MEMS-BASED INERTIAL ATTITUDE NAVIGATION SYSTEM FOR SOUNDING ROCKETS

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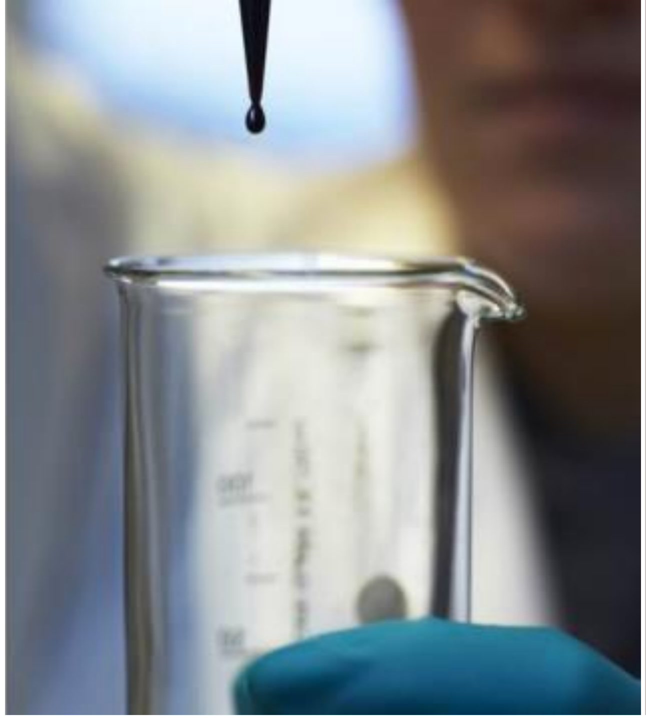
RISE Research Institutes of Sweden

ICT
Acreo
Sensorsystem



Outline

- Project overview
- Project background
- Hardware overview
- Sensor overview
- Signal processing
- Conclusion

Project Overview

- Swedish title: “MEMS-baserade attitydmätsystem för nyttolaster”
- Together with the Swedish Space Corporation and RUAG Space within NRFP 3, Acreo will design an attitude navigation system
  - Based on an Inertial Measurement Unit (IMU)
    - STIM300: compact, high performance
  - The angular velocity integration accumulates error
    - Mitigated using direct attitude observations
    - Using a magnetometer and a sun sensor
  - Perform measurements on a sounding rocket
- Possible applications include
  - Main objective: Attitude navigation of carried instruments
  - Future possibilities: Guidance, alignment etc.

