EC4.404: Mechatronics System Design

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General Information

Mechatronics: Study of the integration of mechanical hardware, electrical/electronic hardware with computer hardware and software. Named by Tetsuro Mori from Japan when working with Yaskawa Electric Coorporation.
Applications: Robotics, Aerospace industry, automotive industry, process industry etc.

Course Objective: To introduce the design and development of a mechatronic system.
Instructors: Harikumar Kandath and Nagamanikandan Govindan.

Course Contents

UNIT 1 ◊ Sensors - structure of measurement systems, static characteristics, dynamic characteristics. ◊ Sensors in robotics - position, speed, acceleration, orientation, range. ◊ Actuators - general characteristics, motors, control valves.

UNIT 2 ◊ Computer based feedback control: Sampled data control, sampling and hold, PID control implementation, stability, bilinear transformation.

Instructor: Harikumar Kandath

Course Contents

UNIT 3 ◊ : Introduction to mechanical elements and

transformations, basic concepts of kinematics and dynamics.

UNIT 4 ◊ Design and analysis of mechanisms.

UNIT 5 ◊ Programming and hardware experiments.

Instructor: Nagamanikandan Govindan

Sensors in Ground Robot

- Wheel Encoder

- Magnetometer

- Inertial Measurement Unit (IMU): contains Accelerometer and Gyroscope.

- Global Positioning System (GPS)

- Range measuring sensor (LIDAR, ultrasonic, camera)

Sensors in UAV

- Inertial Measurement Unit (IMU) contains Accelerometer and Gyroscope.

- Altimeter

- Airspeed sensor

- Magnetometer

- Global Positioning System (GPS)

- Range measuring sensor (LIDAR, ultrasonic, RADAR, camera)

Sensors in Robotic Manipulator

- IMU

- Encoder

- Force-Torque sensor

- Camera

Position Estimation (Odometry)

$$\frac{dx}{dt} = v_x = V \cos \psi \tag{1}$$

$$x(t) = \int_0^t V \cos \psi \, dt + x(0) \tag{2}$$

$$\frac{dy}{dt} = v_y = V \sin \psi \tag{3}$$

$$y(t) = \int_0^t V \sin \psi \, dt + y(0) \tag{4}$$

NB: Errors in the measurement of V and ψ will lead to error in the above-mentioned position estimate.

# Limitations of using only wheel encoder and magnetometer for odometry

- The angle ψ will not change when computed using magnetometer if the robot can move sideways without changing the orientation.

- Error in wheel encoder based speed estimation during wheel slip. Slip is a condition where wheel rotates without changing the position of the robot as observed in the normal case (i.e. one complete rotation of the wheel does not corresponds to a distance of $2\pi r$) .

MEMS Accelerometer

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F(= ma) \qquad (5)$$

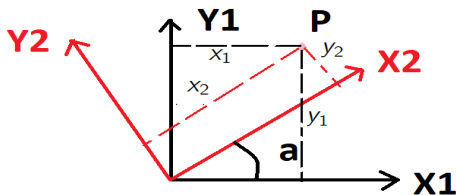For a step input, at steady-state $\frac{d^2x}{dt^2} = 0$, $\frac{dx}{dt} = 0$ making $x \propto F$.

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2 + bs + k} \qquad (6)$$
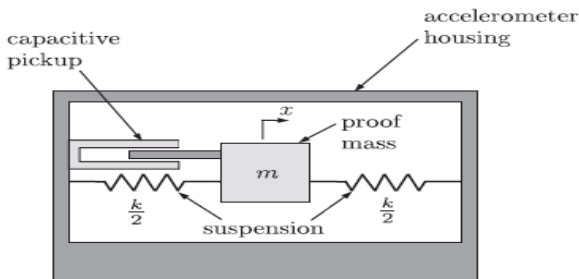
Definition of position, velocity, acceleration and orientation

- Inertial Frame: position (x, y), velocity (v_x, v_y), acceleration (a_x, a_y).
- Body Frame: velocity (v_{xb}, v_{yb}), acceleration (a_{xb}, a_{yb})

Rotation Matrix

$P = [x_1, y_1, z_1]^T$ in $X1 - Y1 - Z1$.

$P = [x_2, y_2, z_2]^T$ in $X2 - Y2 - Z2$.

