Localization

Lecture 4 – Thursday October 20, 2016

Objectives

When you have finished this lecture you should be able to:

- Get familiar with different local, global and hybrid localization techniques of autonomous vehicles.
- Understand the odometry of differential drive.
- Recognize systematic and non-systematic odometry errors and learn how to measure them using UMBmark and extended UMBmark.

Outline

- Autonomous Vehicle Localization
- Local (Relative) Localization
- Global (Absolute) Localization
- Hybrid Localization
- Odometry for Differential Drive
- Systematic and Non-Systematic Odometry Errors
- Measurement of Odometry Errors
- Summary

Outline

- **<u>Autonomous Vehicle Localization</u>**
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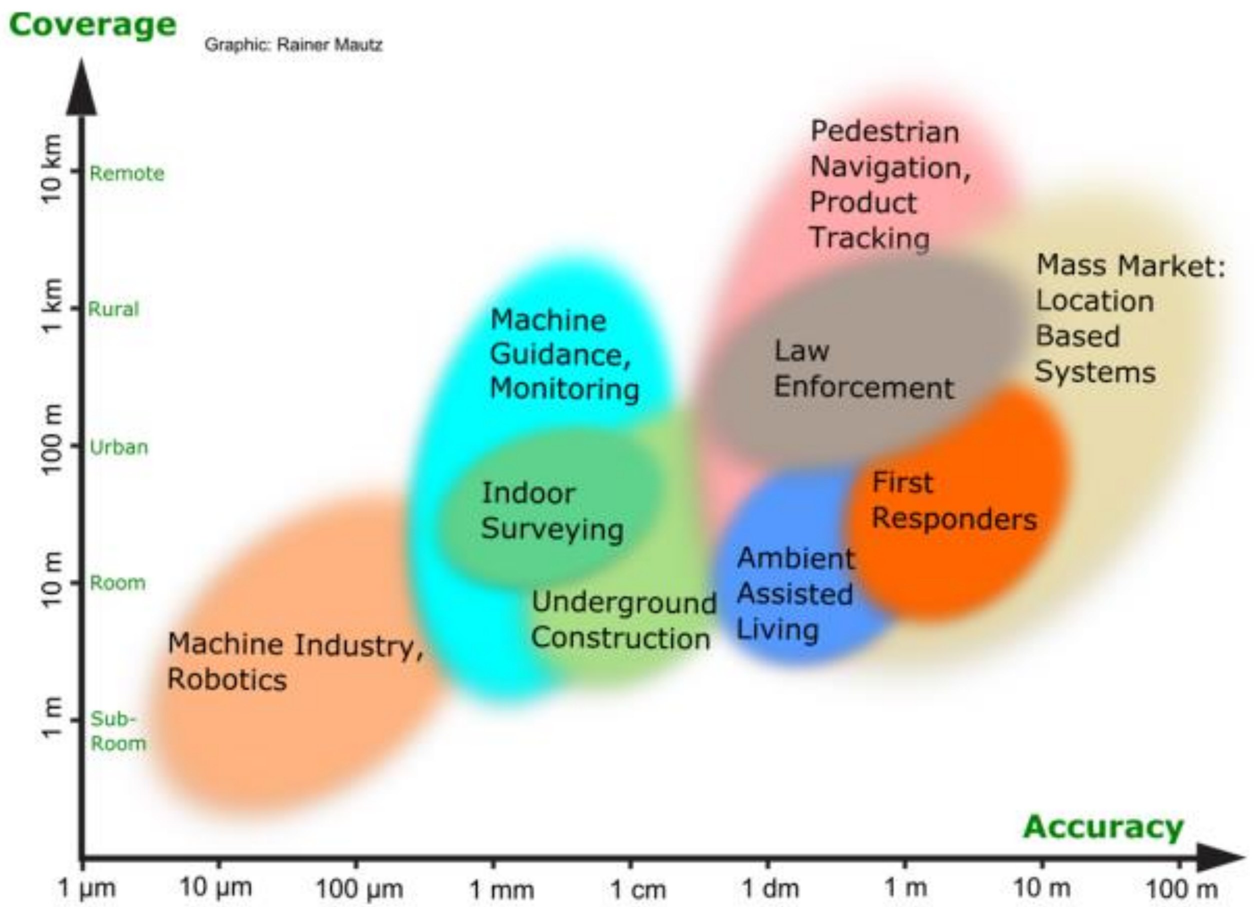
Autonomous Vehicle Localization

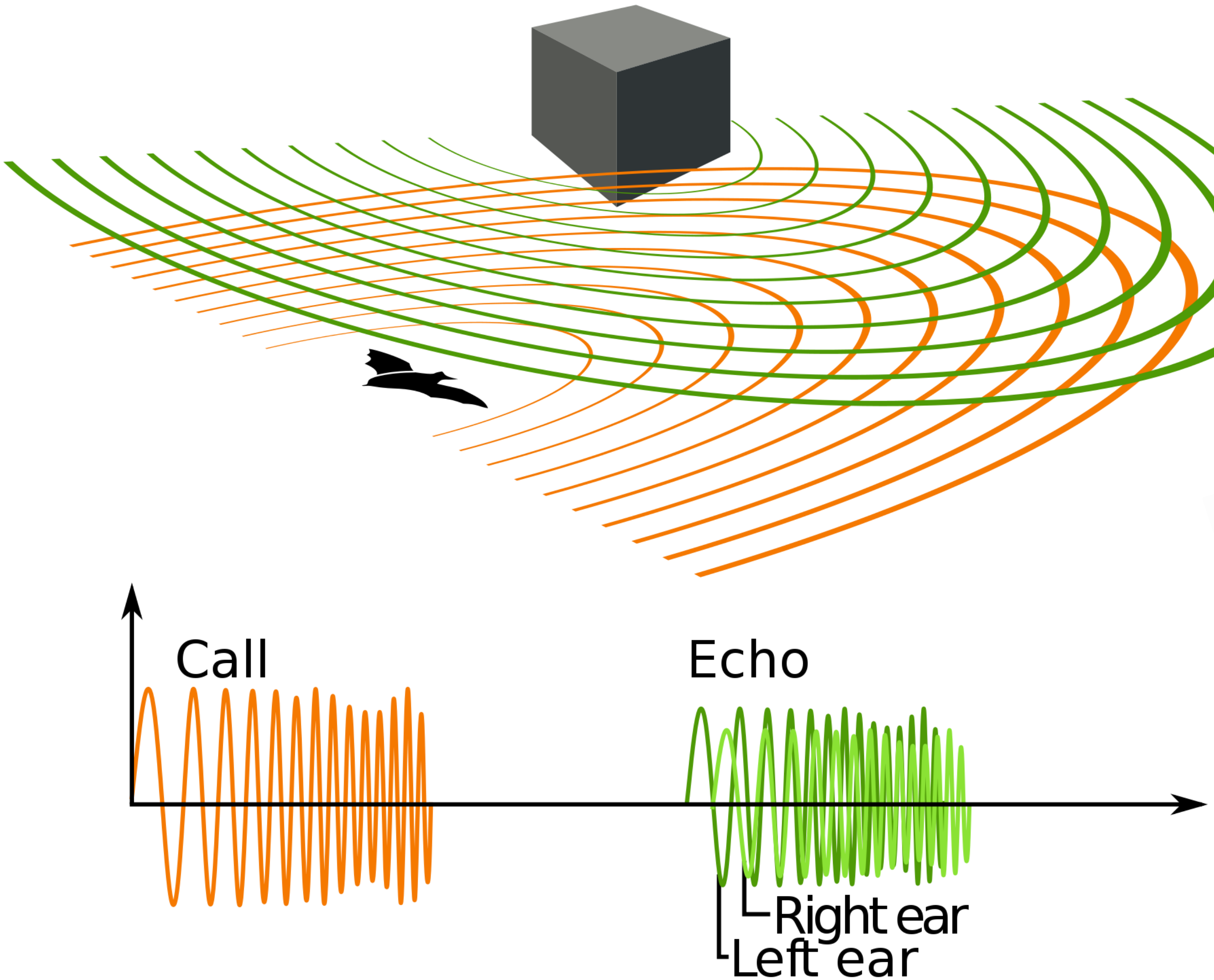
Autonomous vehicle localization provides answer for the question: “**Where am I?**”

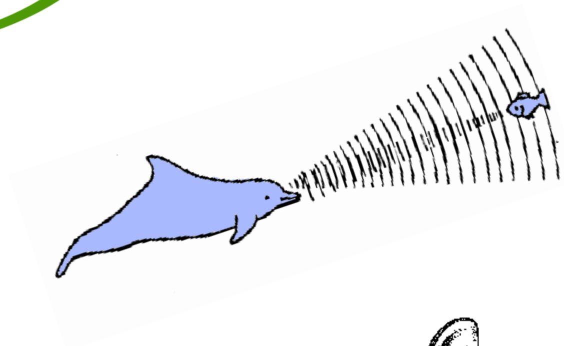


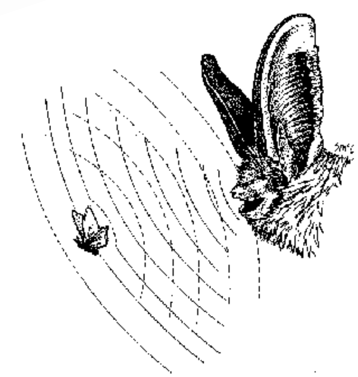
Overview of user requirements in terms of accuracy and coverage [1]