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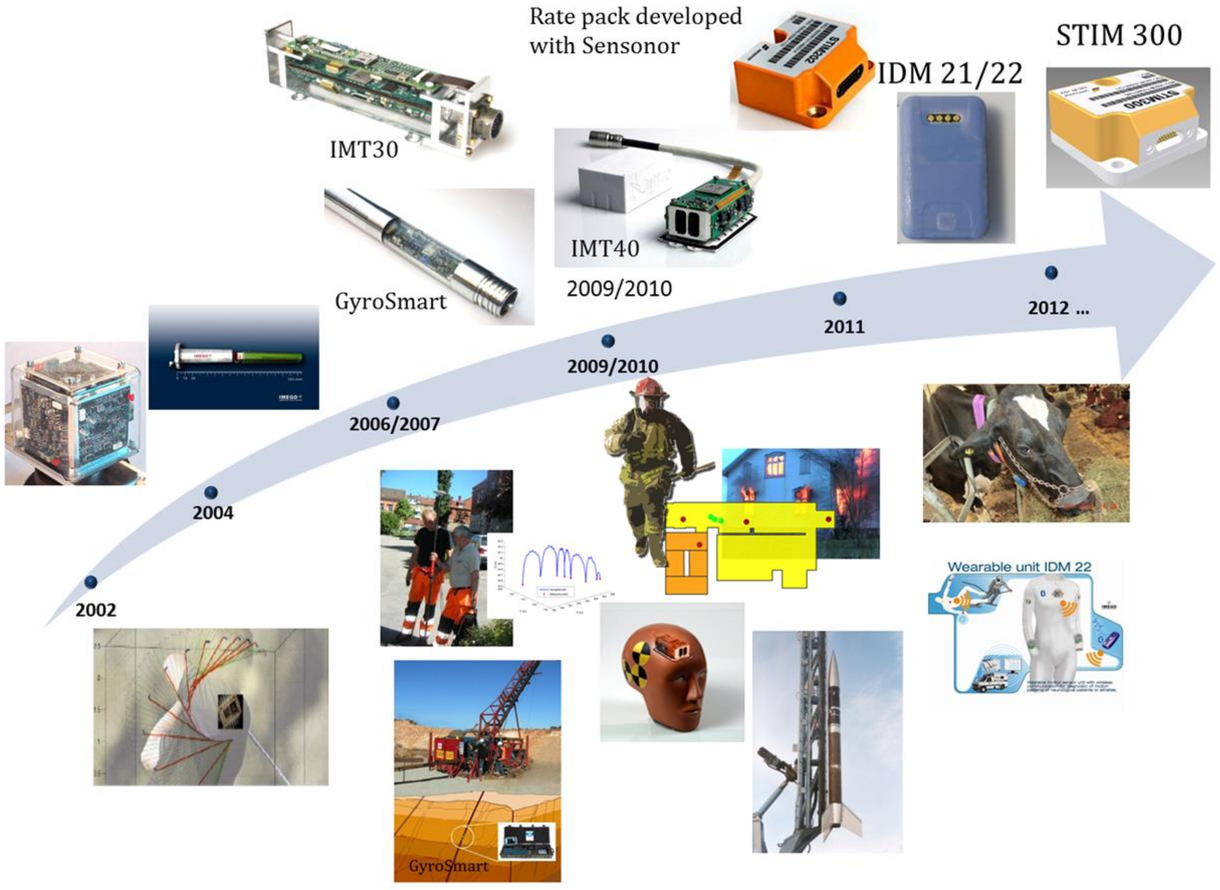
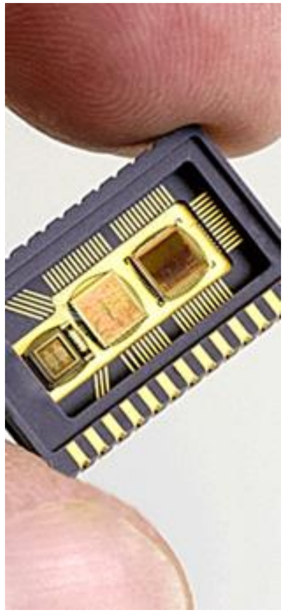
Project Background

- Acreo has been developing MEMS gyroscopes and IMUs for ~20 years
  - Earlier under the name IMEGO (1999-)
- Acreo is now part of RISE, www.ri.se, Research Institutes of Sweden
- Several generations of IMUs for many applications, including
  - Drill hole mapping (GyroSmart)
  - Crash test measurement (IMT40)
  - STIM300 commercialized by Sensonor AS, Horten, Norway



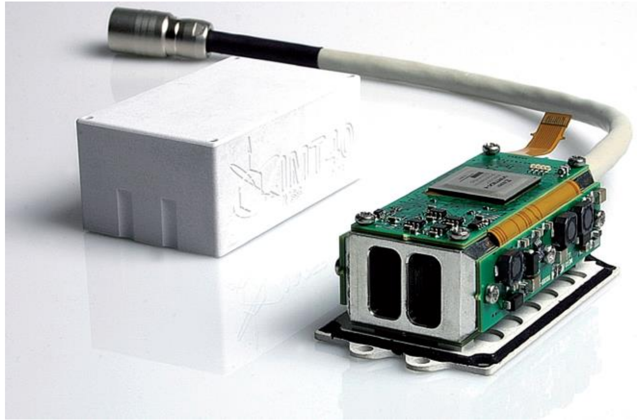
Project Background

- MEMS (microelectromechanical systems) are suitable for IMUs
  - Small, robust, high performance, cheap in mass production
- IMT40 developed by IMEGO ~10 years ago
  - 1 x 3-axis gyroscope
  - 3 x 3-axis accelerometers (different ranges)
  - Fits in the heel of a crash test dummy
- Flew on a Rexus 6 sounding rocket
  - Data was post-processed
  - No magnetometer was available
  - Sun sensor failed in flight
  - Current project is the next step



