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A double stage Kalman filter for sensor fusion and orientation tracking in 9D IMU

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sensordynamics
Leading in micro and wireless sensor products

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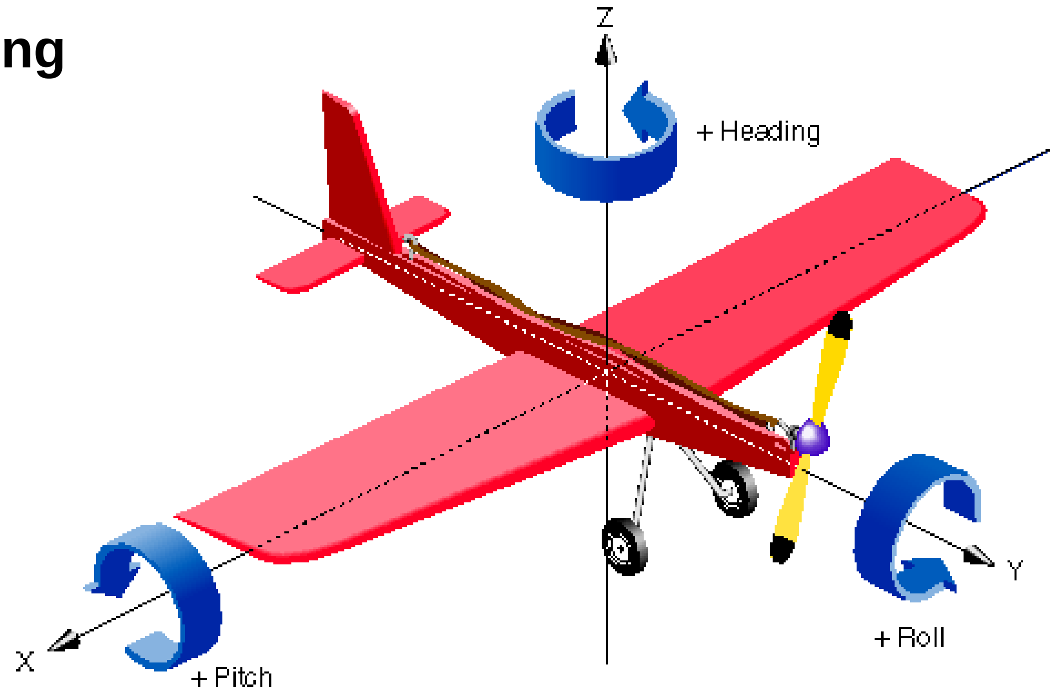
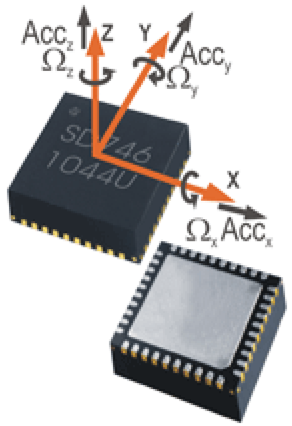
Overview

- Algorithm principles for angular estimation
- Kalman filter algorithm
- ASIP design
- FPGA prototyping
- Testing