Autonomous Vehicle Localization

- **Echolocation in Nature**







Autonomous Vehicle Localization

Autonomous Vehicle Localization

Indoor Localization

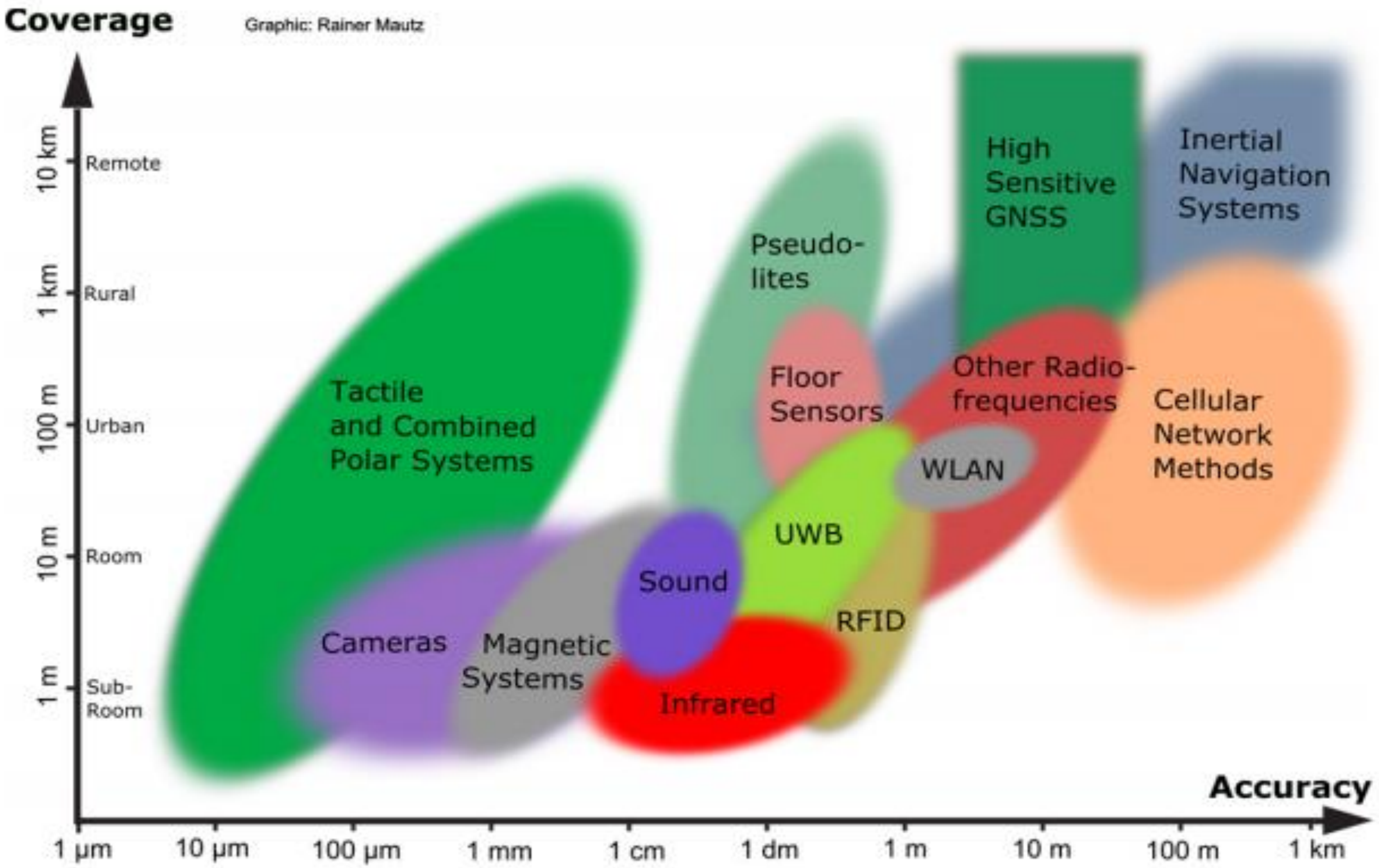
The process of accurately estimate the position and orientation of a mobile vehicle moving inside building's environments

Outdoor Localization

compared to indoor localization, outdoor localization is a more challenging process than indoor localization due to the lack of the ability to control the environment nor to predict it

Autonomous Vehicle Localization

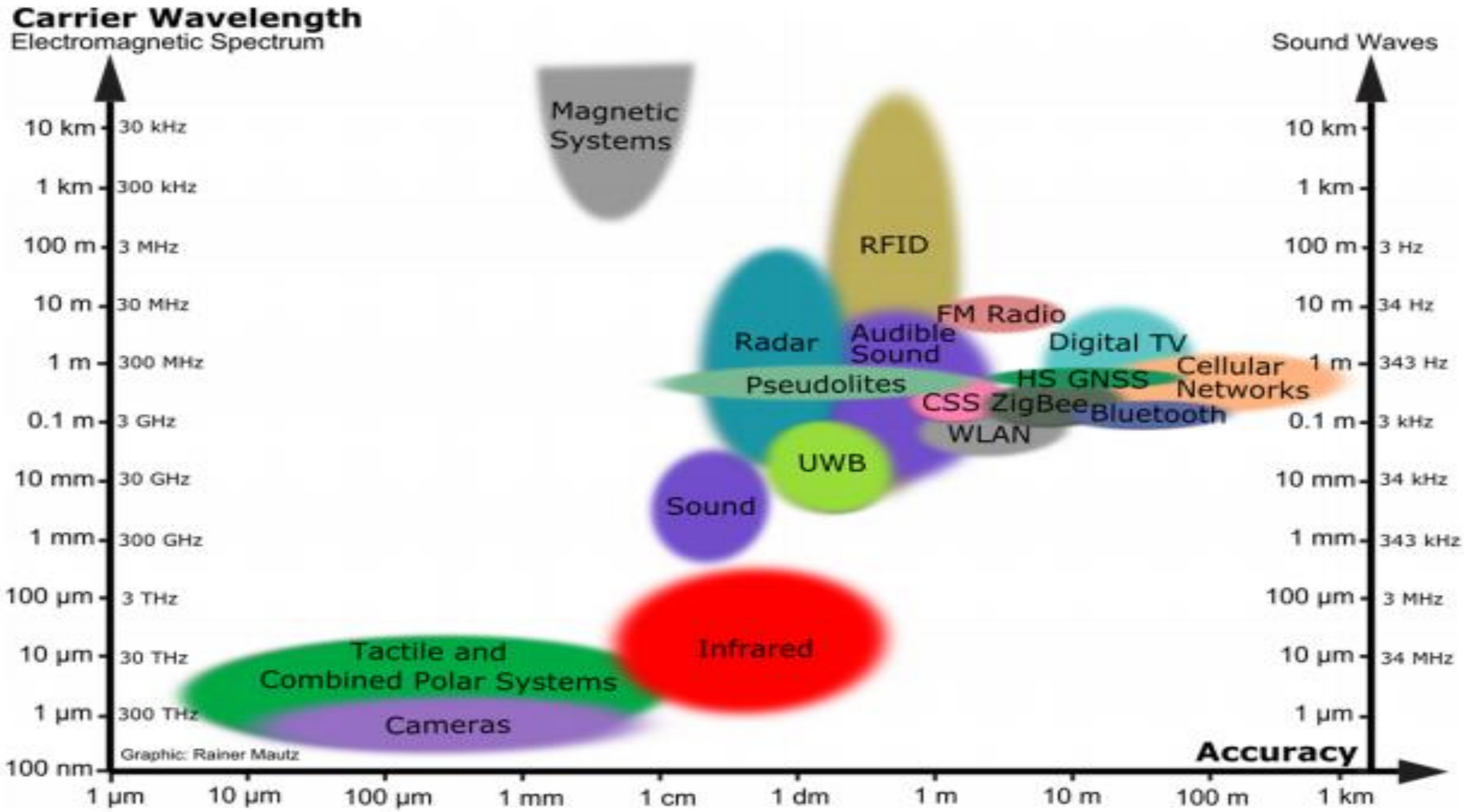
- **Indoor Localization**



Indoor Localization technologies (Accuracy Vs. Coverage) [1]

Autonomous Vehicle Localization

- **Indoor Localization**



Indoor Localization technologies (Accuracy Vs. Carrier Wavelength) [1]

Autonomous Vehicle Localization

- **Outdoor Localization**

Outdoor localization

- Local (Relative) Localization/Dead Reckoning
  - Odometry
    - Optical encoders
      - Absolute
      - Incremental
    - Hall-effect
    - Doppler-effect
    - Visual odometry
    - …
  - Inertial Navigation
- Global (Absolute) Localization
  - Active Beacons
    - Ground based RF systems
    - Active RF systems
    - Real-time Locating Systems
    - GPS
      - Traditional GPS
      - High-precision GPS
  - Passive Beacons
    - Artificial Landmark Recognition
    - Natural Landmark Recognition
    - Model Matching
- Hybrid Localization
  - IMU-GPS, PPP-GPS, RTK-GPS, …

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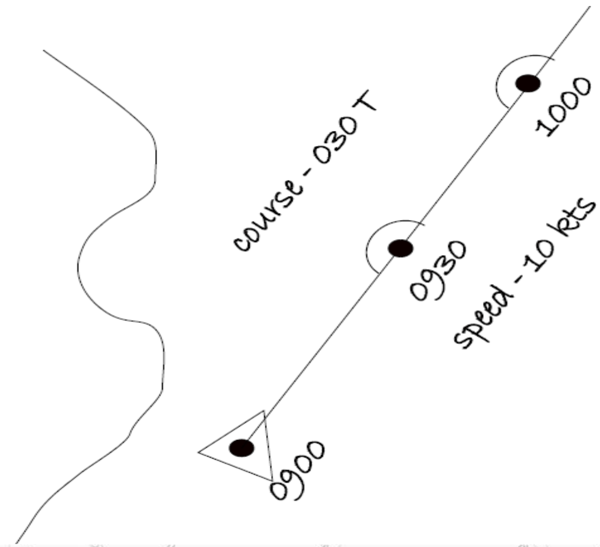
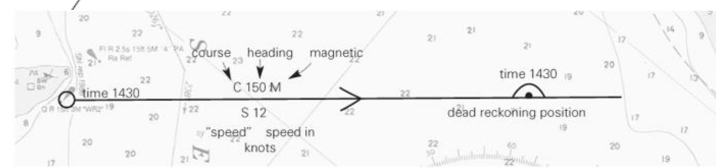
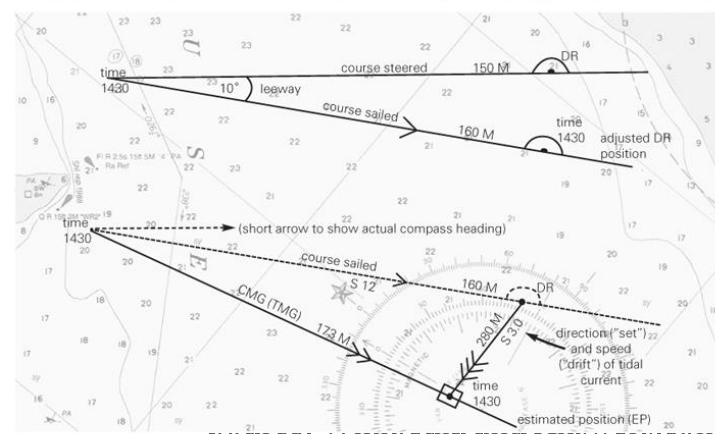
Local (Relative) Localization

- **Dead Reckoning**

  Dead reckoning is a predictive calculation based on inference to estimate the position of an aircraft or a ship **without astronomical observations**, as by applying to a previously determined position the course and distance traveled since.