MEMS gyroscope

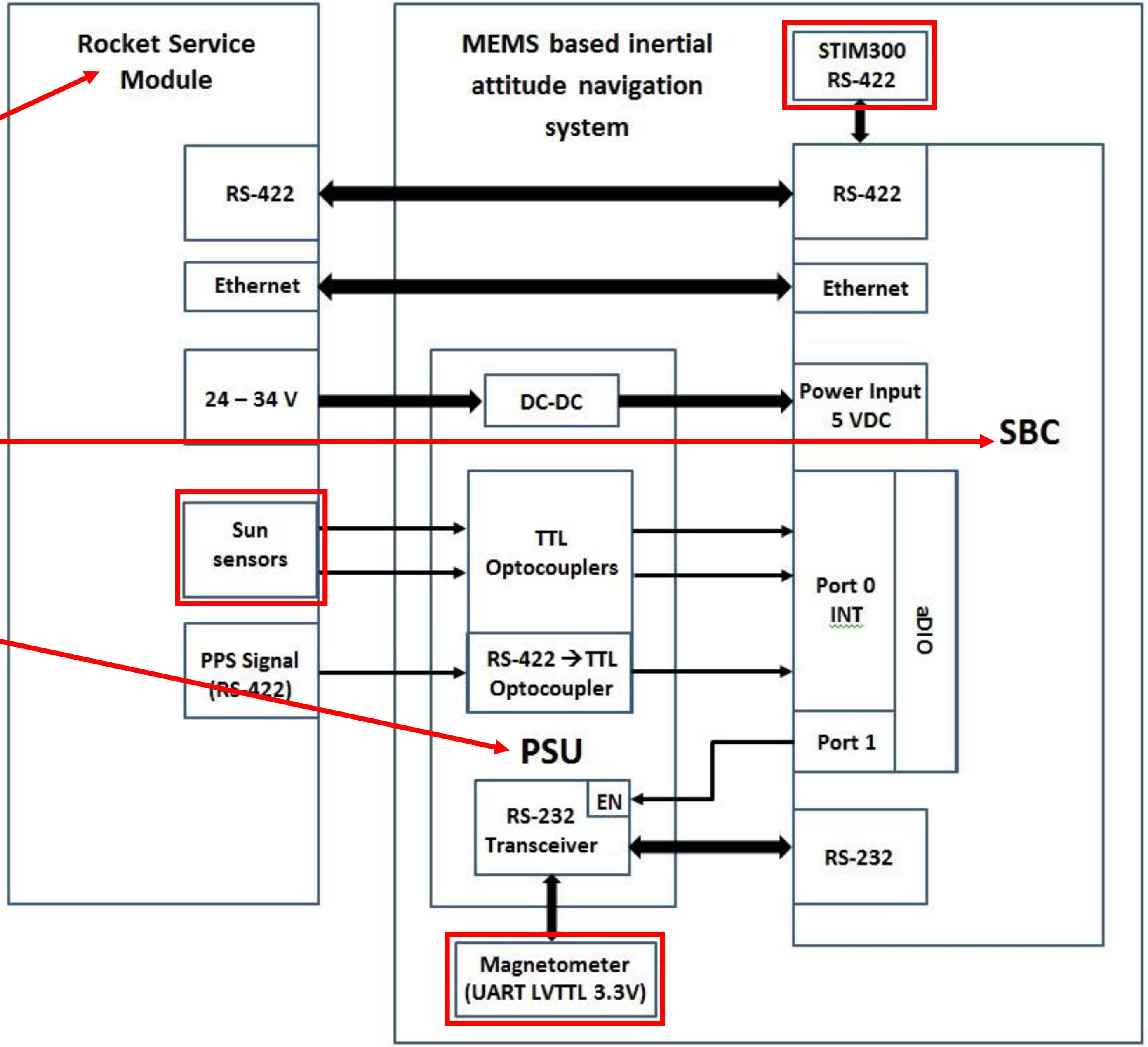
Measuring crash test dummy motion



IMEGO IMT40

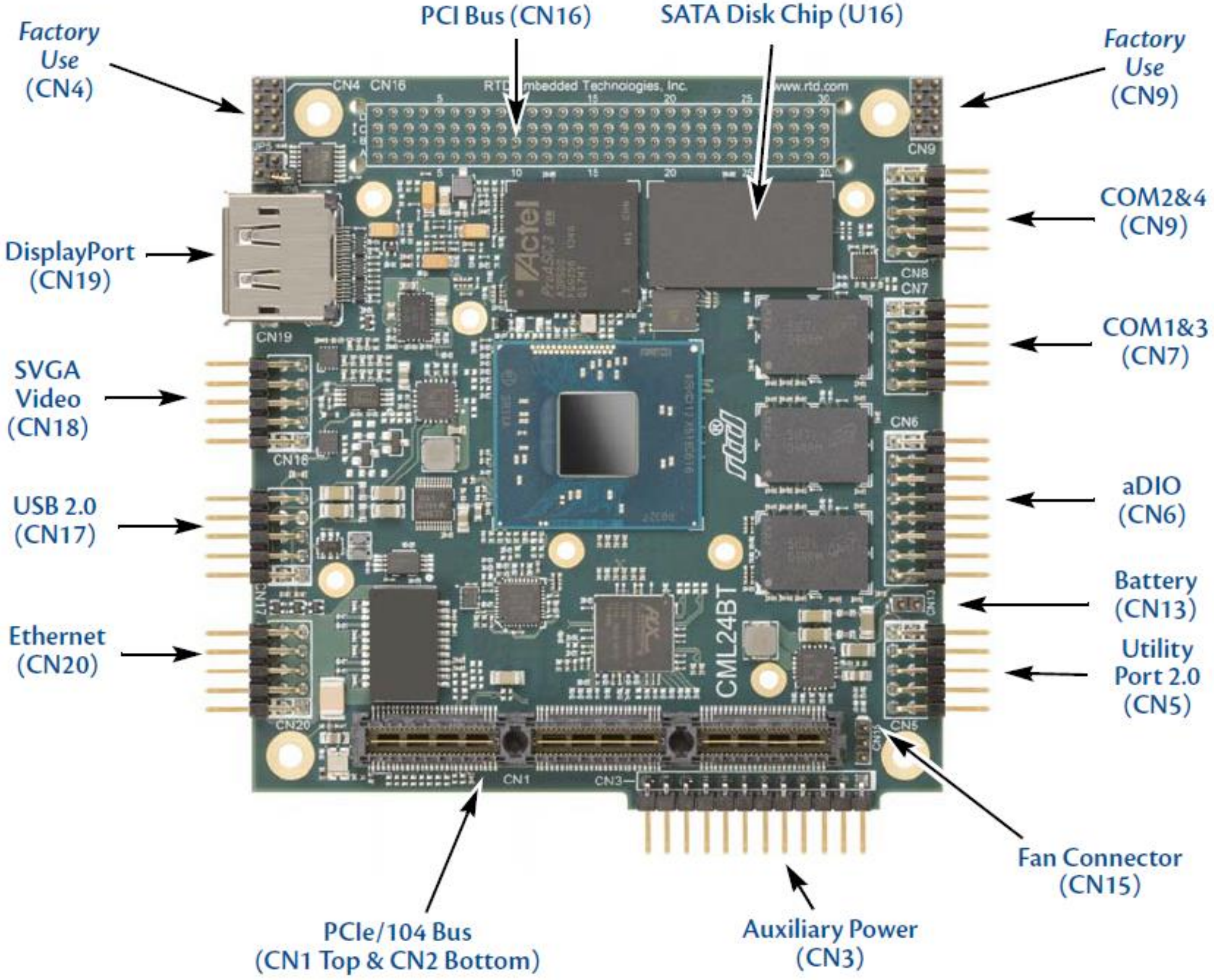
Hardware Overview

- Rocket Service Module
  - Interface present in rocket
- Attitude navigation system
  - Single Board Computer (SBC)
  - Power Supply Unit (PSU) and electronics
  - Sensors
    - Inertial measurement unit
    - Magnetometer
    - Sun sensor
- Hardware has been tested
  - One problem was found and is being fixed



