Sensors and Sensing
Introduction

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Outline

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How do we implement an odometry controller?

- Two tasks:
  - Convert from encoder ticks to position and orientation of the vehicle.
  - Convert a velocity command (linear and angular) into velocity command on the wheels.
- Let's try to work out the math and pseudocode of how we do this.

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From ticks to position and orientation

Given:

- t_s: sampling time at which we are computing odometry
- $p_{l,t}, p_{r,t}$: positions of the left and right encoders at time t.
- $v_{l,t}, v_{r,t}$: velocity of the left and right encoders at time t.
- $u_{r,t}, u_{l,t}$: commanded velocity to the encoders at time t. Note that u should be sampled at a substantially higher frequency.

We also have the equations from the lecture. Note that I have substituted u with v here.

$$\dot{x} = \frac{r}{2}(v_{l,t} + v_{r,t}) \cos\theta \quad (1)$$

$$\dot{y} = \frac{r}{2}(v_{l,t} + v_{r,t}) \sin\theta \quad (2)$$

$$\dot{\theta} = \frac{r}{L}(v_{r,t} - v_{l,t}) \quad (3)$$

From ticks to position and orientation

- Here the coordinate frame is fixed to the robot frame at time t = 0.
- In the figure, the x axis points right, the y axis points to the front of the robot, and the current $\theta = 90°$.
- These equations work for computing instantaneous velocities, if we assume the robot always starts at $(0, 0, 0)$.

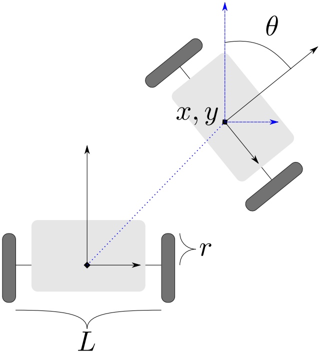


Figure: Differential Drive Kinematic Model

From ticks to position and orientation

Let's calculate the robot motion at time $t + t_s$, relative to it's position and orientation at time t. We integrate:

$$
\begin{aligned}
dx &= t_s \frac{r}{2}(v_{l,t} + v_{r,t}) \cos d\theta &\quad (4)\\
dy &= t_s \frac{r}{2}(v_{l,t} + v_{r,t}) \sin d\theta &\quad (5)\\
d\theta &= t_s \frac{r}{L}(v_{r,t} - v_{l,t}) &\quad (6)
\end{aligned}
$$

As we are integrating over t we can re-write as:

$$
\begin{aligned}
dx &= \frac{r}{2}((p_{l,t+t_s} - p_{l,t}) + (p_{r,t+t_s} - p_{r,t})) \cos d\theta &\quad (7)\\
dy &= \frac{r}{2}((p_{l,t+t_s} - p_{l,t}) + (p_{r,t+t_s} - p_{r,t})) \sin d\theta &\quad (8)\\
d\theta &= \frac{r}{L}((p_{r,t+t_s} - p_{r,t}) - (p_{l,t+t_s} - p_{l,t})) &\quad (9)
\end{aligned}
$$

From ticks to position and orientation

We can now write the formula for the relative transformation ${}_{\mathrm{n}}\mathrm{T}^{\mathrm{n+1}}$ which can be applied to the previous robot pose to obtain the next pose:

$$
{}_{\mathrm{n}}\mathrm{T}^{\mathrm{n+1}} = \begin{pmatrix} \cos \mathrm{d}\theta & -\sin \mathrm{d}\theta & \mathrm{dx} \\ \sin \mathrm{d}\theta & \cos \mathrm{d}\theta & \mathrm{dy} \\ 0 & 0 & 1 \end{pmatrix} \tag{10}
$$

We obtain the new pose of the robot as ${}_{0}\mathrm{T}^{\mathrm{n+1}} =_{0} \mathrm{T}^{\mathrm{n}}\ {}_{\mathrm{n}}\mathrm{T}^{\mathrm{n+1}}$. How do we calculate that?

Pseudocode

At time t_s:

- Read $p_{r,t+t_s}, p_{l,t+t_s}$
- Compute $d\theta, dx, dy$ according to forward kinematics.
- Rotate dx, dy using θ and add them to x and y.
- Add $d\theta$ to θ.

What about the inverse problem?

