AGGIENAV: A SMALL, WELL INTEGRATED NAVIGATION SENSOR SYSTEM FOR SMALL UNMANNED AERIAL VEHICLES

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ABSTRACT
Small UAV performance is limited by the sensors used in the navigational systems. Several solutions of various complexity and cost exist, however no ready-made solutions exist for a high-accuracy, low-cost UAV system. Presented is AggieNav: a small, integrated navigational 6 degree-of-freedom with compass and GPS sensor package designed for ideal navigation of small UAVs. System, hardware, and embedded software design for the system is detailed.

NOMENCLATURE
UAV Unmanned Aerial Vehicle.
IMU Inertial Measurement Unit. Typically a 3-axis roll rate gyro co-axial with a 3-axis accelerometer.
INS Inertial Navigation System. Suggests a combination of IMU and other sensors such as GPS via a software filter.

INTRODUCTION
To accomplish mission goals or to fly passengers to their destinations, all aircraft rely on sensors for the core of their navigational systems. For small UAVs, the sensor suite determines much about the usefulness and capabilities of such a system, and is mostly limited because of the relatively high cost of high-quality navigational sensors and equipment.

The options for low-cost miniature attitude navigation sensing are few; most inexpensive, small fixed-wing UAVs use infrared thermopiles sense the relative heat differential from the black body radiation of the Earth’s surface. While this technique does work, it is not accurate enough for some remote measurement tasks and has problems when flying near large land features such as mountains and through valleys. Combined with a modern civilian GPS receiver, navigation is possible.

Inertial measurement units with roll-rates and accelerometers are the standard sensor for attitude determination in flight. Several solutions exist for navigation in small UAVs, such as, all of which use Kalman or other state-estimation filter of some kind to provide a high-accuracy estimation of the current position and attitude of the system at a given instant. While these systems work well for their intended applications, even the academic prices are prohibitive for integration into inexpensive UAVs. Additionally, the source code is not made available, and users of the systems are forced to accept the filter/algorithm performance of the systems as they are given.

Recently, due to the high-availability of low-cost sensing chips, many consumer-level devices such as the Apple iPhone, Nintendo Wii and Sony PlayStation 3 [1] have integrated accelerometers into their hardware for more immersive user-experiences. Several chip manufactures are producing 3-axis accelerometers, however, the availability of integrated 3-axis roll-rate gyro chips is not as broad. Analog Devices, inc. is, at the time of this writing, the only company producing fully-integrated 6-degree-of-freedom sensor units [2]. Other academic
efforts such as [3] and [4] have been put forth, but this is the most flight-ready and integrated design.

AggieNav is a unique design of cutting-edge sensing, power and processing hardware, paired with highly sophisticated data filtering algorithms, giving it a decisive lead in front of other similar systems.

AggieNav has a unique combination of features:

- Full high-accuracy 6-Degree-of-Freedom IMU
- Full 3-axis tilt-compensated compass
- Universal interface with any GPS unit via a serial port
- Dual pressure sensors for static and dynamic air pressures
- 72 MIPS onboard processing
- Onboard hardware mounts for a 600MHz Gumstix Linux computer, and Paparazzi [5] based autopilot system (“AggiePilot”) for a full UAV system
- Lowest price for any such system
- Open software architecture allows AggieNav to be customized or augmented easily
- Weight: 70g, power: 1.0W total with Gumstix and GPS

LOW-COST UAV NAVIGATION SOLUTIONS AND AGGIENAV COMPARISON

Three different kinds of navigation solutions:

1. No IMU (typically IR sensor-based) + GPS
   Least expensive option for navigation. Has many drawbacks (inaccurate and difficult to tune), but is functional.

2. Loosely integrated INS IMU (Microstrain 3DM-GX2) with uncoupled GPS
   Estimations are workable, and better than IR-based navigation, but are not the most ideal.

3. Tightly integrated INS IMU+GPS+Compass+Pressure etc. w/Kalman Filter. These are the best current solutions for small (and large) UAV flight. Several companies are making solutions target UAV flight, but most very expensive.
   - Micropilot (full autopilot solution) ($8,000)
   - Xsens MTI-G ($7000)
   - Crossbow Micronav + Stargate Processor (discontinued, $1,900)
   - Procerus Kestral ($5,000)
   - AggieNav ($1,200)

More specific information on the closest competitors to AggieNav can be found in Table. 1

ENTER AGGIENAV

AggieNav has been developed as a “best of” between low-accuracy thermopile sensors and high-cost, closed navigation systems. By leveraging new digital MEMS sensors such as Analog Devices ADIS1635x IMU parts, a new level of performance vs. cost can be achieved. Fig. 1 provides a block diagram of AggieNav’s sensors and system design.

