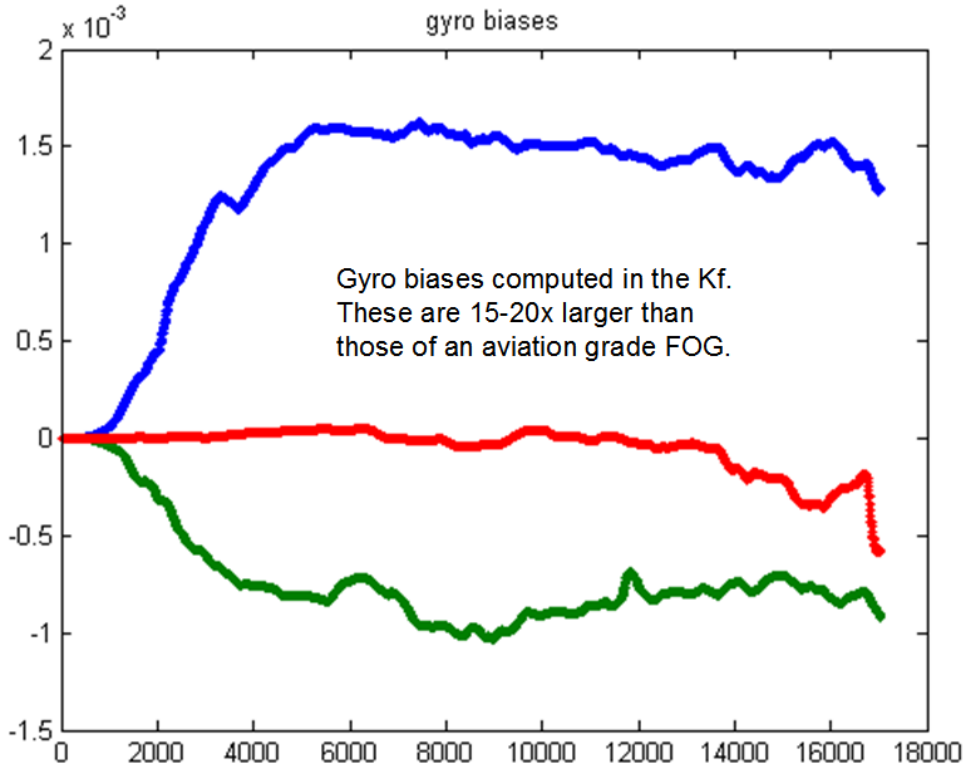


... and next graphic is a detail showing the GPS and IMU fixes.



There is much to show that exhibits the functioning of a Kf, but the accelerometer and gyro biases are perhaps most representative. They follow.


accelerometer biases
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Accelerometer biases computed in the Kf. These are ~5x larger than those of a tactical-grade MEMS accelerometer.


x 10-3
gyro biases
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Gyro biases computed in the Kf. These are 15-20x larger than those of an aviation grade FOG.

The x-axis of both plots are in IMU events at 25Hz or about 660 seconds (11 minutes) of data from start to finish. The y-axis of the accelerometer-bias plot is in mG (one-thousandth of the acceleration of gravity). The y-axis of the gyro bias plot is in milli-degrees per second. It's important to note that all 3 accelerometers and all 3 gyros reach steady state a couple of minutes into the exercise, a very good indication of the success of the Kf despite the sensors being hand mounted. Although these biases are of poor quality relative to aviation and marine navigation standards, the IMU only cost $5 in lots of one. It lends itself to the same algorithmic enhancement that one might apply to a higher quality sensor. More Kf graphics can be found in this report (needing some corrections): http://www.hydrometronics.com/downloads/Kalman%20Filter%20for%203D%20Robotics%20ArduPilot%202x.pdf

And here are some other links on the ArduPilot and its sensors:
https://diydrones.com/
http://ardupilot.org/copter/docs/common-apm25-and-26-overview.html
https://www.ardupilot.co.uk/
https://en.wikipedia.org/wiki/ArduPilot#cite_note-5
http://dronefever.com/APM-2.5-Assembled-Set-Side-entry.html
https://www.digikey.com/catalog/en/partgroup/mpu-6000-series/39618
https://www.u-blox.com/en/product/lea-6-series

As I concluded in another LinkedIn post available here, which takes a different approach to evaluating IMU quality, "Hobby boards nurture professional competence".