Given $\dot{x}, \dot{y}, th\dot{e}ta$, find u_l, u_r.
Formulate the linear velocity as the norm of the vector $v = [\dot{x}, \dot{y}]^T$.

$$v = \sqrt{(\frac{r}{2}(v_{l,t} + v_{r,t}) \cos\theta)^2 + (\frac{r}{2}(v_{l,t} + v_{r,t}) \sin\theta)^2} \quad (11)$$

Which simplifies to:

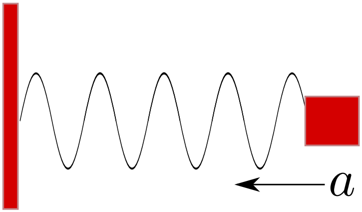
$$v = \frac{r}{2}(v_{l,t} + v_{r,t}) \quad (12)$$

Combining with $\dot{\theta}$ we now have two linear equations with two unknowns, which we can easily solve.

Outline

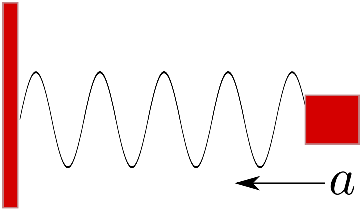
Linear Acceleration: accelorometers

- Accelorometers are sensors that can detect the relative linear acceleration along an axis.
- The basic principle of operation can be thought of as an object suspended on a spring.
- When the system is acelerated along the spring direction, the mass moves, relative to the spring mounting point.



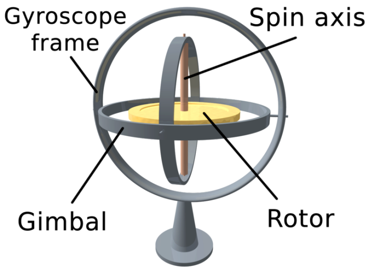
Linear Acceleration: accelorometers

- The displacement of the object is proportional to the spring constant, its mass, and the acceleration.
- Only measure acceleration component along one dimension.
- Often implemented as MEMS.



Angular Acceleration: gyros

- Gyroscope sensors rely on the gyroscopic effect to measure angular acceleration.
- The flywheel gyro uses a spinning disc, suspended on a mobile ring.
- When a torque is applied to the input axis, the angular momentum of the wheel transfers the torque to the output axis.
- A sensor on the output axis measures the angular acceleration along the input axis.



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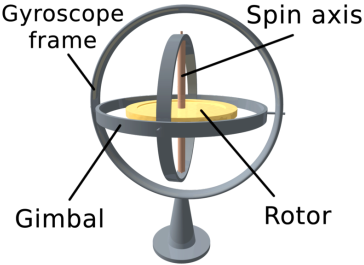

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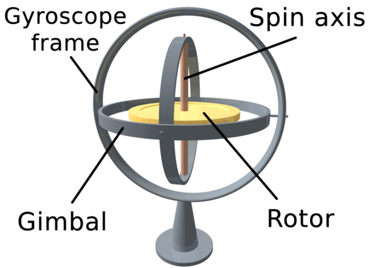

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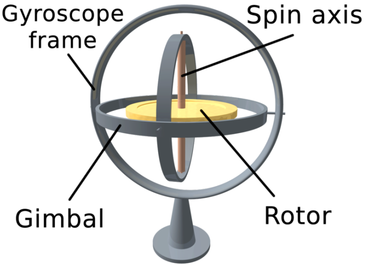

Physical Implementation

- Both accelorometers and gyroscopes are usually implemented using cheap on-chip systems.
- MEMS implementations, based on vibrations.
- Each sensor only measures along a single axis: linear or rotational.
- If a torque/force is applied to the system, we only see the projection along that axis.

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Integral Measurements and Errors

- Accelorometers and gyros provide instantaneous measurements of linear and angular acceleration.
- We are often interested not in acceleration, but rather speed, or more often position (linear/angular).
- To obtain linear/angular velocity from acceleration, we need to integrate measurements over a time window.
- To obtain position/orientation, we need to integrate linear/angular velocities over time again.
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- Thus, a lot of drift over time. Reliable only over short intervals.

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- A different mode of sensing orientations is by using a magnetic compass.
- A compass aligns with the magnetic field of earth and measures absolute orientation in the XY-plane (relative to magnetic north).
- Implementation using hall effect sensors is common.
- Only for in-plane orientation.