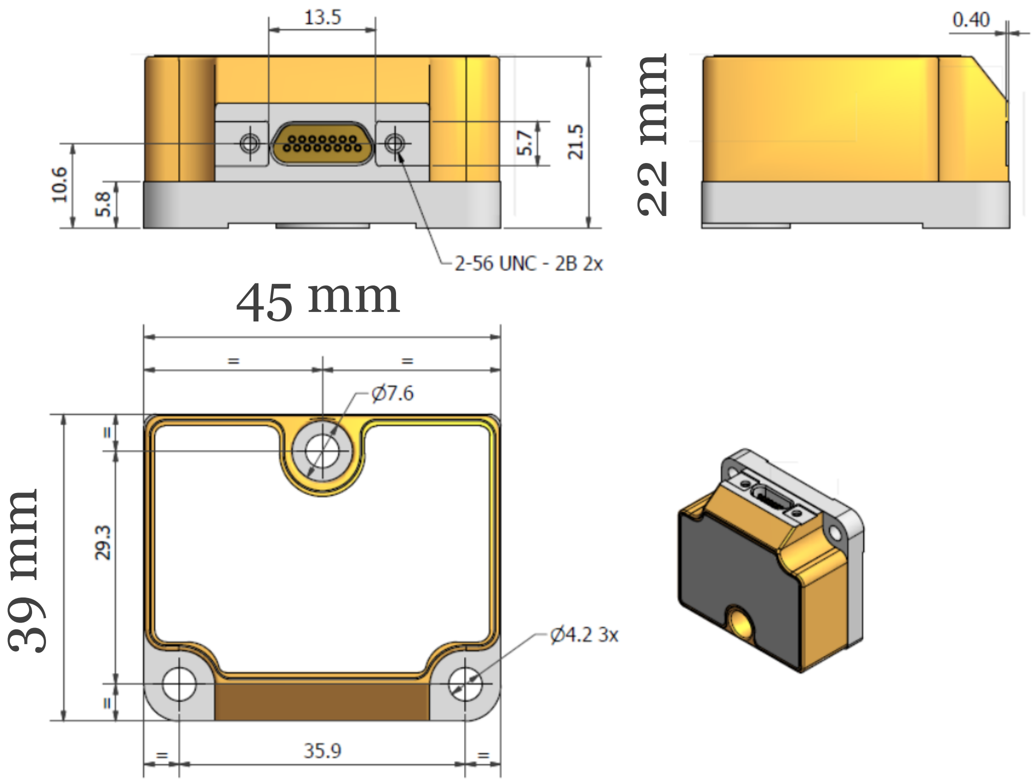
Single Board Computer (SBC)

- Intel quad-core processor, 1.9 GHz
  - 4 GB SDRAM, 32 GB SSD
- Serial Ports
  - RS-422 and RS-232
  - Communication, data acquisition
- Ethernet interface
  - Communication with the Rocket Service Module
  - CCSDS compatible
- Extended temperature range
- Isolated digital inputs and outputs



Sensors: Inertial Measurement Unit (IMU)

- STIM300 by Sensonor
  - 3-axis MEMS gyroscope (using 2000 deg/s)
    - Scale factor accuracy: 500 ppm
    - Bias Instability (Allan deviation): 0.7 deg/h
    - Angular Random Walk: 0.20 deg/sqrt(h)
  - 3-axis MEMS accelerometer (using 30 *g*)
    - Scale factor accuracy: 300 ppm
  - 3-axis inclinometer (low range, low bandwidth)
    - For initial alignment
  - Standard RS-422 interface
  - Weight: 55 g



Sensors: Magnetometer and Sun Sensor

Magnetometer

- Small Magnetometer In Low mass Experiment (SMILE)
  - Provided by Dr. Nickolay Ivchenko (KTH)
  - Miniaturized digital fluxgate magnetometer
  - Mass is 21 g, 20 mm per side
  - Sampling rate of 250 sample/s
  - LVTTL level (3.3 V high) serial UART interface
  - Internal non-volatile flash memory of 4 Gbit