Rotation about Z axis $(R(a)_1^2)$, i.e. $Z1 = Z2 \implies z_1 = z_2$.

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{pmatrix} cos(a) & sin(a) & 0 \\ -sin(a) & cos(a) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} \tag{7}$$

Accelereometer measurement

Accelerometer measures acceleration along body-axis denoted by a_{xb} and a_{yb} respectively.

$$\begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} cos\psi & -sin\psi \\ sin\psi & cos\psi \end{pmatrix} \begin{pmatrix} v_{xb} \\ v_{yb} \end{pmatrix} \tag{8}$$

$$\begin{pmatrix} a_x \\ a_y \end{pmatrix} = \begin{pmatrix} cos\psi & -sin\psi \\ sin\psi & cos\psi \end{pmatrix} \begin{pmatrix} a_{xb} \\ a_{yb} \end{pmatrix} \tag{9}$$

$$\dot{\psi} = r \tag{10}$$

$$a_{xb} = \dot{v}_{xb} - rv_{yb} \tag{11}$$

$$a_{yb} = \dot{v}_{yb} + rv_{xb} \tag{12}$$

MEMS Gyroscope - 1

Coriolis acceleration

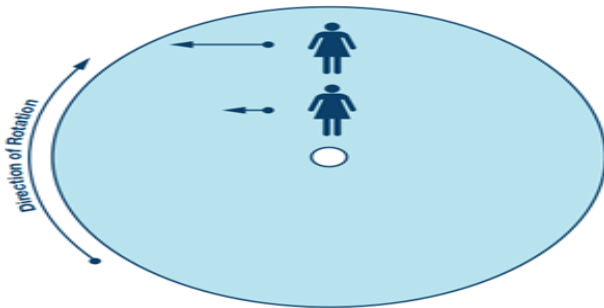$$a_c = 2\omega \times v \qquad (13)$$

Figure: Motion along a rotating platform

MEMS Gyroscope - 2

Coriolis acceleration

$$a_c = 2\omega \times v \qquad (14)$$
$$|a_c| = 2|\omega||v| \qquad (15)$$

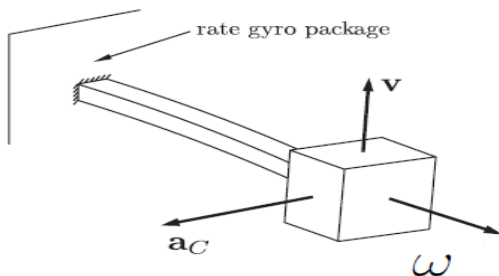For a known $'|v|'$, $|\omega|$ can be obtained after measuring $|a_c|$.

Figure: Working of a gyro

IMU-Encoder Data Fusion for Position Estimation

Wheel encoder based position estimate $(x_w(t), y_w(t))$

$$x_w(t) = \int_0^t V(t) \cos \psi(t) \, dt + x(0), \ y_w(t) = \int_0^t V(t) \sin \psi(t) \, dt + y(0) \quad (16)$$

IMU based position estimate $(x_i(t), y_i(t))$

$$\psi(t) = \int_0^t r(t) \, dt + \psi(0) \tag{17}$$

$$\begin{pmatrix} a_x(t) \\ a_y(t) \end{pmatrix} = \begin{pmatrix} \cos\psi(t) & -\sin\psi(t) \\ \sin\psi(t) & \cos\psi(t) \end{pmatrix} \begin{pmatrix} a_{xb}(t) \\ a_{yb}(t) \end{pmatrix} \tag{18}$$

$$v_x(t) = \int_0^t a_x(t) \, dt + v_x(0), \ x_i(t) = \int_0^t v_x(t) \, dt + x_i(0) \tag{19}$$

$$v_y(t) = \int_0^t a_y(t) \, dt + v_y(0), \ y_i(t) = \int_0^t v_y(t) \, dt + y_i(0) \tag{20}$$

$$x(t) = \alpha x_w(t) + (1-\alpha)x_i(t), \ y(t) = \alpha y_w(t) + (1-\alpha)y_i(t), \ 0 \le \alpha \le 1 \quad (21)$$

Position

- GPS- Global Positioning System (satellite)