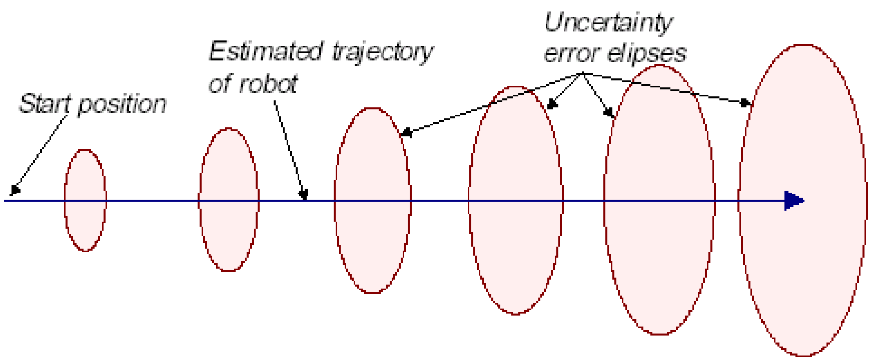


Source: Wikipedia and Answers.com

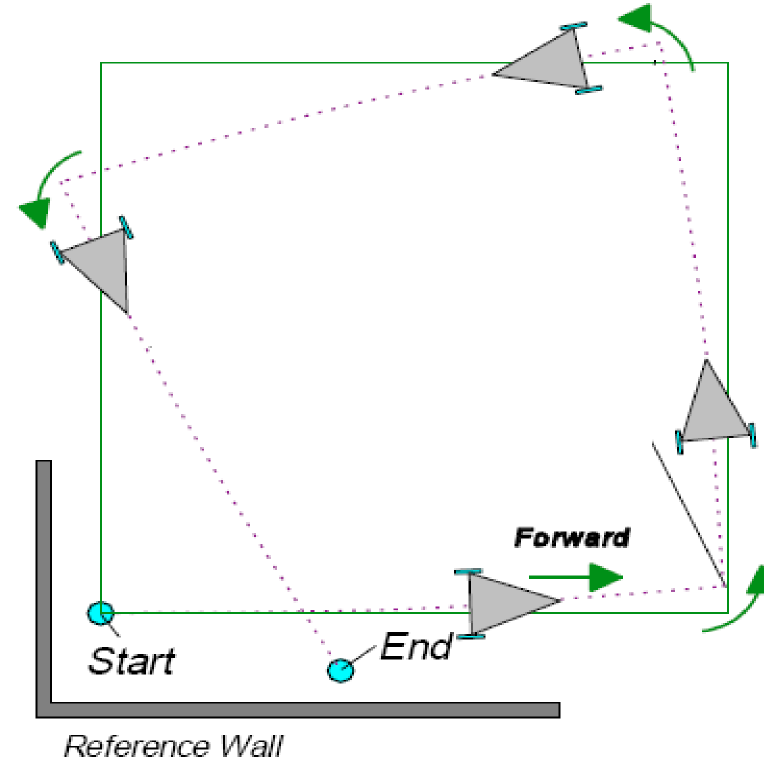
Local (Relative) Localization

- **Dead Reckoning**

A **disadvantag**e of dead reckoning is that since new positions are calculated solely from previous positions, the errors of the process are **cumulative**, so the error in the position fix **grows with time**.



Accumulated errors



Local (Relative) Localization

- **Dead Reckoning**

Relative Position Measurements

(Dead Reckoning)

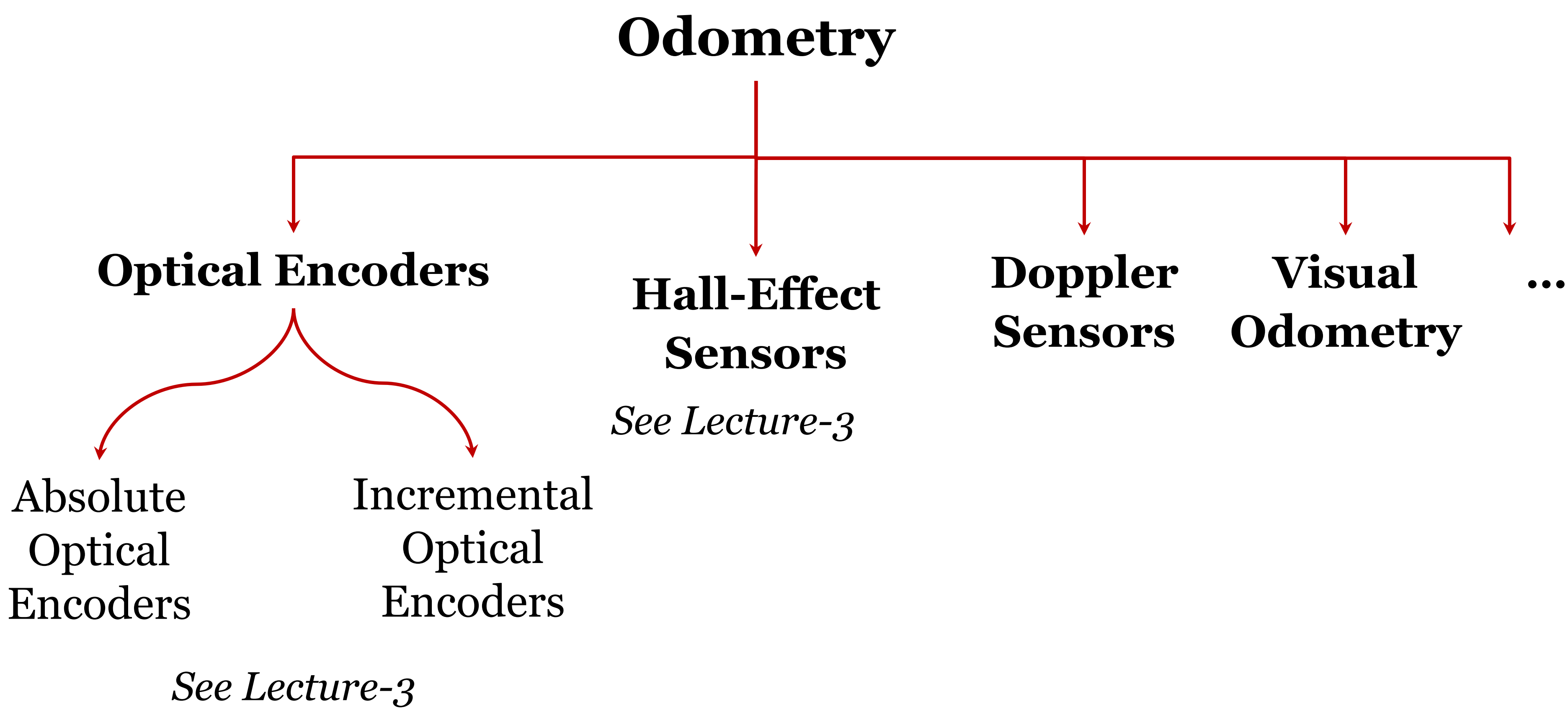
Odometry

Inertial Navigation

Local (Relative) Localization

- **Odometry**

This method uses encoders to measure wheel rotation and/or steering orientation.

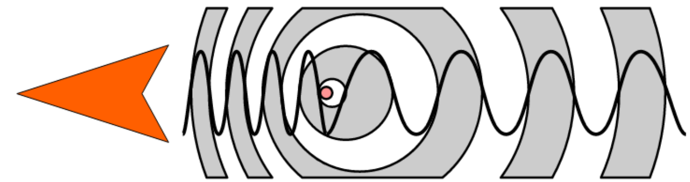


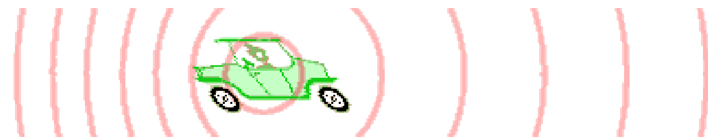
Local (Relative) Localization

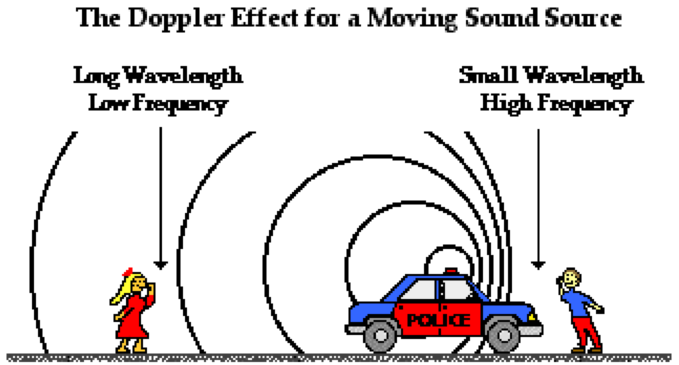
- **Doppler Sensor**

The Doppler effect (or Doppler shift), is the change in **frequency** of a wave (or other periodic event) for an observer moving relative to its source. The received frequency is higher (compared to the emitted frequency) during the approach, it is identical at the instant of passing by, and it is lower during the recession.