Since many of our missions at Utah State University (and indeed, the general filtering of AggieNav’s sensor data) require the use of a Gumstix Linux computer, a mounting footprint and connector has been included, as well as a 5V powered USB-host port. This allows the high-level flight software to be aware of the current flight/mission state, creating many possibilities such as location-based science and swarm/mesh networked behavior.

AGGIENAV SUBSYSTEMS

AggieNav has a unique combination of sensors to support high quality flight navigation. All devices on AggieNav are factory calibrated and have digital interfaces to shift the testing and verification load off out the system assembly stage and allow for
Table 1. AGGIENAV VS OTHER SMALL UAV INS SOLUTIONS

<table>
<thead>
<tr>
<th>INS Unit</th>
<th>AggieNav</th>
<th>Stock Microstrain 3DM GX2</th>
<th>Crossbow MNAV</th>
<th>Procerus Kestral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Gyro Bandwidth</td>
<td></td>
<td></td>
<td>250Hz</td>
<td>25Hz</td>
</tr>
<tr>
<td></td>
<td>700Hz (unfiltered)</td>
<td></td>
<td></td>
<td>9Hz</td>
</tr>
<tr>
<td>Max Gyro Dynamic Range</td>
<td>±300deg/sec</td>
<td>±300deg/sec standard</td>
<td>±150deg/sec</td>
<td>±300deg/sec</td>
</tr>
<tr>
<td>Accelerometer Dynamic Range</td>
<td>±10g</td>
<td>±5g</td>
<td>±2g</td>
<td>±10g</td>
</tr>
<tr>
<td>Accelerometer Resolution</td>
<td>14bit</td>
<td>16bit</td>
<td>NA</td>
<td>14bit</td>
</tr>
<tr>
<td>Accelerometer Bandwidth</td>
<td>700Hz (unfiltered)</td>
<td>250Hz</td>
<td>25Hz</td>
<td>9Hz</td>
</tr>
<tr>
<td>Magnetics Rate</td>
<td></td>
<td></td>
<td>250Hz</td>
<td>1-100Hz</td>
</tr>
<tr>
<td></td>
<td>5Hz heading solution</td>
<td>250Hz</td>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>Magnetics Accuracy</td>
<td></td>
<td></td>
<td>0.001Gauss</td>
<td>NA</td>
</tr>
<tr>
<td>GPS Rate</td>
<td></td>
<td></td>
<td>No GPS</td>
<td>4Hz</td>
</tr>
<tr>
<td>Max GPS Accuracy</td>
<td></td>
<td></td>
<td>No GPS</td>
<td>2.5m</td>
</tr>
<tr>
<td>Pressure Rate</td>
<td></td>
<td></td>
<td>No Pressure</td>
<td>1.8Hz</td>
</tr>
<tr>
<td>Pressure Accuracy (Abs)</td>
<td>1.5Pa</td>
<td>No Pressure</td>
<td>NA</td>
<td>2.44Pa</td>
</tr>
<tr>
<td>Power Draw</td>
<td>600mW</td>
<td>470mW (minimum)</td>
<td>400mW</td>
<td>700mW</td>
</tr>
</tbody>
</table>

INERTIAL MEASUREMENT UNIT The primary sensor for AggieNav is a Analog Devices ADIS1635x Inertial Measurement Unit (Fig. 5, with 6 full axis of roll-rate and accelerometer data. Analog devices manufactures several different models in the same IMU family which vary in sensing range and sensor suite. The ADIS1635x sensors are factory calibrated and require little integration during manufacturing of an AggieNav unit. The ADIS1635x sensors have comparable performance to (and in many cases, better performance than) all competing small UAV INS solutions (see Table. 1).

MAGNETIC COMPASS A Honeywell HMC6343 tilt-compensated magnetic compass provides slower, but accurate absolute heading data. (Fig. 6). The HMC6343 compass includes an MSP430 ASIC as well as internal accelerometers to provide a tilt-compensated heading independent of orientation. The internal filtering algorithms have been enabled and set to their maximum low-pass settings to eliminate mechanical resonances generated by the flight dynamics.

GPS RECEIVER A high-rate civilian GPS receiver, a 4Hz uBlox LEA-5H unit, provides lower bandwidth data about the UAV’s global position. This GPS receiver is pictured alongside AggieNav in Fig. 2 and includes a LNA-powered helical antenna from Sarentel. Although requiring 100mW of extra power beyond a passive antenna, this GPS solution gives AggieNav and the host UAV the best possible gain towards the sky and the best possible 3D GPS lock accuracy.