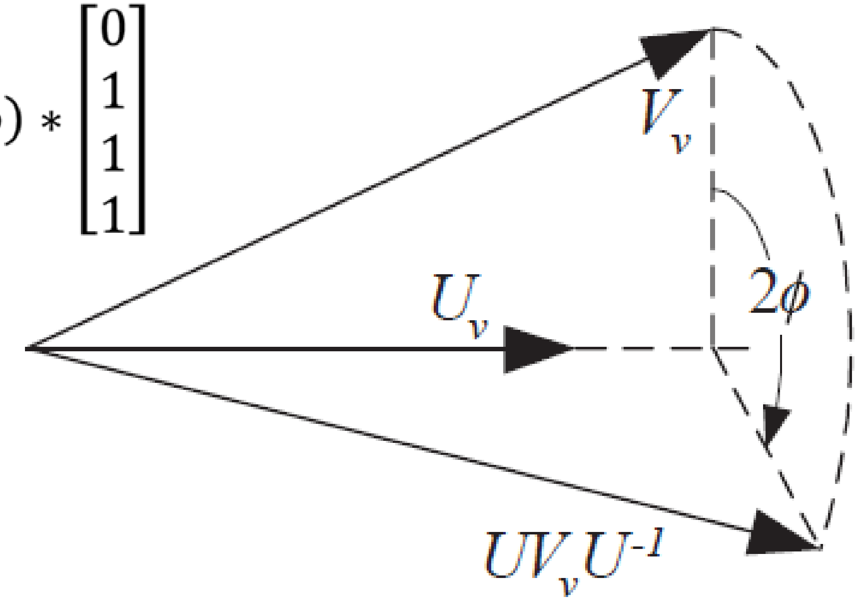
Introduction

- MEMS accelerometers and a gyros are widely used
- Sensor fusion algorithms are executed via software on CPU
- Integrated 6D IMU sensor (3D gyro + 3D accelerometer) are on the market
- It's nice to have a 6D IMU capable of sensor fusion data processing, interfacing with an external magnetic compass to enable a full 9D data fusion



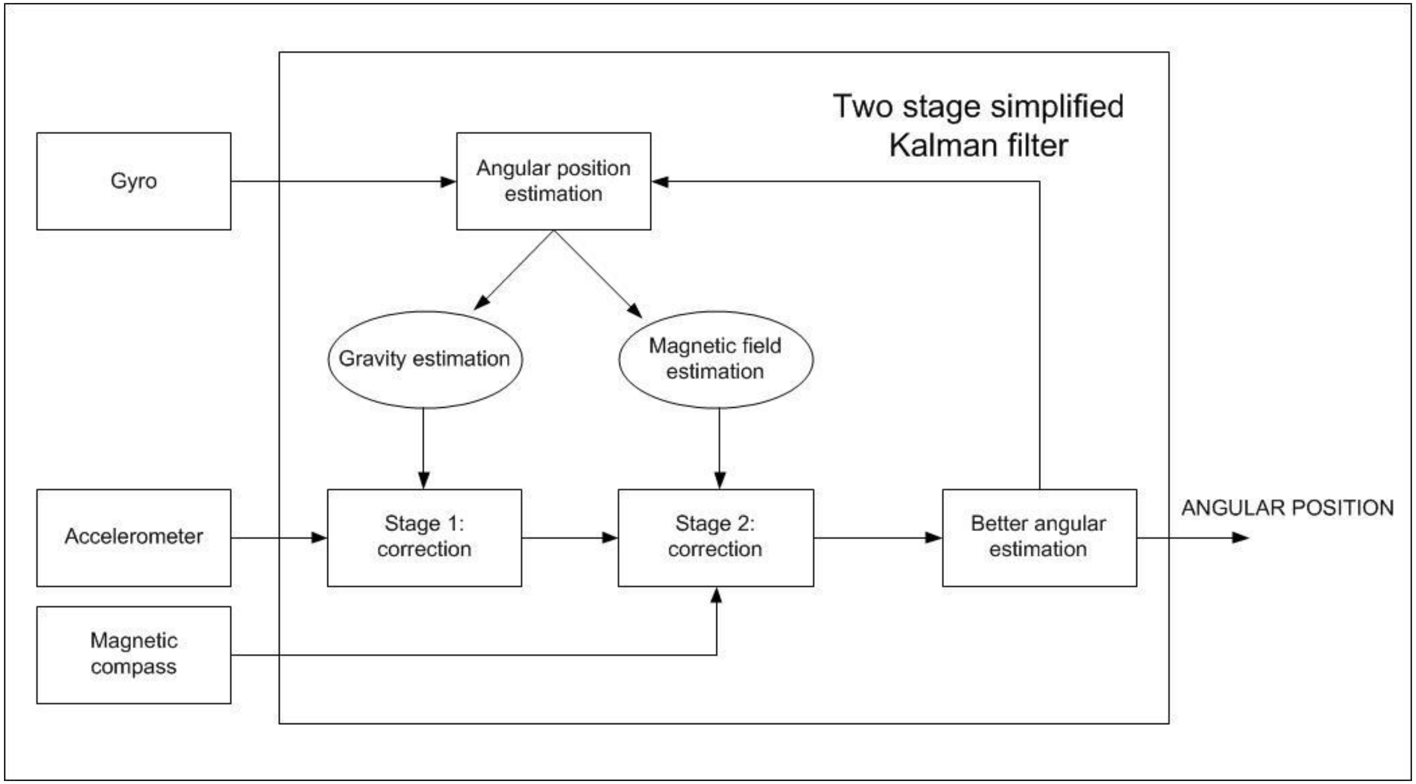
Algorithm principles (1)