Source: Wikipedia







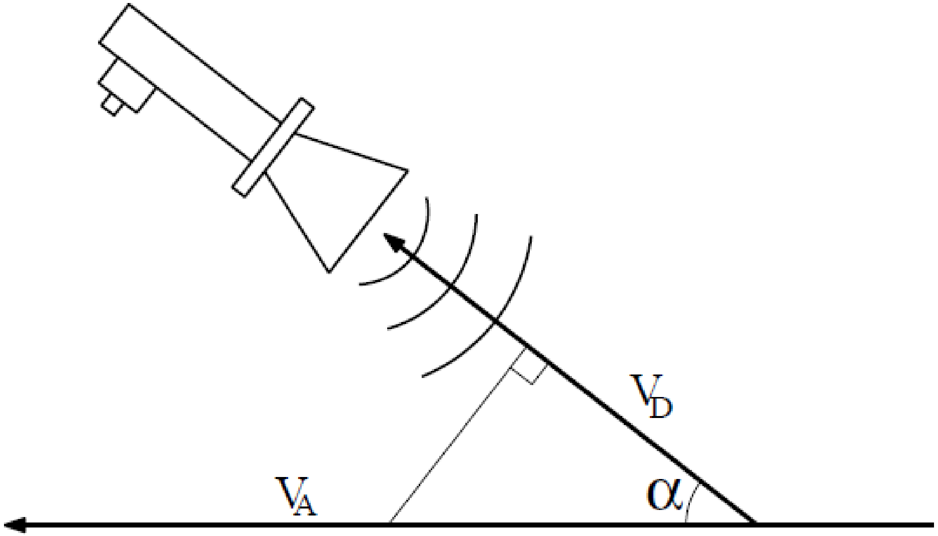
It is commonly heard when a vehicle sounding a siren or horn approaches, passes, and recedes from an observer.

Local (Relative) Localization

- **Doppler Sensor**

The microwave **radar (radio detection and ranging)** sensor is aimed downward at a prescribed angle (typically 45°) to sense **ground movement**.

Actual ground speed V_A is derived from the measured velocity V_D according to the following equation.

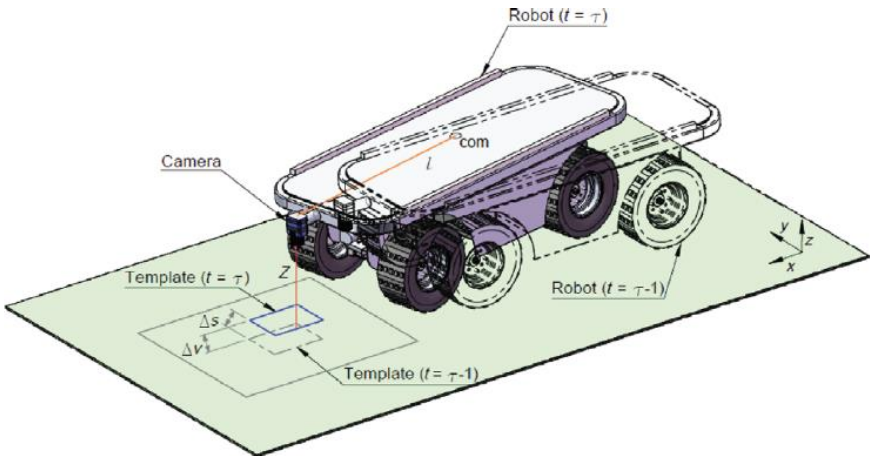


$$V_A = \frac{V_D}{\cos\alpha} = \frac{cF_D}{2F_0\cos\alpha}$$

V_A = actual ground velocity along path
V_D = measured Doppler velocity
α= angle of declination
c = speed of light
F_D = observed Doppler shift frequency
F_o = transmitted frequency.

Local (Relative) Localization

- **Visual Odometry**
  - ◇ Visual Odometry (VO) is the process of determining the position and orientation of a robot by analyzing the associated camera images. This has been used in different robotic applications, such as on the Mars Exploration Rovers [2].
  - ◇ It is the process of incrementally estimating the pose of the vehicle by examining the changes that motion induces on the images of its onboard cameras.



Local (Relative) Localization

- **Visual Odometry**

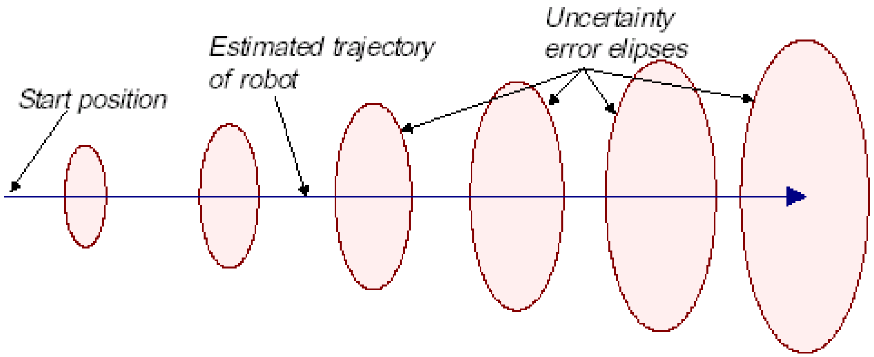
In order to guarantee the reliability of Visual Odometry estimates, several assumptions are considered [3]:

- ◊ Sufficient illumination in the environment.
- ◊ Dominance of static scene over moving objects.
- ◊ Enough texture to allow apparent motion to be extracted.
- ◊ Sufficient scene overlap between consecutive frames.

Local (Relative) Localization

- **Odometry**

Advantages	Disadvantages
Odometry is totally **self-contained**, and it is always capable of providing the vehicle with an estimate of its position.	The position error grows without bound unless an independent reference is used periodically to reduce the error.



Accumulated odometry errors

Local (Relative) Localization

- **Inertial Navigation**

Heading Sensors
- Mechanical Gyroscopes
  - Space-Stable Gyroscopes
  - Gyrocompasses
- Piezoelectric Gyroscopes
- Optical Gyroscopes
  - Active Ring Laser Gyros
  - Resonant Fiber Optic Gyros
- Geomagnetic Sensors
- Hall-Effect Compasses
- Magnetoresistive Compasses
- Digital Compasses

Local (Relative) Localization

- **Inertial Navigation**

  This method uses gyroscopes and sometimes accelerometers to measure rate of rotation and acceleration.

  ◊ **Advantages**

  – Measurements are **integrated once (or twice)** to yield position.

  – Inertial navigation systems also have the advantage that they are **self-contained**.

Local (Relative) Localization

- **Inertial Navigation**
  - ◇ **Disadvantages**
    - – Inertial sensor **data drifts with time** because of the need to integrate rate data to yield position; **any small constant error increases without bound after integration**. Inertial sensors are thus **unsuitable** for accurate positioning over an **extended period of time**.

Local (Relative) Localization

- **Inertial Navigation**
  - ◊ **Disadvantages**
    - – Another problem with inertial navigation is the **high equipment cost**. For example, highly accurate gyros, used in airplanes, are inhibitively expensive.

      Very recently **fiber-optic gyros** (also called **laser gyros**), which are said to be very accurate, have fallen dramatically in price and have become a very attractive solution for mobile robot navigation.

Outline

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- **Global (Absolute) Localization**
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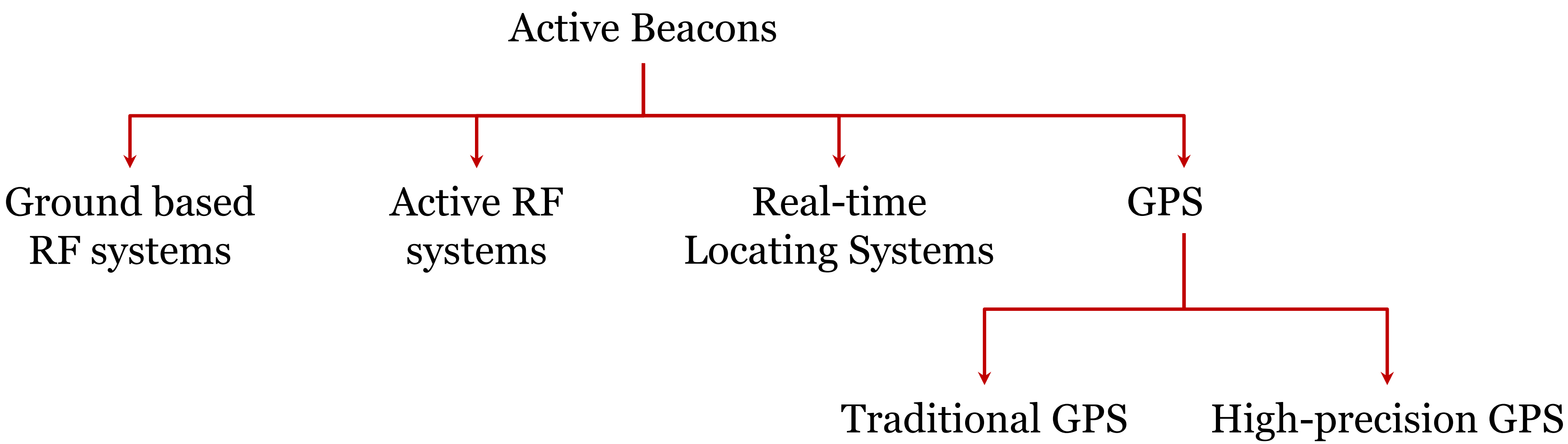
Global (Absolute) Localization