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- Earth's magnetic field is not perfectly uniform.
- Electronic equipment induces local magnetic fields.
- Metllic and fero-magnetic objects distort the field.
- Problems with shielding.

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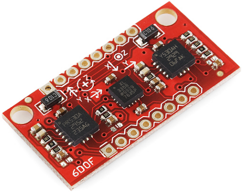
IMUs

- Inertial Measurement Units (IMUs) usually integrate several inertail sensors on a single board.
- Usually 3 accelorometers and 3 gyros for 6DoF pose, may inlude compass.
- High-end IMUs use redundant additional sensors and perform additional filtering operations to increase reliability.
- Calibration procedures to reduce sensor drift. E.g. common to measure for a time window without moving to remove systematic background noise.



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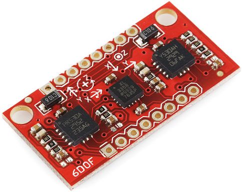

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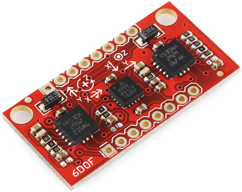

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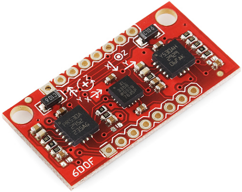
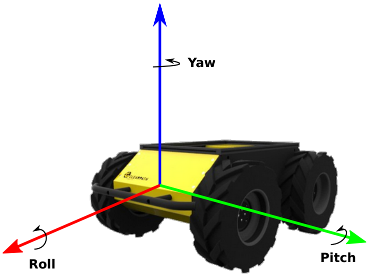


Representing orientations

- There are several alternative ways to represent the relative orientation between two coordinate frames.
- From the sensor point of view, a Gyro / IMU sensor usually measures rotations relative to a fixed sensor-centric frame.
- The Roll, Pitch and Yaw (RPY) of a vehicle are common concepts.



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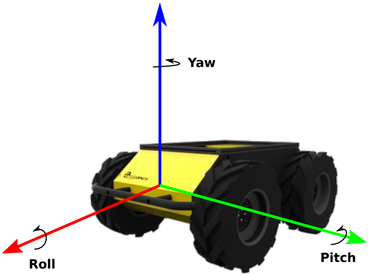

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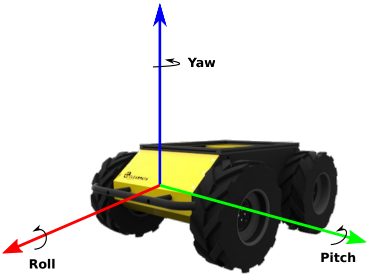

Representing orientations

- RPY is an Euler angles paramerization of orientation.
- Transfering from Euler angles to rotation matrices can be done by stacking the rotation matrices along each axis.
- Euler angles however suffer from singularities.
- In mechanical gyros this is known also as gimbal lock : two of the gimbals are aligned in the same plane, loosing a degree of freedom.
- Depending on Euler angles chosen (XYZ, XYX, etc.) singularities are at different orientations
- An alternative is to use unit quaternions.

$$q = ix + jy + kz + w \tag{13}$$

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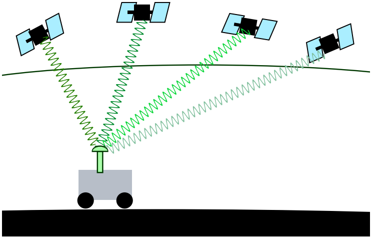
Global Positioning System (GPS)

- Sattelite-based localization is often used for outdoor robotic platforms, as well as on ships/airplanes/etc.
- Systems like GPS/ GLONASS / GALILEO operate a fleet of sattelites in lower earth orbit.
- GPS receivers measure the signal from visible sattelites and use it to deduce an absolute 3D position in geo-reference frame.



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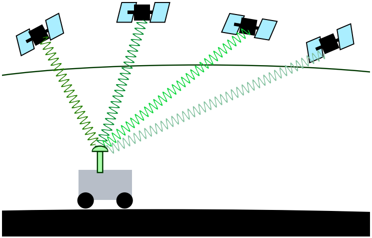

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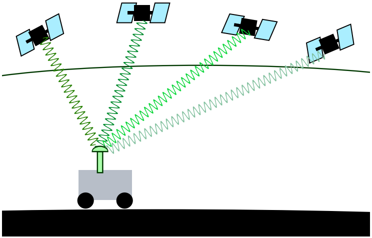

GPS operation principle

- How does it work exactly?
- Each sattelite sends a pseudo-random sequence of bits, encoded on top of a carrier signal.
- The code transmitted is related to the internal clock of the sattelite.
- Receiers generate the same sequence based on their local clocks. By aligning the two codes, the receiver can measure the time of travel of the signal.
- The time of travel of the singal t_t is:

$$t_t = t_r - t_s + t_{off}$$

where t_r is the measured time of receiving the signal, t_s is the measured time of sending and t_{off} is an unknown offset between the receiver and sender clocks.

