Attitude Estimation using low-cost MEMS Sensors

EE617 Sensors in Instrumentation (Instructor: Prof. Siddharth Tallur)

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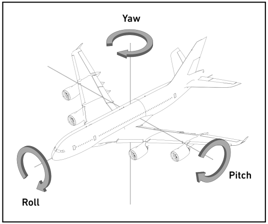
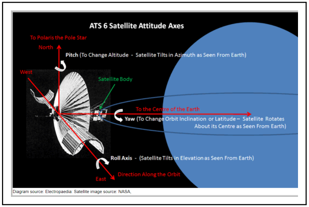
Why Attitude Matters

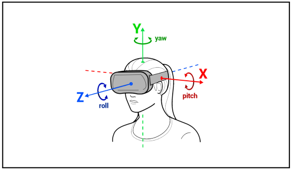
- Attitude (not to be confused with disposition or state of mind) of any rigid body describes how it is oriented in space with respect to some frame of reference
- In various applications such as in spacecrafts, aeroplanes, navigation systems, land vehicles, smartphones, VR gadgets, fitness trackers, etc, estimating the attitude accurately is of utmost importance



Source: Wikipedia



Source: https://www.mpoweruk.com/satellites.htm



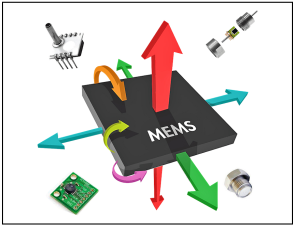
Source: https://www.awwwards.com/vr-is-ready-for-consumers-are-you-ready-for-it.html

Mathematically Describing Attitude

- There are 2 ways to describe attitude which are commonly used:
  - Euler Angles - (α, β, γ) or (ψ, θ, ϕ) or (yaw, pitch, roll)
  - Quaternions - $a + b\mathrm{i} + c\mathrm{j} + d\mathrm{k}$
- Euler angles represent the orientation in terms of angles by which body underwent sequence of rotations along principal axes
- Quaternions have 2 parts - scalar 'a' which represents amount of rotation and vector (b, c, d) which represents axis of rotation
- There are other ways to describe orientation such as rotation matrices

Sensors for measuring Attitude

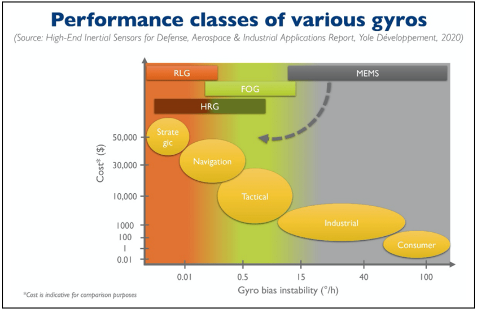
- Today, in almost all applications where we want to measure attitude, we use a class of sensors called **Microelectromechanical Systems (MEMS)**
- MEMS **Accelerometers** measure the proper acceleration while MEMS **Gyroscopes** measure the rate of change of orientation along primary axes in body frame
- MEMS **Inertial Measurement Units (IMUs)** use a combination of accelerometers, gyroscopes and sometimes magnetometer, to report the same quantities



Source: https://www.fierceelectronics.com/components/roger-grace-authors-eight-part-series-sensor-mems

Sensors for measuring Attitude

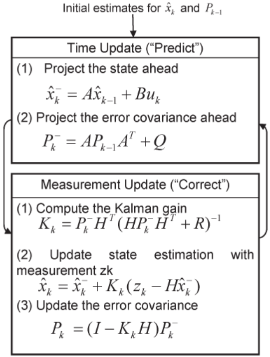
- Typically, the performance of gyroscopes is limited by drift while performance of accelerometers is limited by high frequency noise due to vibrations
- To get more precision we need high grade sensors which are costly