- **Active Beacons**

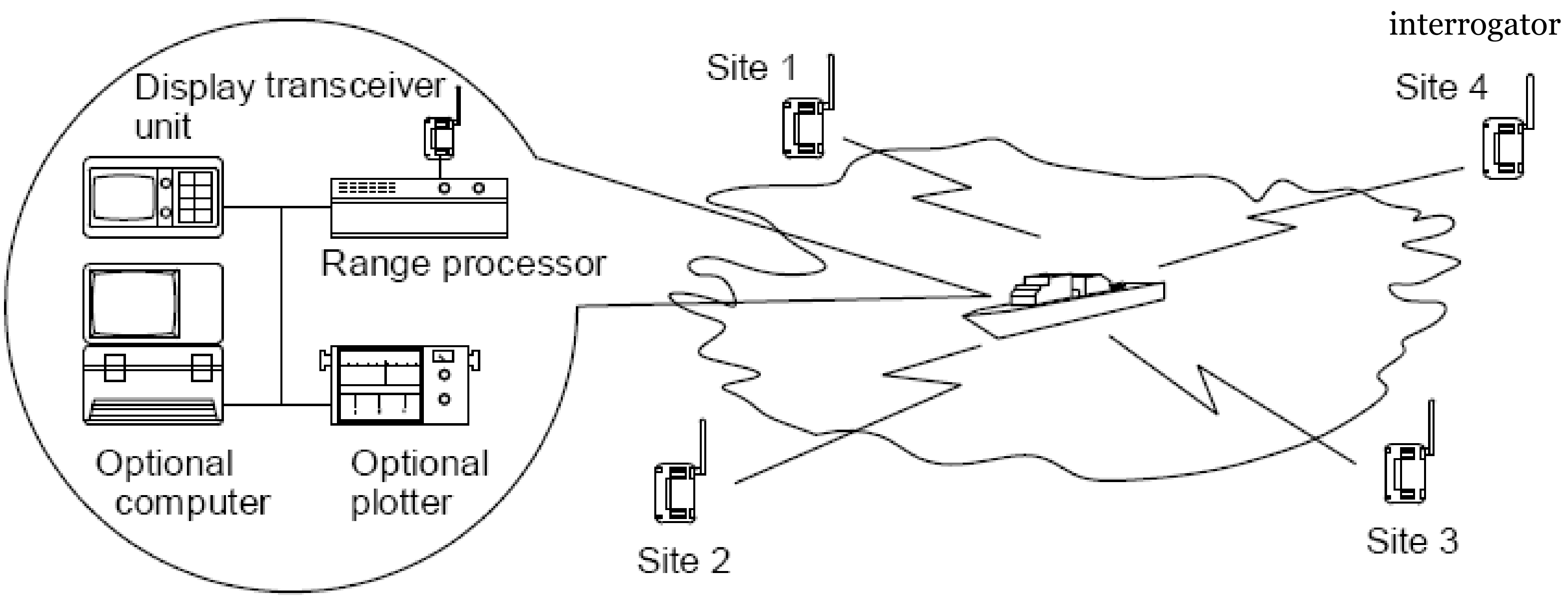
This method computes the **absolute position** of the robot from measuring the direction of incidence of **three or more actively transmitted beacons**.

The transmitters, usually using light or radio frequencies, must be located at known sites in the environment.



Global (Absolute) Localization

- **Active Beacons: Ground-Based RF Systems**



Motorola's Mini-Ranger Falcon 484 R position-location system provides 2 m accuracy over ranges of 100 m to 75 km.

The **actual distance** between the **interrogator** and a given **transponder/transceiver** is found by:

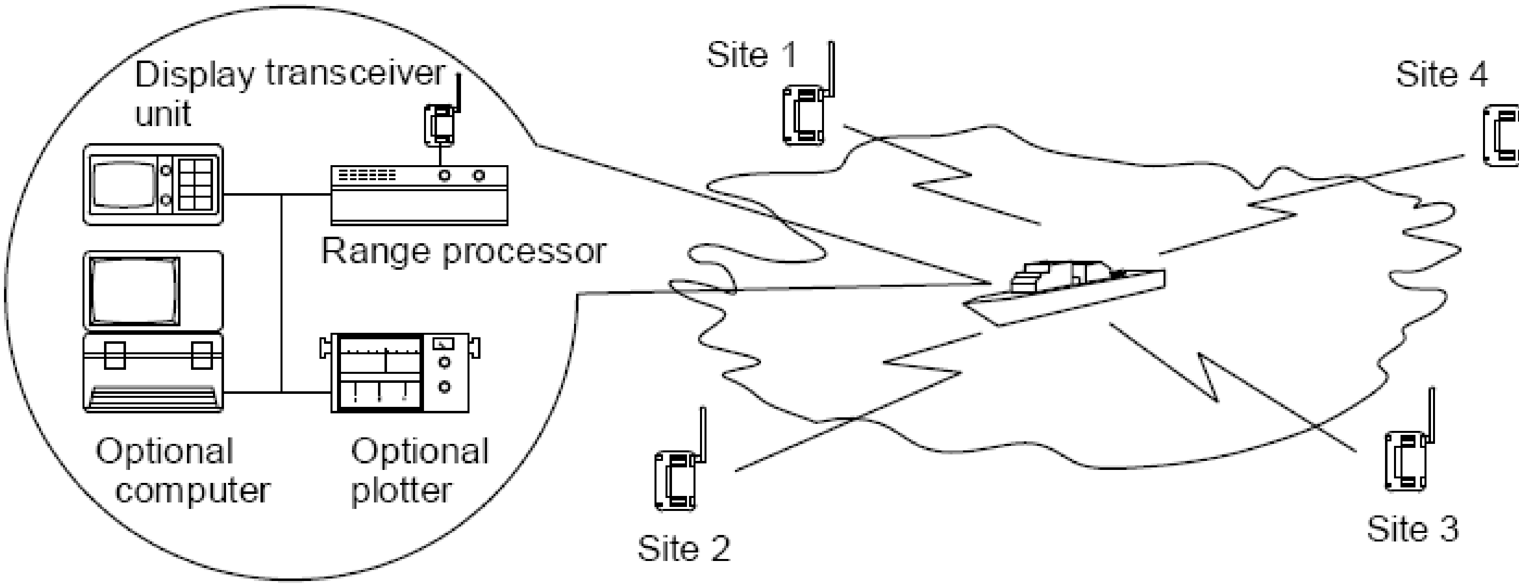
$$D = \frac{(T_e - T_d)c}{2}$$

where D = separation distance, T_e = total elapsed time

T_d = transponder turn-around delay, c = speed of light.

Global (Absolute) Localization

- **Active Beacons: Ground-Based RF Systems**

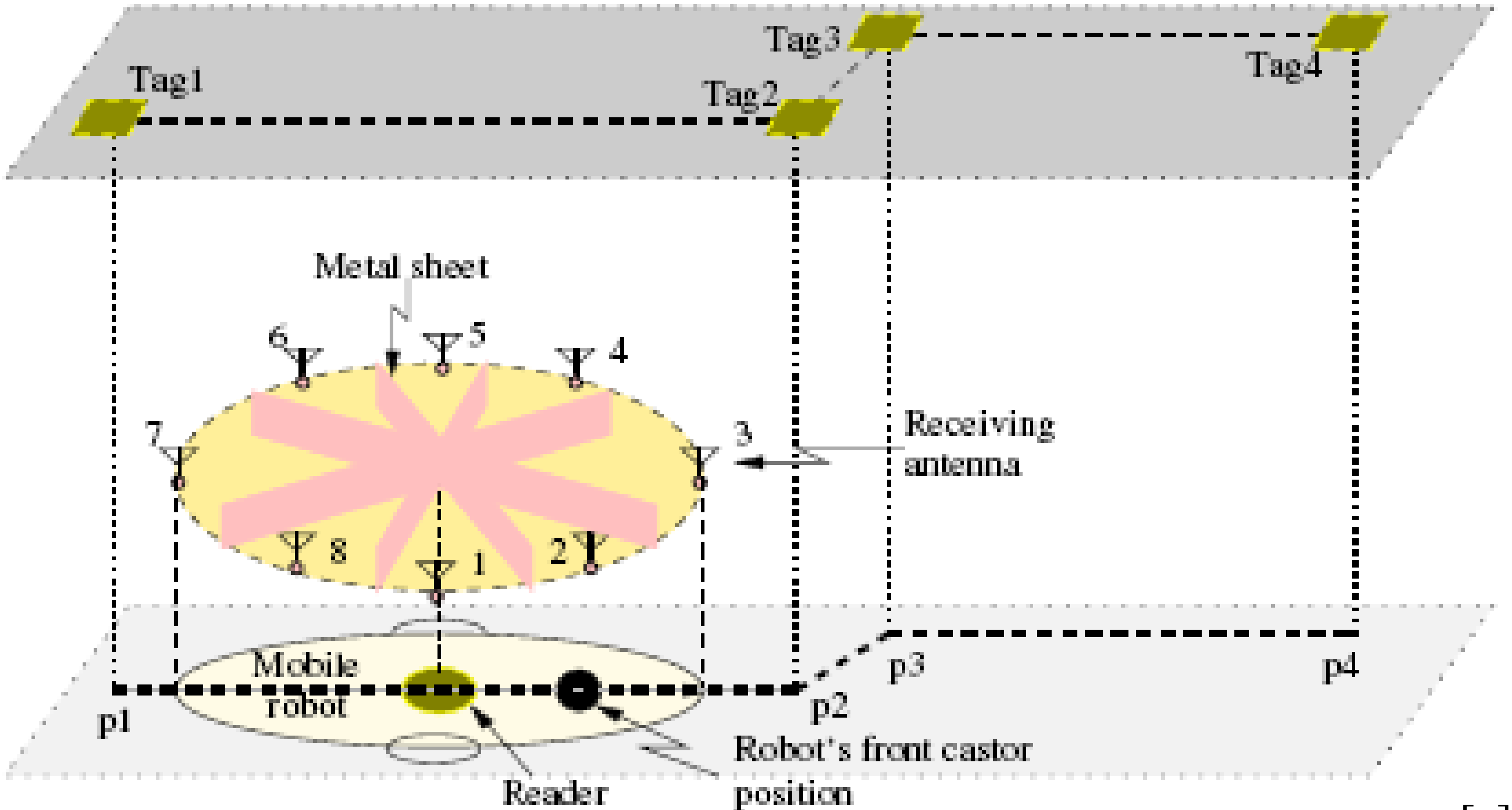


Motorola's Mini-Ranger Falcon 484 R position-location system provides 2 m accuracy over ranges of 100 m to 75 km.