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GPS operation principle

- The clocks of all sattelites are synchronized by the central operations point, correcting for relativistic effects.
- Given two sattelite signal travel times t_{t1} and t_{t2}, we can compute

$$t_{t1} - t_{t2} = t_{r1} - t_{s1} + t_{r2} - t_{s2}$$

- this elliminates the clock offset t_{off}.
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- Using more than 4 satelites allows for a least-squares solution to minimize the error in position.

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GPS Errors

GPS systems have several common issues:

- Clouds and stratospheric effects can alter significantly the measurements as they cause refractions.
- Multi-path reflections can cause sporradic jumps in the position estimate.
- The height estimate is usually substaantially more unreliable than the xy-position.
- Low visibility of sattelites causes issues in proximity to tall buildings and of course indoors.
- Position accuracy is on the order of 1-2 meters.

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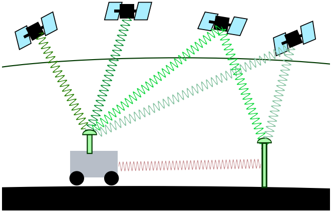
Differential GPS

- Differential GPS relies on additional ground-based stations.
- Each ground station observes the same sattelites as the receivers.
- Positions of ground stations are precisely known.
- Ground stations compute a differential between measured and known position and transmit corrections.
- Different ways to correct signals. Usually D-GPS refers to code-space correction.



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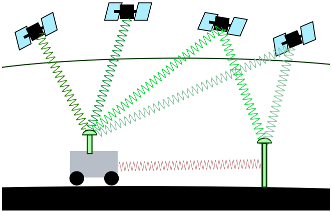

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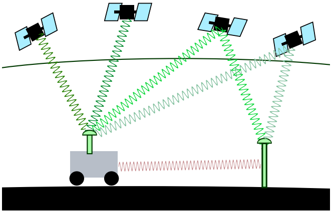

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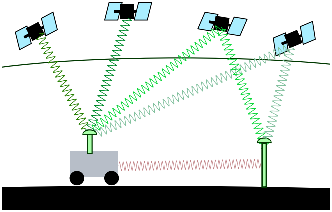

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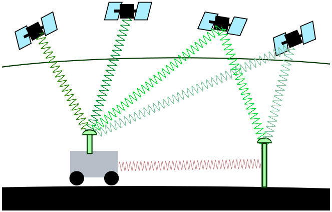
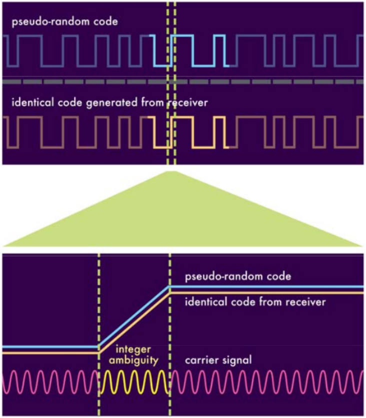


Real-time Kinematic (RTK) GPS

- RTK-GPS is a form of differential GPS.
- RTK receivers and base stations use the carrier signal, instead of the code.
- Carrier signals are modulated at ~ 15MHz, code signal is modulated at ~ 1MHz.
- Precise alignment of carrier signals gives a more accurate estimate of the travel time t_t.
- Accuracy in centimeter range.