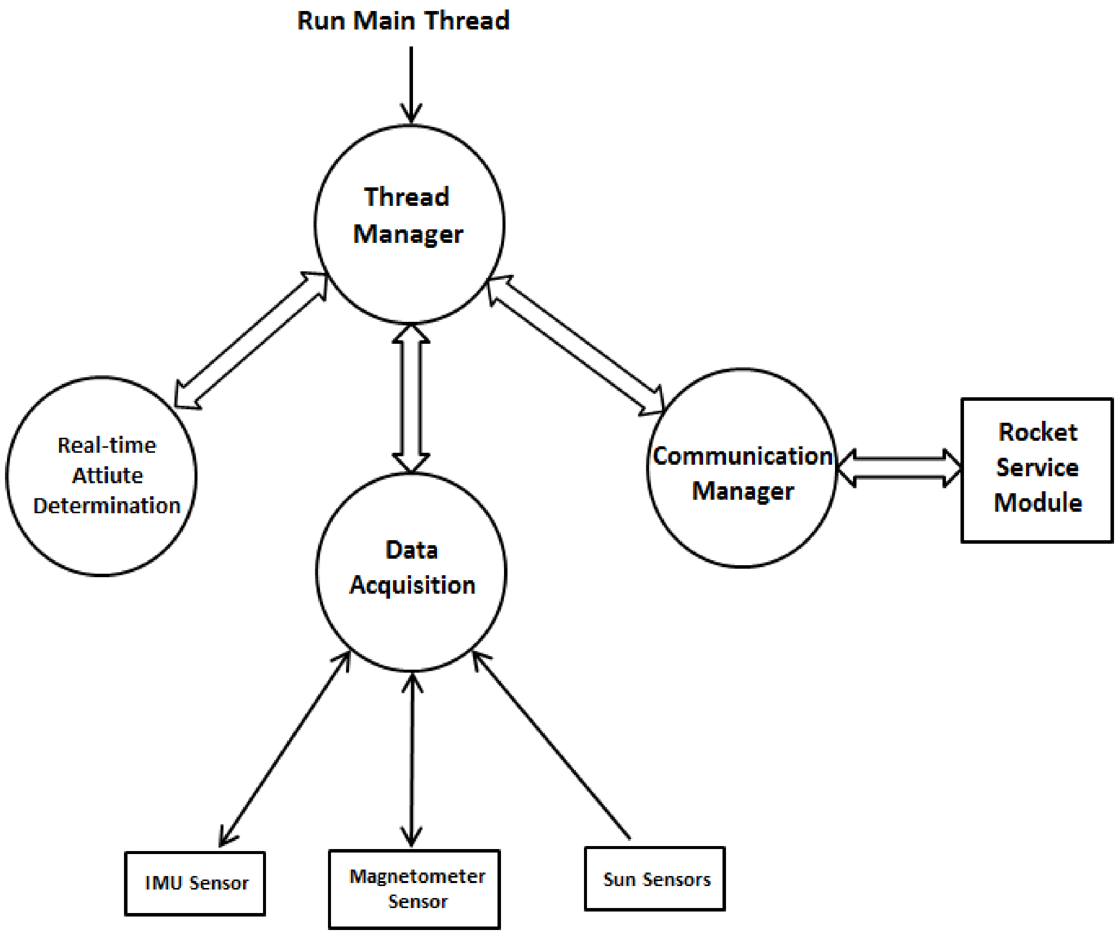
Photograph from M.Sc. thesis by I. A. Arriaga Trejo

Sun Sensor

- Placed on the rocket
- Determines the direction to the sun
- Produces pulses when sun light hits the aperture slits
- Second channel rotated 45 deg from first channel
  - Two digital sensor channels

System Software

- Multi-threaded C++ platform running on Linux
- Software components
  - Communication with the Rocket Service Module
  - Data acquisition from sensors
  - Buffering of data
  - Possibility for real-time attitude determination
    - First launch will *not* perform real-time navigation
    - Aim is to gather data and develop/evaluate the navigation algorithm in post-processing
    - Everything must of course be real-time compatible



Attitude Navigation

- The attitude can be found by integrating the angular velocity
- Project purpose: Obtaining instrument orientation during the entire flight
  - Target accuracy: ~1 deg
- Motion in the previous project flight:
  - Angular acceleration followed by steady rotation
    - 4 revolutions per second until 240 s
    - In total, 380 000 deg rotation
- Attitude navigation error dominated by the scale factor error
  - 1 deg total error would require a scale factor error of < 3 ppm
    - Such performance expectation is unrealistic
    - Additional attitude sensors are essential
- Error must be bounded using sensor fusion

Kalman Filtering, Overview

- The system is described by
  - State vector
  - Covariance matrix
    - Uncertainty about the state vector parameters
- Optimal state estimation using
  - State prediction
    - A system model
  - State observation
    - Observation using noisy sensors

- A typical Kalman filter loop
  - State is extrapolated in time…
  - … and process noise is added
  - Observations are predicted…
  - … and compared to actual observations
  - State and covariance is updated

Attitude Navigation, Kalman Filtering

- Let us try to do that!
  - Let the state contain the attitude
  - State prediction
    - Gyroscope data
    - Attitude equations
  - State observation
    - Magnetometer
    - Sun sensor
    - Two directions (up and direction to the sun) allows complete observation of the state

- However, we get a problem…
  - Q: What is the process noise?
    - That is, how accurate is the predicted attitude?
  - A: We do not know without modeling the gyroscope
- Without knowledge of both the process and observation noise, we cannot do optimal estimation
- We use an error state formulation