An initial calibration is performed at a known location to determine the **turn-around delay (TAD)** for each transponder (i.e., the time required to transmit a response back to the interrogator after receipt of interrogation).

Global (Absolute) Localization

- **Active Beacons: RFID-based Localization**



[4]

Global (Absolute) Localization

- **Real Time Locating System (RTLS)**

  Wireless RTLS tags are attached to objects or worn by people, and fixed reference points receive wireless signals from tags to determine their location.

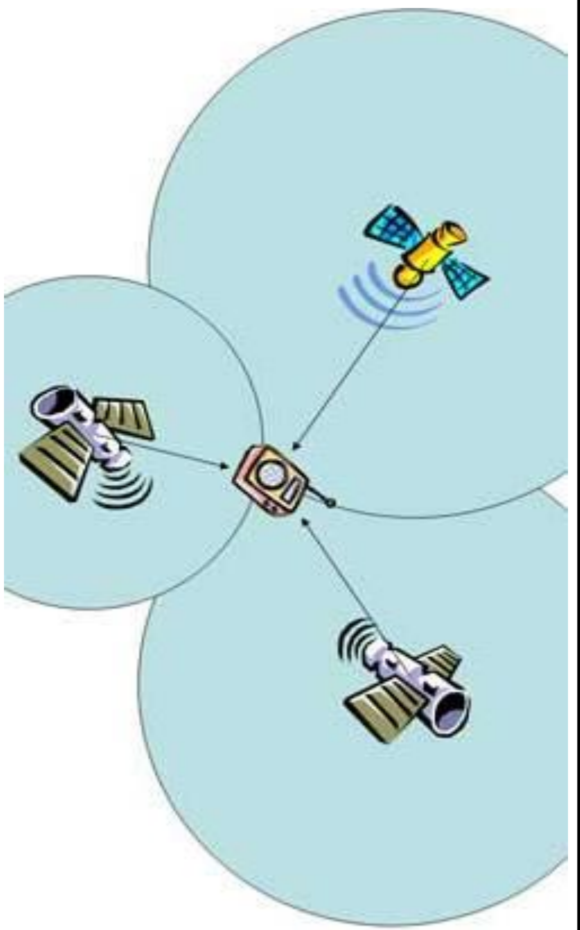
  A pulse with sharp edges is needed to accurately locate an object with radio waves.

Global (Absolute) Localization

- **Real Time Locating System (RTLS)**
  - ◊ **UWB RTLS Advantages:**
    - o Precise localization of tagged objects (from 10cm up to 300 m in Line-of-Sight (LOS) mode)
    - o Cost effective.
    - o Localization of multiple devices using the same setup.
    - o Low power consumption.
  - ◊ **UWB RTLS Disadvantages:**
    - o Antennas should be installed in the working site
    - o Range limitation 300m maximum.

Global (Absolute) Localization

- **Active Beacons: GPS**
  - GPS satellites **broadcast** the time and data about their locations.
  - a GPS receiver compares signals from **at least three or four GPS** satellites to determine it's own location.
  - A GPS receiver figures out **how far away** it is from each satellite based on **how much time** it takes a broadcast signal to travel from the satellite to the receiver.



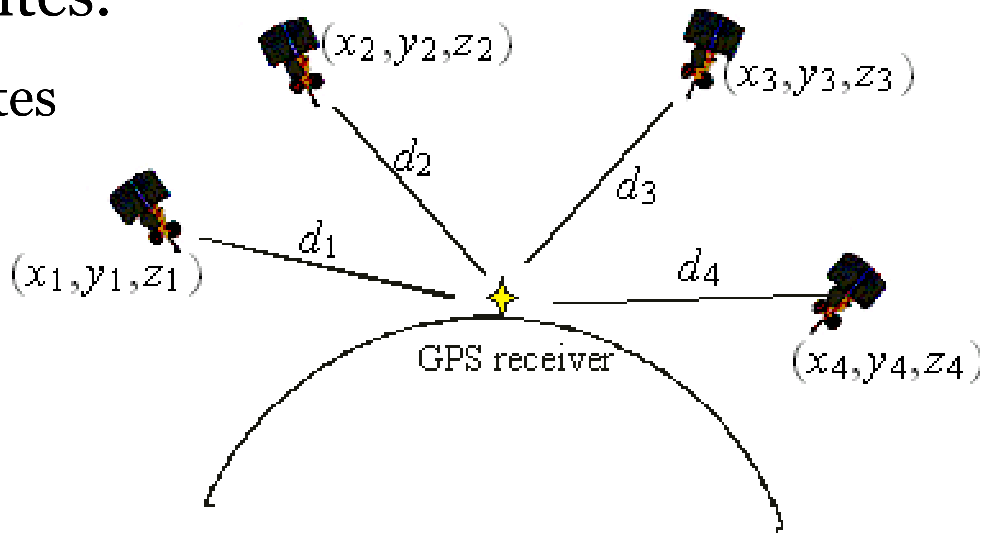
Source: http://www.how-gps-works.com/

Global (Absolute) Localization

- **Active Beacons: GPS**
  - Since the location of each GPS satellite is known, the receiver's location can be determined by "**triangulating**" the distances from several satellites.

For perfectly synchronized satellites

$$\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}+ct_B=d_1$$
$$\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2}+ct_B=d_2$$
$$\sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2}+ct_B=d_3$$
$$\sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2}+ct_B=d_4$$



where c is the speed of light and t_B is the receiver clock offset time. The receiver clock offset is the difference between GPS time and internal receiver time. t_B is the same, which means the all the satellites must have perfectly synchronized clocks

More info: http://www.math.tamu.edu/~dallen/physics/gps/gps.htm

Global (Absolute) Localization

- **Active Beacons: High-precision or Sub-meter GPS**
  - ◊ Satellite-based Augmentation System (SBAS)
  - ◊ Precise Point Positioning (PPP)
  - ◊ Real Time Kinematic (RTK)

Global (Absolute) Localization

- **Sub-meter GPS: SBAS**

  Satellite-based augmentation systems (SBAS), such as EGNOS, complement existing global navigation satellite systems (GNSS). SBAS compensate for certain disadvantages of GNSS in terms of accuracy, integrity, continuity and availability.

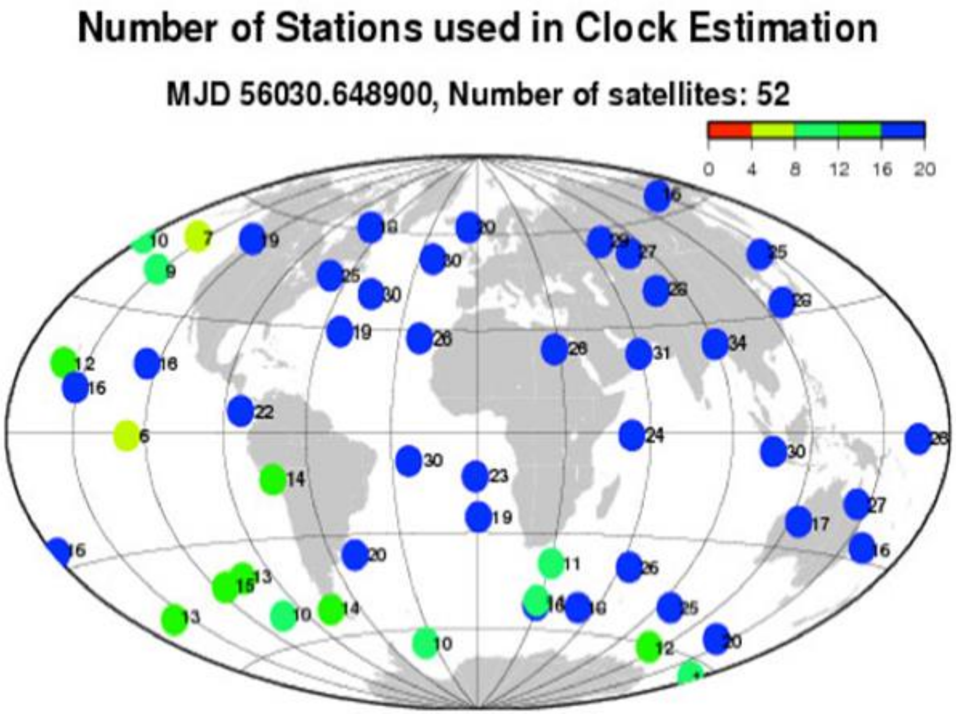
Existing Satellite based Augmentation Systems (SBAS) [5]

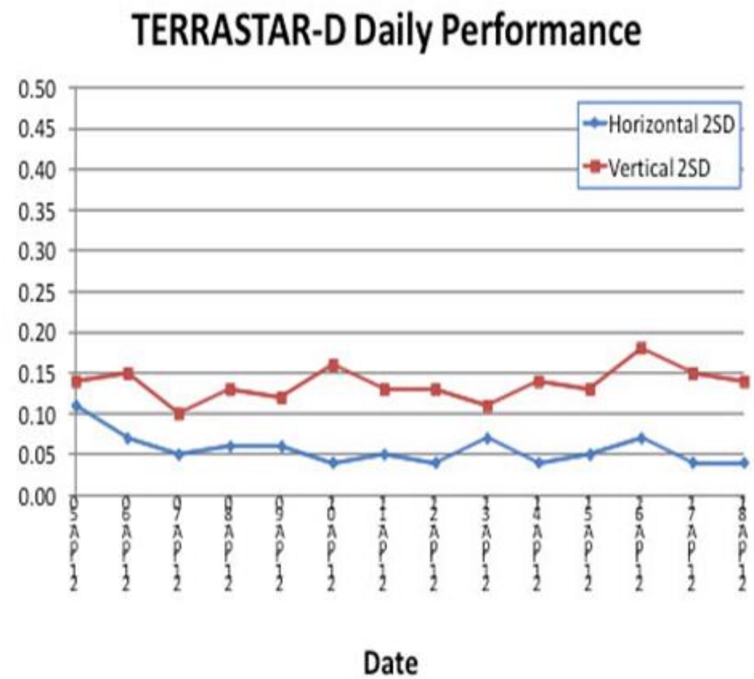
For EGNOS, Egypt lies at around 2.5 meters in Vertical, and 2.5 meters Horizontal. This means that the 0.6 and 0.8 meters accuracies of EGNOS are inside Europe.