- Angular position is represented using a quaternion
- A Two Stage Extended Kalman filter is used as sensor fusion algorithm between gyro, accelerometer and magnetic compass data
- A MathWorks Simulink model was built for first testing with simulated and real acquired data
- $\boldsymbol{U} = cos(\boldsymbol{\phi}) * \begin{bmatrix}1\\0\\0\\0\end{bmatrix} + \boldsymbol{U_v} * sin(\boldsymbol{\phi}) * \begin{bmatrix}0\\1\\1\\1\end{bmatrix}$



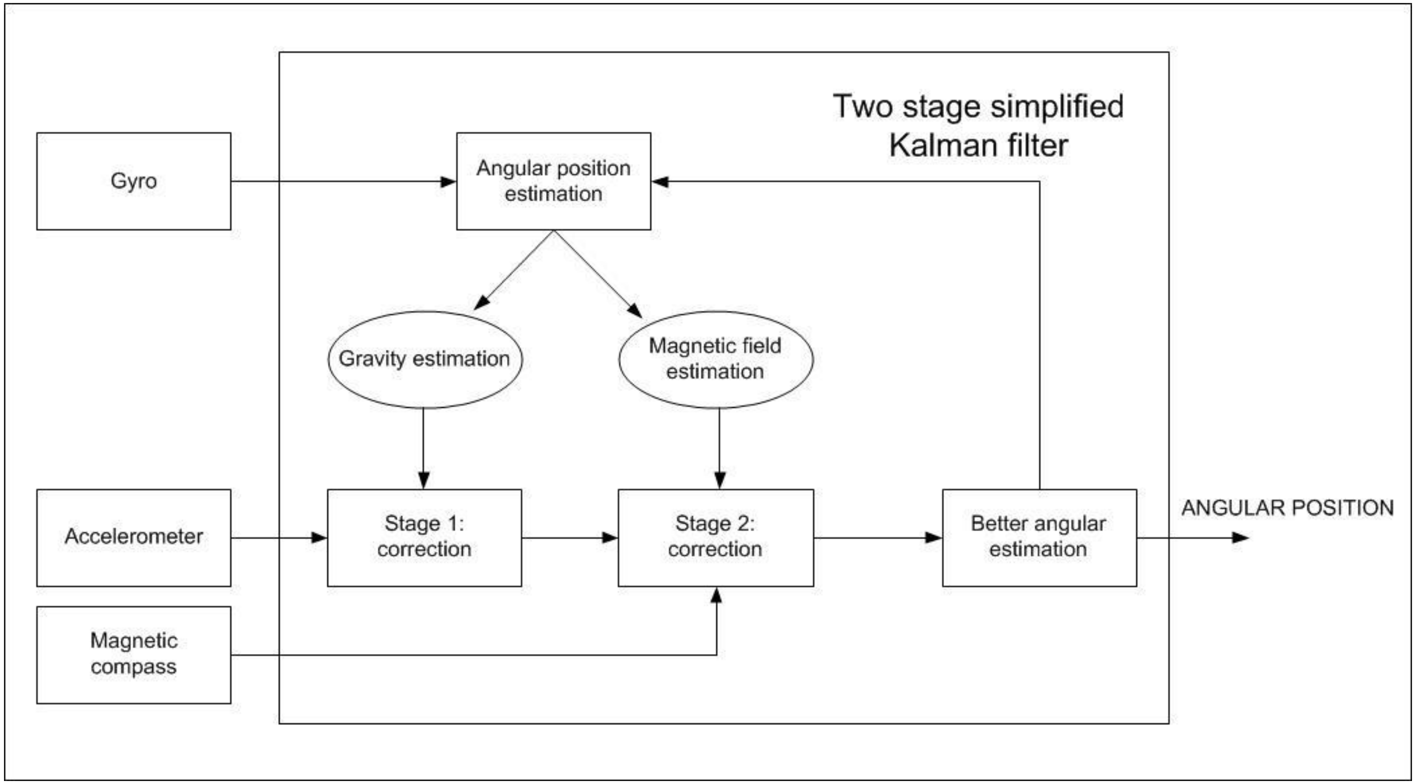
Algorithm principles (2)