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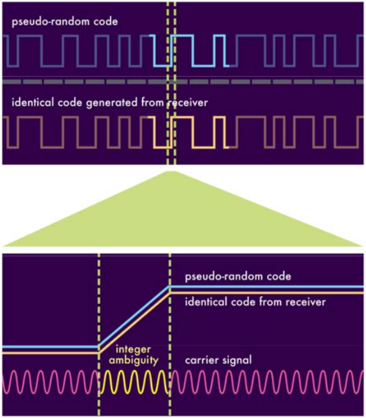

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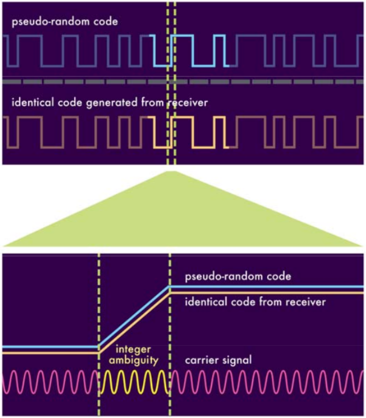

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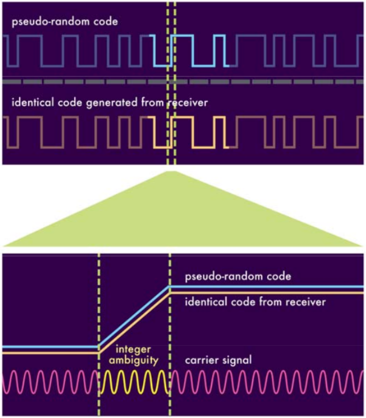

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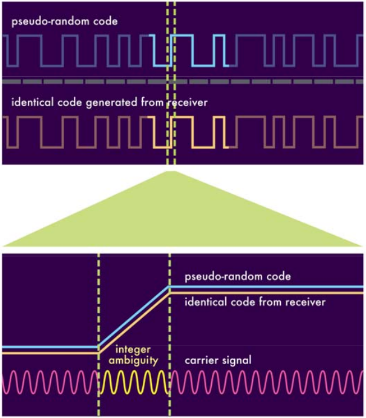

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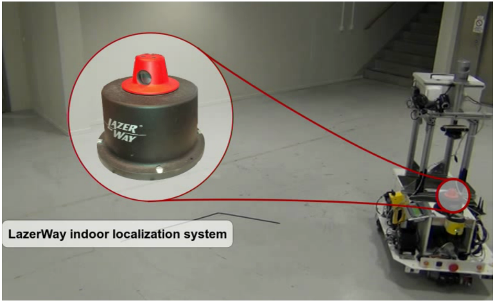
Indoor Positioning Systems

- Indoor global positioning systems use a set of landmarks, distributed in the environment.
- Landmark observations are fused in a filter.



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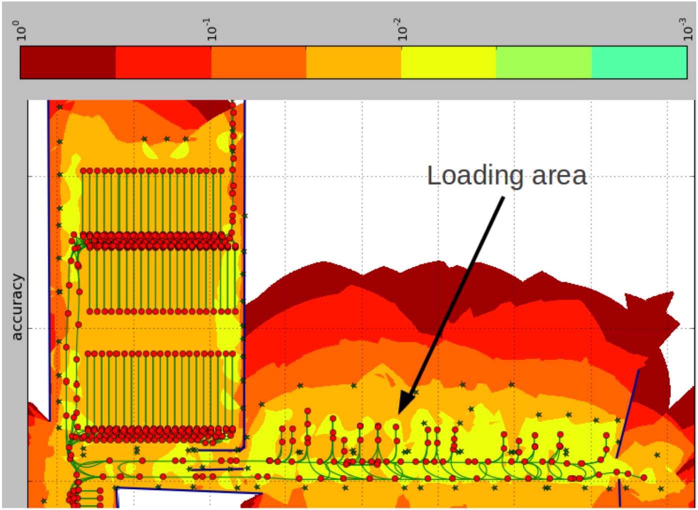
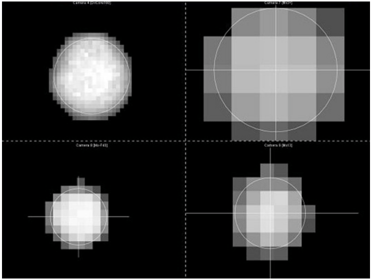


Motion capture systems

- Motion capture systems are sometimes used for tracking in robotics as well.
- Targeted application is in filming: capture motion for a digital actor.
- A number of active infrared cameras and markers.

Motion capture systems

- Markers are triangulated to obtain 3D position.
- Distribution of markers on the model is important to guarantee correct data association
- So is camera resolution and good calibration.
- In robotics, often used for ground truth motion measurement.



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Sensors and Sensing
Introduction

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