Global (Absolute) Localization

- **Sub-meter GPS: PPP**

Terrastar-D is a precise point positioning (PPP) service which delivers position accuracy at better than 10cm (95%) globally.

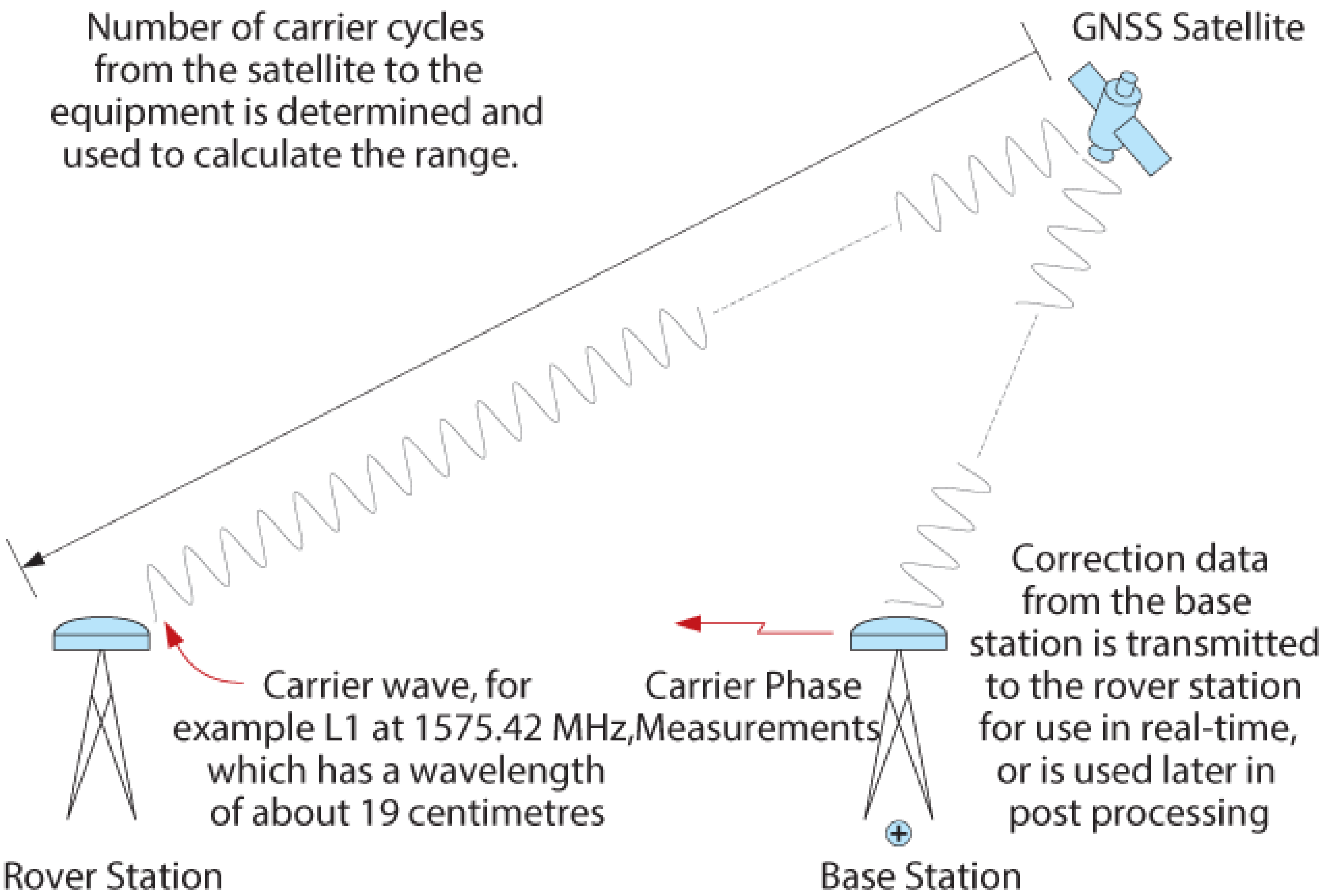




For more info, visit http://www.terrastar.net/

Global (Absolute) Localization

- **Sub-meter GPS: RTK**



Global (Absolute) Localization

- **Sub-meter GPS**

Specification	GPS (PPP)	GPS (RTK)	UWB
Accuracy	10 cm	> 10 cm	30 cm
Update Rate	20 Hz	20 Hz	3 Hz
Power Consumption	1.6 W - 3 W	2.1 - 3.5 W	3 W
Additional Requirement	PPP subscription ~ 2500 Euro/Year/ Module	Single RTK Station Installation ~ 5275 Euro	Need antenna/s to be installed in the field

Source: Alaa Khamis, MineProbe project: http://www.mineprobe.org/

Global (Absolute) Localization

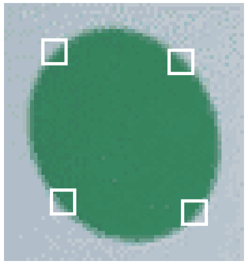
- **Passive Beacon**

Passive Beacons

- Artificial Landmark Recognition
- Natural Landmark Recognition
- Model Matching

Global (Absolute) Localization

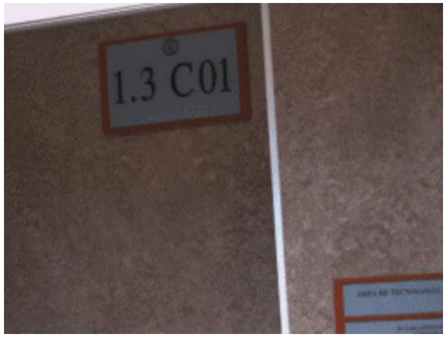
- **Artificial Landmark Recognition**
  - ◇ In this method distinctive artificial landmarks are placed at known locations in the environment.
  - ◇ The advantage of artificial landmarks is that they can be designed for **optimal detectability** even under adverse environmental conditions.



  - ◇ As with active beacons, **three or more landmarks** must be "in view" to allow position estimation. Landmark positioning has the advantage that the **position errors are bounded**, but **detection of external landmarks** and real-time position fixing may **not always be possible**.

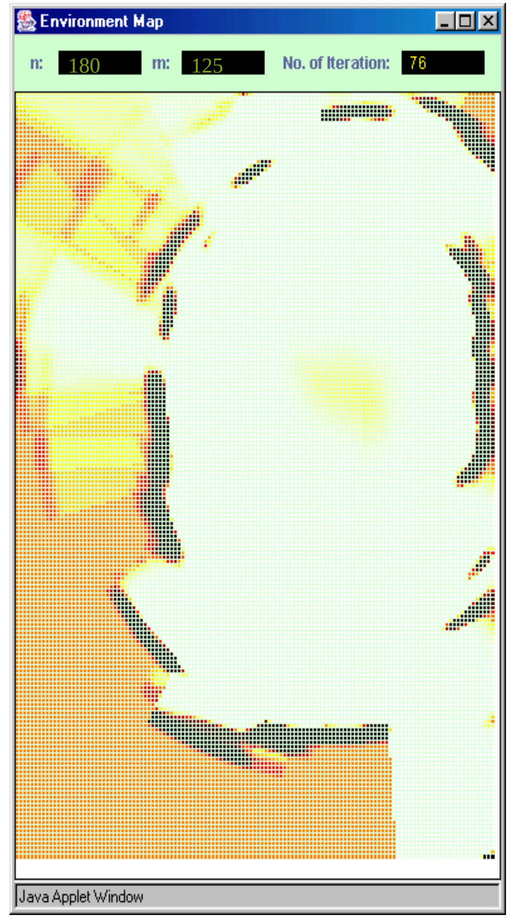
Global (Absolute) Localization

- **Natural Landmark Recognition**
  - ◇ Here the landmarks are distinctive features in the environment.
  - ◇ There is **no need for preparation** of the environment, but the environment must be known in advance.
  - ◇ The **reliability** of this method is **not as high** as with artificial landmarks.