- Updated angular position is calculated using gyro data
- A correction of roll and pitch angles is done on the first stage comparing the expected gravity with accelerometer data
- A correction of yaw angle is done on the second stage comparing expected magnetic field with the measured one



Algorithm principles (3)

- **Advantages of the two stage filter:**
  - **A lot less computational intensive**
  - **A magnetic anomaly does not influence roll and pitch angles**
  - **Easy to adapt to work with accelerometer correction only**



Kalman filter algorithm

- **A priori state equation**

$$x_k^- = A\hat{x}_{k-1} + Bu_k$$

- **A priori system covariance matrix**

$$P_k^- = AP_{k-1}A^T + Q$$

- **Kalman gain**

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$$

- **A posteriori system correction**

$$\hat{x}_k = \hat{x}_k^- + K(z_k - H\hat{x}_k^-)$$

- **A posteriori covariance matrix**

$$P_k = (I - K_k H)P_k^-$$

Algorithm simplifications

- The final error covariance P is considered constant
- Gyro, accelerometer and magnetic compass noise are considered constant and known
- Several optimisations done on matrix algebra

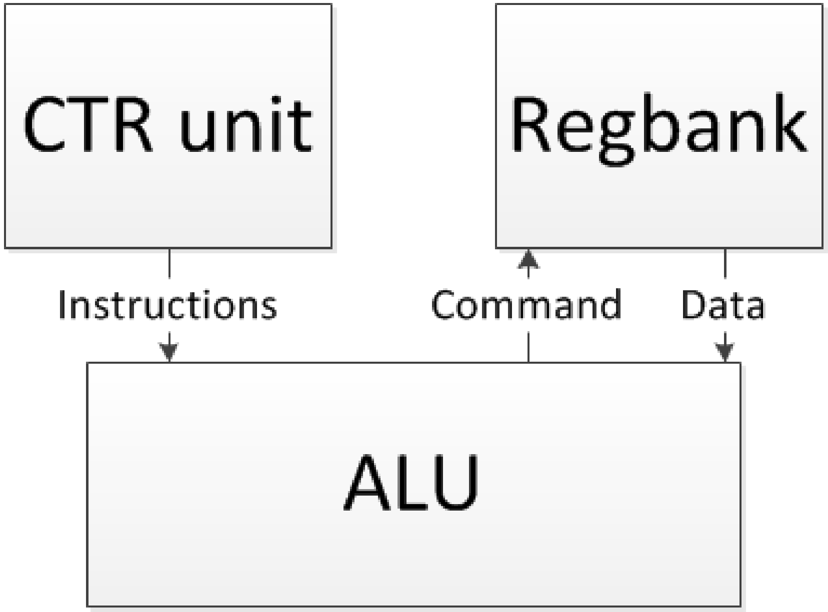
  - Simplified bit true model in Simulink
  - ASIP design
  - FPGA prototyping for full testing

ASIP design

- **ASIP design was done using TSMC 0.18 µm technology, used for SensorDynamics ASIC design**
- **Constrains:**
  - **area 0.5 mm^2**
  - **power consumption 100 µA**
- **An ASIP with RISC architecture allows to meet area and power requirements and remains flexible for future algorithm updates**