AggieNav’s GPS receiver is designed to be replaceable/upgradable as newer and better GPS units appear on the
market, and for this reason the GPS receiver is a separated by a length of wire and a interface connector. This technique also allows the GPS system to be relocated anywhere on the UAV for the best possible RF interference avoidance.

PRESSURE SENSORS Two small yet accurate pressure sensors (Fig. 7) from VTI give accurate (1.5Pa) pressure, allowing for the calculation of both absolute elevation (with launch time calibration) and wind speed (differential via Pitot tube [7]).

POWER SYSTEM The power system is designed for the full voltage range of the batteries in the CSOIS UAVs [8] (5.1-17.0V), and provides additional power to the Gumstix computer and the onboard host-mode mini-USB port. Two power rails, 5.0 and 3.3V are implemented with Texas Instruments TPS62110-series step-down switching power converters implemented as in the datasheet [9]. This power system has been tested in flight conditions and efficiently provides clean power to the AggieNav system and hosted Gumstix board.

MICROPROCESSOR AND EMBEDDED SOFTWARE AggieNav is based on the 32-bit AVR32A256B Microprocessor from Atmel Corporation [10]. This processor gives 72 MIPS at 60 MHz with one of the lowest watt-per-MIP ratings in its class. AggieNav is fully programmable from both the Linux and Windows operating systems via an Atmel JTAG-ICE MkII programming unit. All system software is written in the C language and compiled with the GNU C toolset, also provided by Atmel in their AVR32Studio product. This combination has proved to be a workable and inexpensive solution to a high-performance development problem.

The AggieNav software architecture is almost entirely interrupt-based for hard real-time performance. Fig. 8 provides a flowchart of the main data collection loop, which occurs at 100Hz. Other interrupts process the GPS data (binary-mode character processing), as well as the SPI interrupt requests from the autopilot for filtered attitude and position data.

The main loop for the software is not idle, however, and is tasked with a secondary Kalman filter for the data as seen below.

THE GUMSTIX PROCESSOR AND AGGIENAV EKF An Extended Kalman State Filter is employed for processing the large amount of sensor data created by AggieNav. This filter runs on the mounted Gumstix board as a co-process, and is being developed on the Gumstix for ease of testing. The filter is under heavy development and as such requires a great deal of processing power. Additionally, many UAV missions demand control over payloads or other high-level computing, and therefore the flexibility of a full traditional Operating System is re-
quired for many missions. A 600MHz Gumstix Linux computer is mounted and powered by AggieNav, allowing the sensor data to be processed and filtered, then returned to AggieNav for reporting to the attached Paparazzi autopilot.

SOFTWARE FAILOVER

This system design allows AggieNav to fail-over to an internal filter should the Gumstix crash or otherwise become disabled, and is depicted in Fig. 9. AggieNav waits a sufficient period (in this case, 50 missed packets, or 0.5 seconds), and starts sending the Autopilot the internal data. This decision is made every sensor data pass, and could be adapted to other fault/failover scenarios.

COMMUNICATION WITH OTHER UAV SYSTEMS

AggieNav is designed to integrate tightly into the CSOIS AggieAir system design, as well as function well on its own in any application demanding a well coupled INS solution. The main AggieNav communication channel is a TTL-level serial port, over which AggieNav transmits 100 packets/sec of sensor data. The guest Gumstix computer is used as a co-processor, filtering the location and sensor data, and transmitting it back to AggieNav, which then relays the filtered data to the autopilot (AggiePilot) whenever it is requested to do so as a slave on the SPI bus linking the two.

CONCLUSION

Cellular phone and other consumer technologies such as gaming hardware have driven useful sensors and power-densities toward smaller and less expensive UAV hardware. In this paper, a small, low-cost, integrated small UAV navigation sensor unit has been presented, AggieNav, includes a 6-DoF IMU, a 3D tilt-compensated compass, two pressure sensors for barometric information, and a low-power general-purpose 32-bit microprocessor with 72 MIPS of computational power. Aspects of the system design, software design and data flow have been covered, as well as filtering of the data. Comparison with other lower-cost UAV navigation systems was shown, and failover functionality with other parts of the CSOIS UAV system was discussed.

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Figure 8. AGGIENAV MAIN DATA COLLECTION FLOWCHART

Figure 9. AGGIENAV EKF FALLOUT DIAGRAM

REFERENCES
[10] ATMEL CORPORATION. AVR32 32-Bit Microcontroller Datasheet. 2325 Orchard Parkway, San Jose, CA 95131, USA.