Source: https://semiengineering.com/are-todays-mems-gyros-good-enough/

Getting high accuracy with low-cost sensors

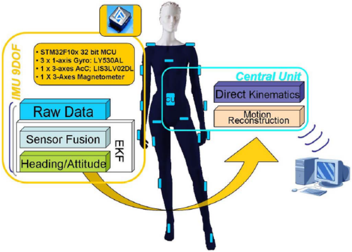
- Over the years, lot of research has been done in the field of State Estimation and Control
- We borrow some of these ideas which allow us to combine information from multiple noisy sensors and produce estimates whose accuracy is comparable to high grade sensors
- The literature that I reviewed used 4 kinds of filtering algorithms:
  - Kalman Filter (KF)
  - Extended Kalman Filter (EKF)
  - Unscented Kalman Filter (UKF)
  - Digital Complementary Filter

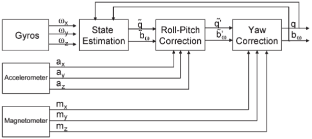


Source: Carmen M. N. Brigante, Nunzio Abbate, Adriano Basile, Alessandro Carmelo Faulisi, and Salvatore Sessa, "Towards Miniaturization of a MEMS-Based Wearable Motion Capture System", *IEEE Transactions on Industrial Electronics*, vol. 58, no. 8, August 2011.

Case Study 1 - Wearable Motion Capture System

- This work presents a modular architecture to develop a wearable system for real-time human motion capture
- A **quaternion based EKF** algorithm is used for fusing the information from three-axis accelerometer, a three-axis magnetometer, and a three-axis gyroscope
- Compared to commercial systems, the cost of the proposed system was reduced by a factor of about eight due to an embedded design based on MEMS sensors





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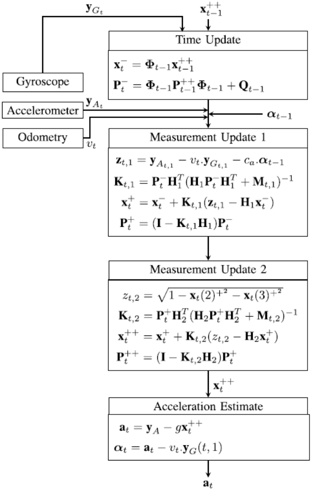
Case Study 2 - Moving Land Vehicle

- Typically, an accelerometer is used to correct gyroscope drift by measuring the attitude from gravitational acceleration
- This is difficult in vehicular applications as accelerometer measurements are corrupted by external accelerations produced due to vehicle movements
- Authors show that vehicle kinematics allow the removal of external accelerations from the lateral and vertical axis accelerometer measurements

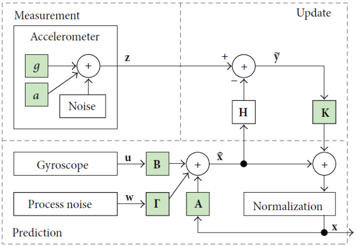


Ref: Hamad Ahmed and Muhammad Tahir, "Accurate Attitude Estimation of a Moving Land Vehicle Using Low-Cost MEMS IMU Sensors", *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 7, July 2017.

Simulations

- In order to compare how different algorithms perform for simple attitude stimation task, I implemented KF, EKF and UKF in MATLAB
- The input data was taken from my smartphone's accelerometer and gyroscope when it was in motion
- True states were simulated by adding gaussian noise with specified covariance matrices using MATLAB functions
- All the estimates were plotted on the same graph to see how well they track true states