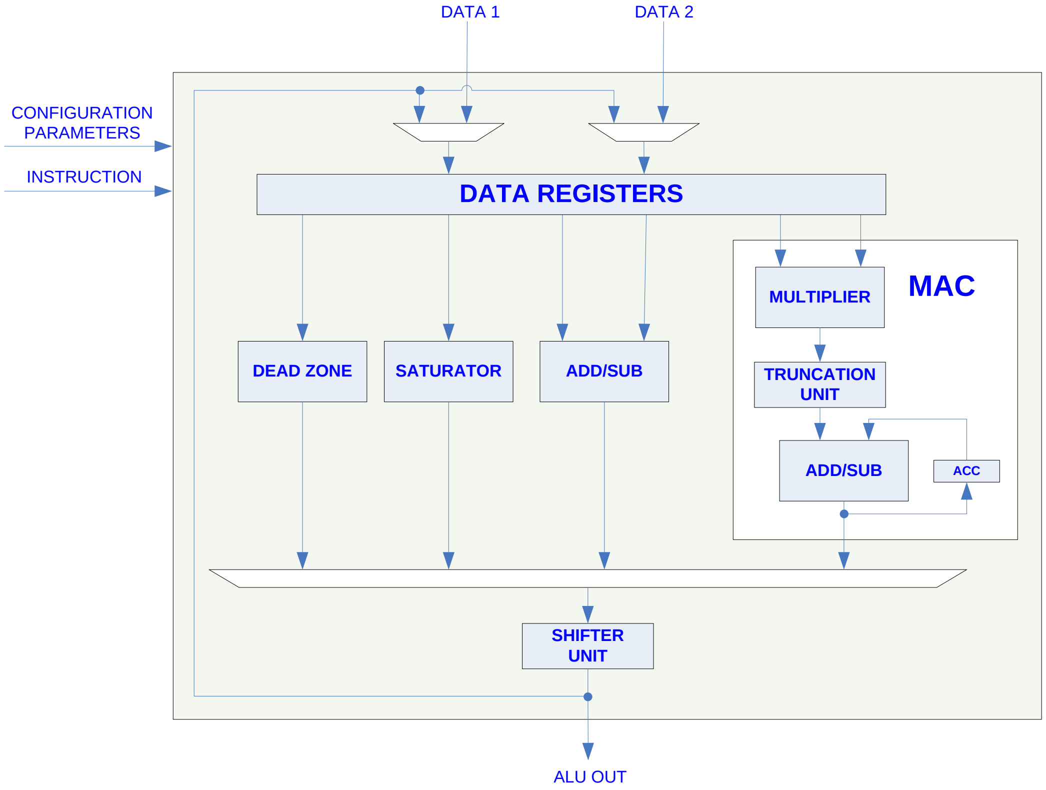
ASIP architecture (1)

- 3 main parts: Control Unit, ALU and Regbank
- The instructions to be executed are stored on a ROM
- The control unit has a mixed approach between the hardwired and the programmed solution
- The regbank is composed by two register groups to maximize performance for ALU data loading



ASIP architecture (2)

- **ALU is capable of sum, multiplications, MAC operations, dead zone and saturations on 20 bit input data**
- **Each instruction of the computation unit is performed into two steps: the fetch and decode operation and the execute and write operation**