Signal frequency $L_1 = 1575.42$ MHz, $L_2 = 1227.60$ MHz.
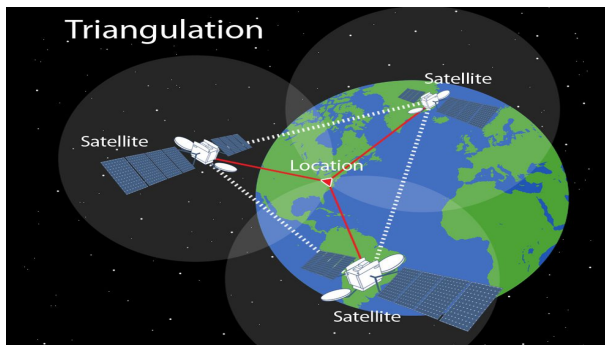Accuracy within a few meters (expressed in CEP (circular error probability).

Triangulation

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = d_1^2 \qquad (22)$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = d_2^2 \qquad (23)$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = d_3^2 \qquad (24)$$
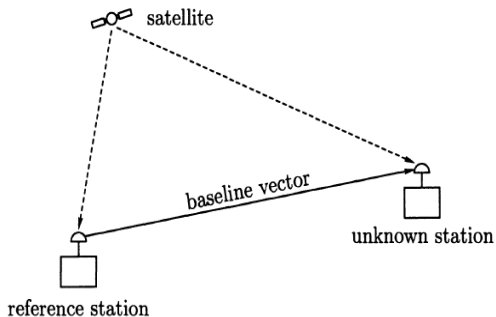
Differential GPS

Figure: Relative position estimation

Ellipsoidal and ECEF
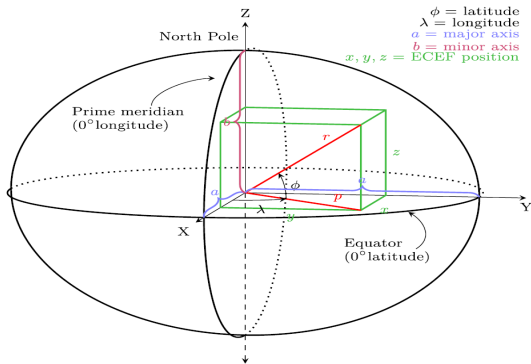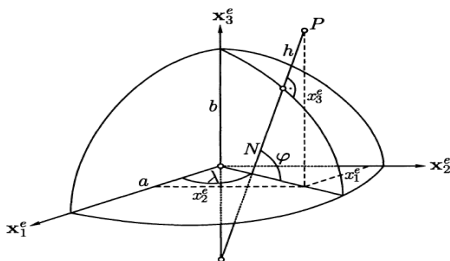
ECEF - earth centered earth fixed frame

Figure: Ellipsoidal and ECEF frame

Ellipsoidal to ECEF transformation

NB: Here $(\mathbf{x}_1^e, \mathbf{x}_2^e, \mathbf{x}_3^e)$ frame denote the (X, Y, Z) frame (ECEF frame shown in the previous slide).
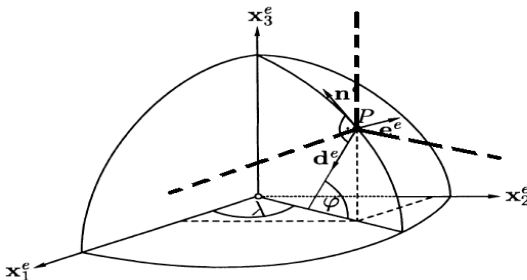
$N = \frac{a^2}{\sqrt{a^2 \cos^2\phi + b^2 \sin^2\phi}}$, $a = 6378137m$, $b = 6356752m$.

$$\begin{pmatrix} x_1^e \\ x_2^e \\ x_3^e \end{pmatrix} = \begin{pmatrix} (N+h)\cos\phi\cos\lambda \\ (N+h)\cos\phi\sin\lambda \\ (\frac{b^2}{a^2}N + h)\sin\phi \end{pmatrix} \tag{25}$$

ECEF to NED frame

NED - North, East, Down.

$$\begin{pmatrix} -sin\phi cos\lambda & -sin\lambda & -cos\phi cos\lambda \\ -sin\phi sin\lambda & cos\lambda & -cos\phi sin\lambda \\ cos\phi & 0 & -sin\phi \end{pmatrix} \quad (26)$$

THANK YOU