Simulations



Source: Heikki Hyyti, Arto Visala, "A DCM Based Attitude Estimation Algorithm for Low-Cost MEMS IMUs", *Hindawi Publishing Corporation International Journal of Navigation and Observation*, Volume 2015, Article ID 503814

```matlab
for k=1:999
    % Linearization
    A_EKF = delf_delx(x_hat_EKF(:,k),u(:,k),freq);

    % Prediction
    x_hat_predict_EKF(:,k) = process(x_hat_EKF(:,k),u(:,k), freq); % Non Linear
    P_predict_EKF(:,:,k) = A_EKF*P_EKF(:,:,k)*A_EKF' + (Gamma^2).*Q;

    % Kalman Gain Computation
    R_EKF = meas_noise_cov(f(k+1),x_hat_predict_EKF(1:3,k),var_a, var_f, g);
    L_EKF(:,:,k) = P_predict_EKF(:,:,k)*H'/(H*P_predict_EKF(:,:,k)*H' + R_EKF);

    % Update
    e_EKF(:,k) = y(:,k+1)-H*x_hat_predict_EKF(:,k);
    x_hat_EKF(:,k+1) = x_hat_EKF(:,k) + L_EKF(:,:,k)*e_EKF(:,k);
    P_EKF(:,:,k+1) = (eye(6)-L_EKF(:,:,k)*H)*P_predict_EKF(:,:,k);

    % Normalization
    norm_mat = cat(1, cat(2, eye(3)./norm(x_hat_EKF(1:3,k+1)),zeros(3,3)),cat(2,zeros(3,3),eye(3)));
    J = norm_jacobian(x_hat_EKF(:,k+1));
    x_hat_EKF(:,k+1) = norm_mat*x_hat_EKF(:,k+1);
    P_EKF(:,:,k+1)=J*P_EKF(:,:,k+1)*J';

    %Estimated Angles
    theta_hat_EKF(k+1)=asin(-x_hat_EKF(1,k+1));
    phi_hat_EKF(k+1)=atan2(x_hat_EKF(2,k+1),x_hat_EKF(3,k+1));
end
```

Source: MATLAB code written by me

Simulations

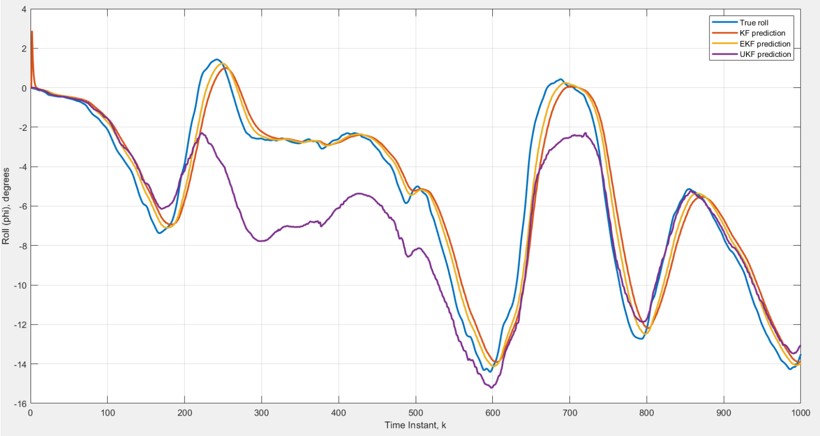


Figure: Estimating Roll (ϕ)

Simulations

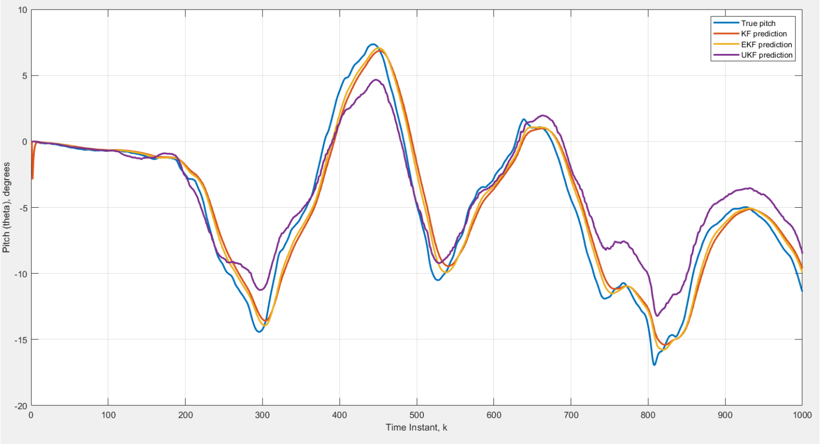


Figure: Estimating Pitch (θ)

Simulations

Table: Root Mean Squared Error comparison

	KF	**EKF**	**UKF**
RMSE for θ (radians)	0.0241	0.0189	0.0321
RMSE for ϕ (radians)	0.0231	0.0155	0.0428

For this system it is evident that EKF performs better than both KF and UKF. Among KF and UKF, KF performs better.

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