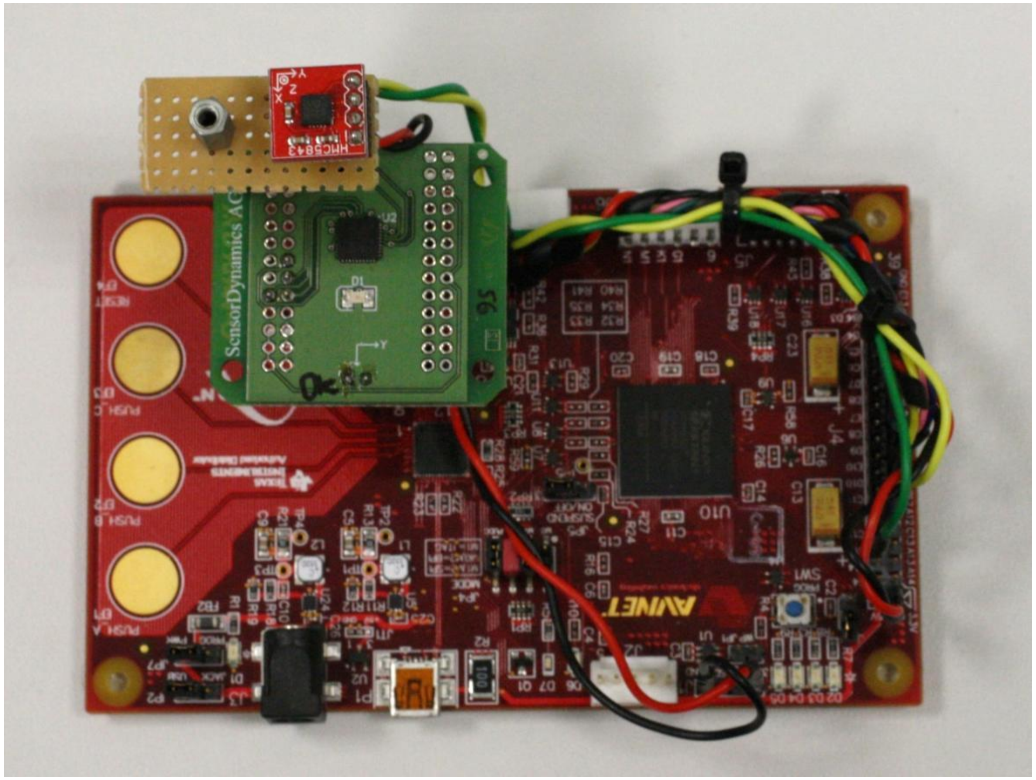


ASIP synthesis

- **ASIP was synthesized with TSMC 0.18 µm standard cells**
- **Final area occupation is 0.36 mm^2 that is 16.8 Kgate equivalent**
- **Estimated power consumption is 75 µA in active mode and 1.5 µA for leakage current**
- **Area and power constrains are met**

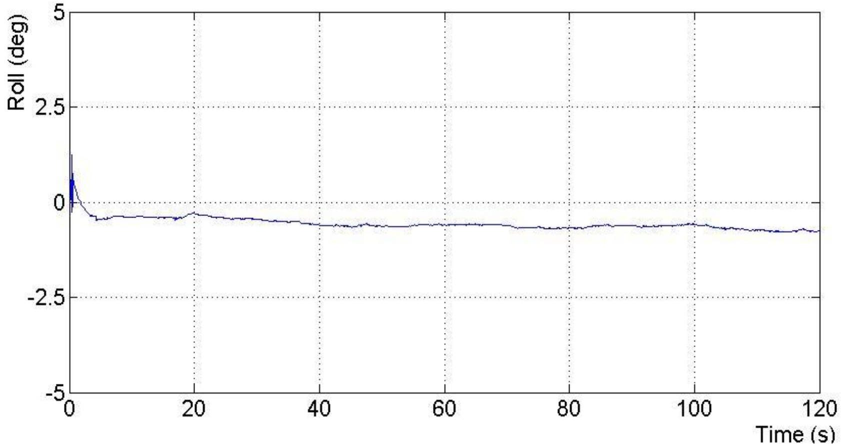
FPGA prototyping

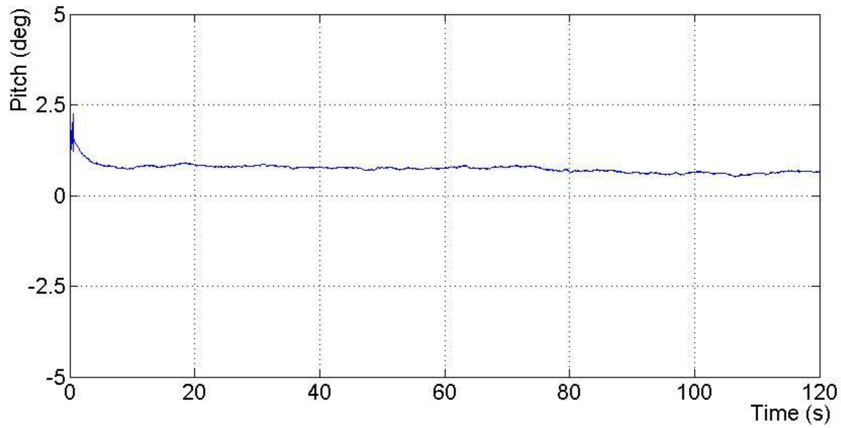
- A proof of concept was synthesized on Xilinx Spartan FPGA
- The FPGA is interfaced via SPI with an existing 6D sensor SD746 by SensorDynamics, via I2C with Honeywell HMC5843 Magnetic compass and via UART to a PC for data acquisition and for a real time demo