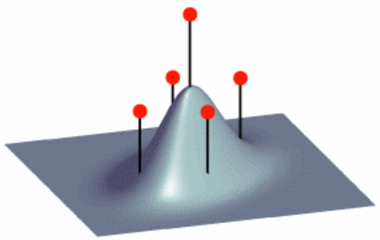
Attitude Navigation, Kalman Filtering, Error State Formulation

- Error state formulation
  - Let the state contain gyroscope parameters
    - Bias, scale factor correction etc. according to the application
  - Predict the attitude
    - Using gyroscope model
  - Observe the attitude...
    - ...and update the gyroscope error parameters
- The error state formulation allows
  1. Correction of the attitude
  2. Feedback to the gyroscope model
     - Will improve the performance of the gyroscope by adjusting drifts etc.

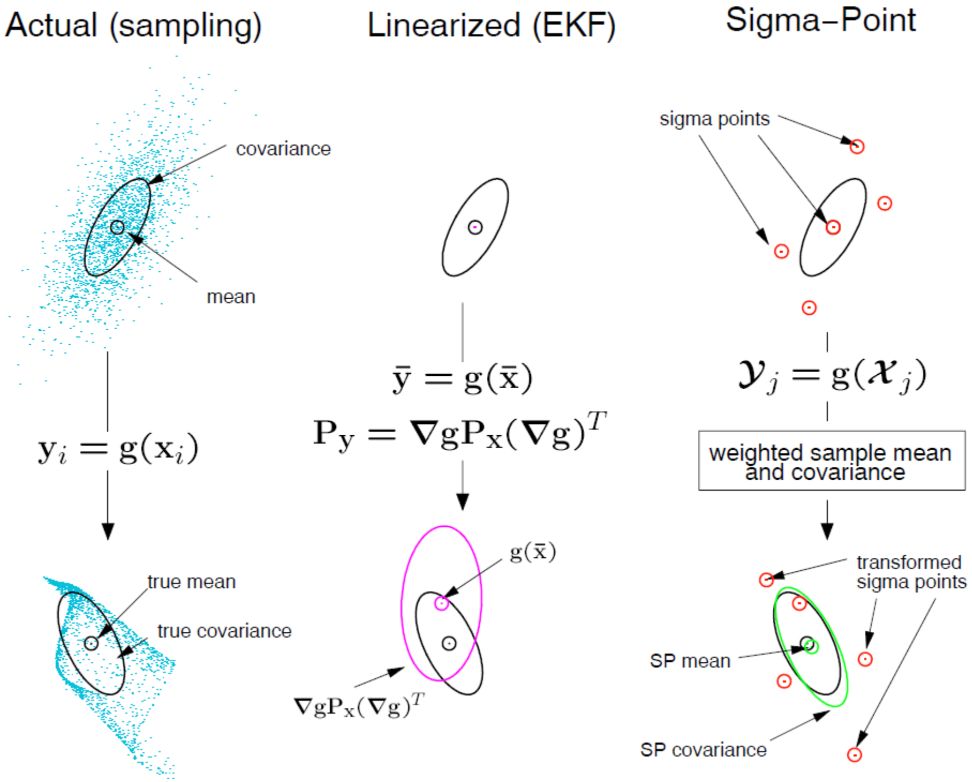
- Sensors complement each other
  - Gyroscope provides high-bandwidth updates
  - Additional sensors limit long-term error and correct the gyroscope output

Sigma-Point Kalman Filters

- Traditional Kalman filters work for linear prediction and observation functions
- In our nonlinear case, the problem is to transform the covariance matrix through the prediction/observation functions
- Traditionally: Linearization (extended Kalman filter, EKF)
  - Requires significant analytical work (differentiation)
- Alternatively: Using a set of representative points (sigma-point Kalman filter, SPKF)
  - Easier to implement
  - Similar computational complexity
  - Similar or better performance as EKF



The sigma-point approach



EKF and SPKF, from van der Merwe et al., AIAA Guidance, Navigation, and Control Conference and Exhibit, p. 5120 (2004)

Conclusion

- An attitude navigation system has been designed
  - Based on an IMU (STIM300), a magnetometer, and a sun sensor
- Accuracy target is ~1 deg
  - Using a Kalman filter in an error state formulation
  - IMU enables accurate high-bandwidth navigation on a short time scale
  - Additional sensors limit the error on a long time scale
- System is being finalized
  - One hardware problem is being corrected

Thank you for your attention