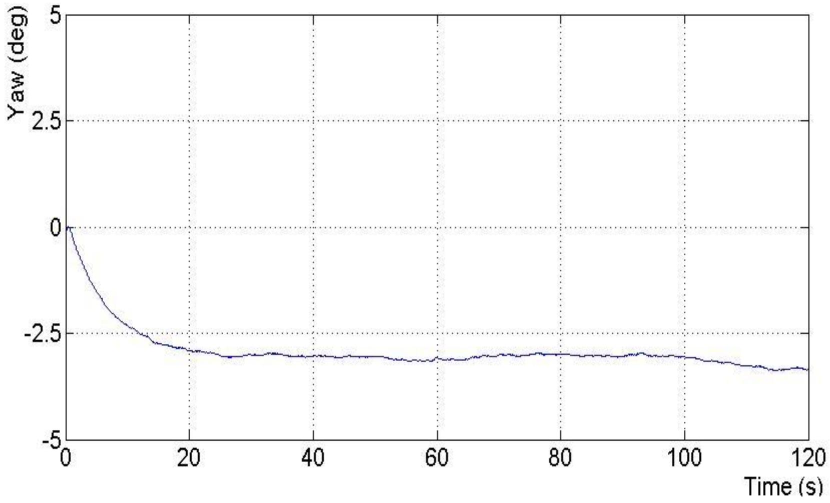


Testing (1)

- **Drift due to gyro bias is eliminated**

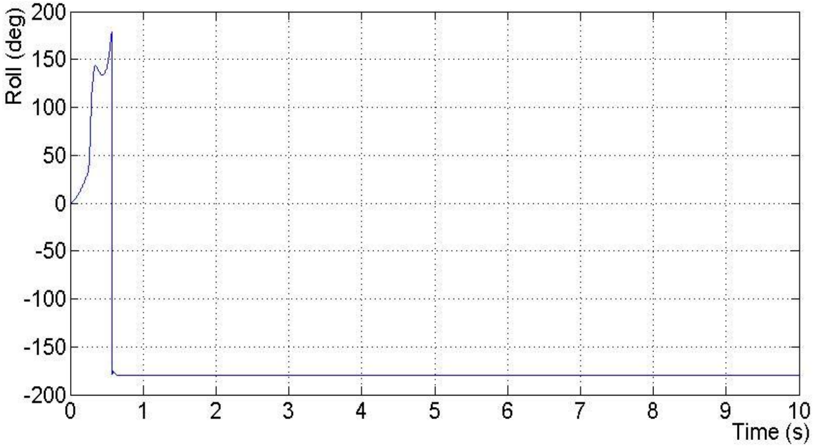


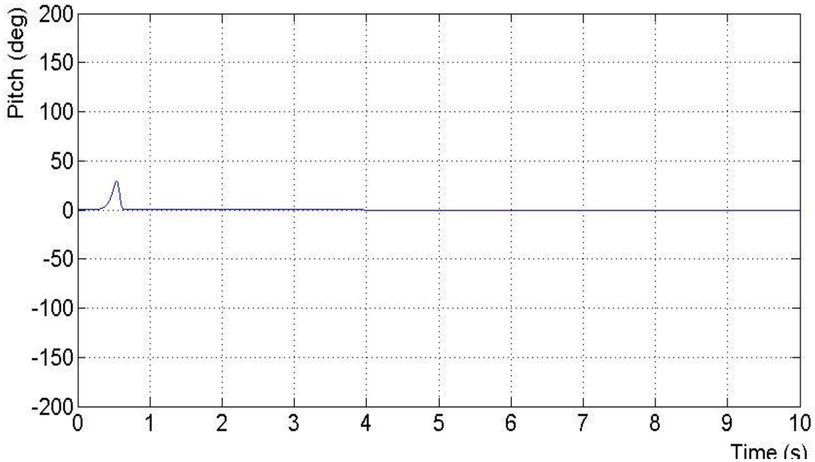


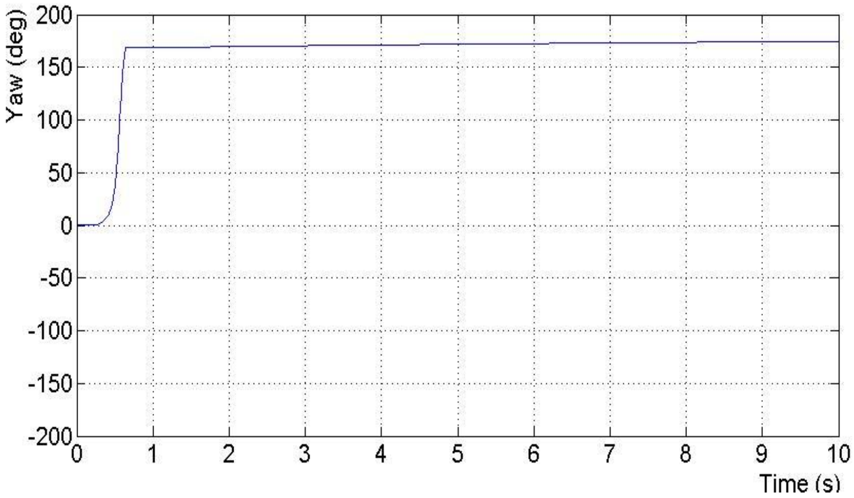


Testing (2)

- **The initial position is quickly estimated also if the system is starting up-down**



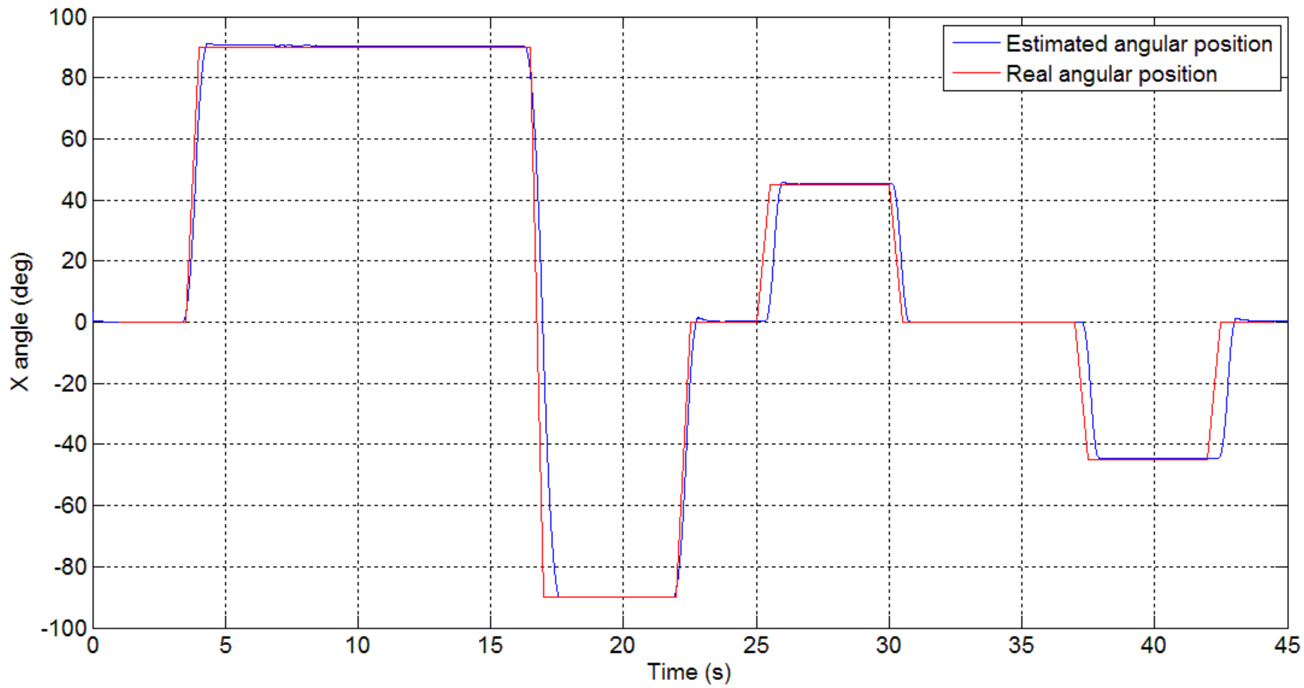




Testing (3)

- **Random movements on a test machine: the final error is less than 1 degree**

X angle with Kalman filter on



Conclusions

- **Simplified Two Stage Kalman filter algorithm development**
- **ASIP design and FPGA prototype**
- **Good results for all the tree axes**

  - **What’s next?**
  - **Gyro bias estimation**
  - **Magnetic compass calibration**
  - **ASIP on silicon integration within sensor logic**

Thank you!!!