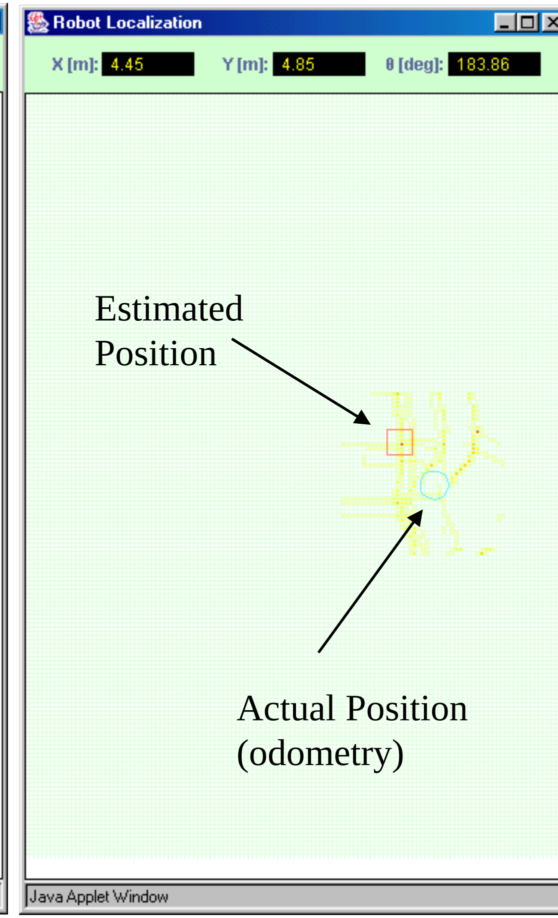



Global (Absolute) Localization

- **Model Matching**
  - ◇ In this method information acquired from the robot's onboard sensors is **compared to** a map or world model of the environment [6].
  - ◇ If features from the sensor-based map and the world model map match, then the vehicle's absolute location can be estimated.



Sonar-based Environment Map



Self Localization

Outline

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- **Hybrid Localization**
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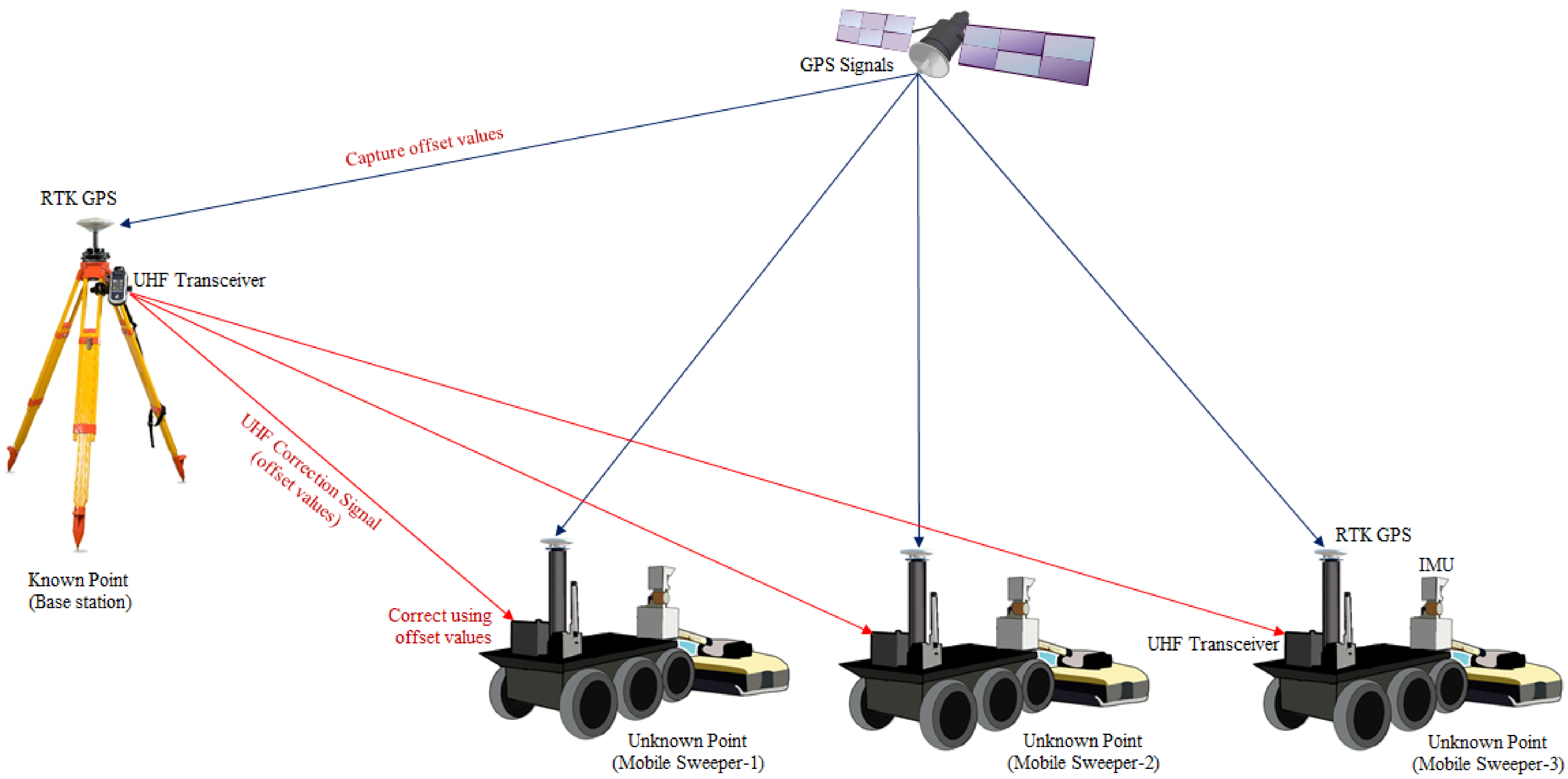
Hybrid Localization



Source: Alaa Khamis, MineProbe project: http://www.mineprobe.org/

Hybrid Localization

Localization Technique	Complexity	Range	Cost	Reliability	Infrastructure Req.	Computational Cost
Dead Reckoning	√	√	√	√	--	√
Inertial Navigation	√ √	√	√√	√	--	√√
Visual Odometry	√√	√	√√	√√	√	√√√
Ground based RF	√	√√	√√√	√√	√√√	√√
Active RFID	√√	√√	√√√	√√	√√	√√
RTLS	√√	√√	√√	√√√	√√	√√
PPP GPS	√√	√√√	√√	√√√	√	√√√
RTK GPS	√√	√√√	√√	√√√	√	√√√

Source: Alaa Khamis, MineProbe project: http://www.mineprobe.org/

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Odometry for Differential Drive

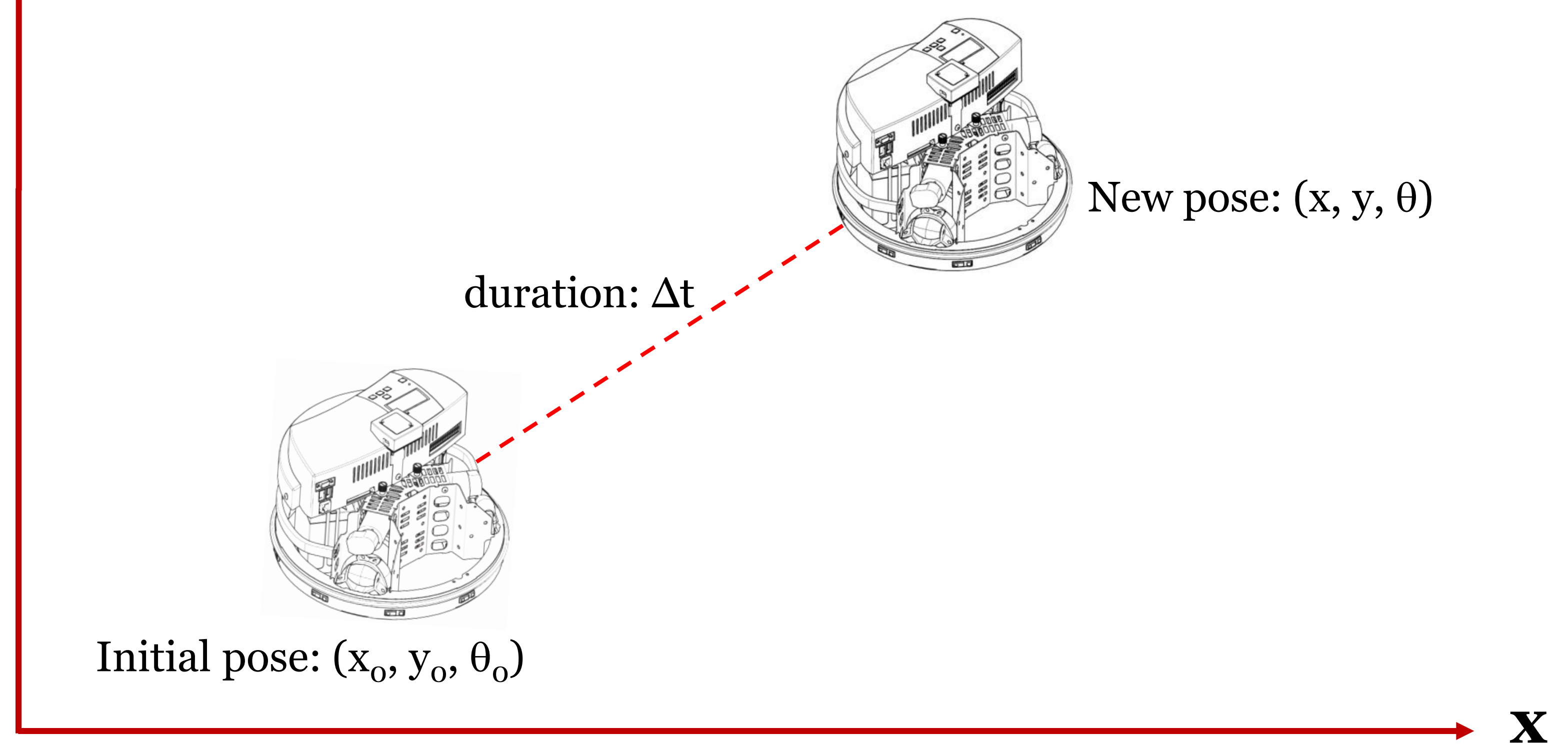
Given:

- Robot geometry
- Right and left wheels' velocities or travelled distances by each wheel.
- Initial pose: (x_o, y_o, θ_o)

⇨ **Odometry-based Positioning** ⇨

Required:

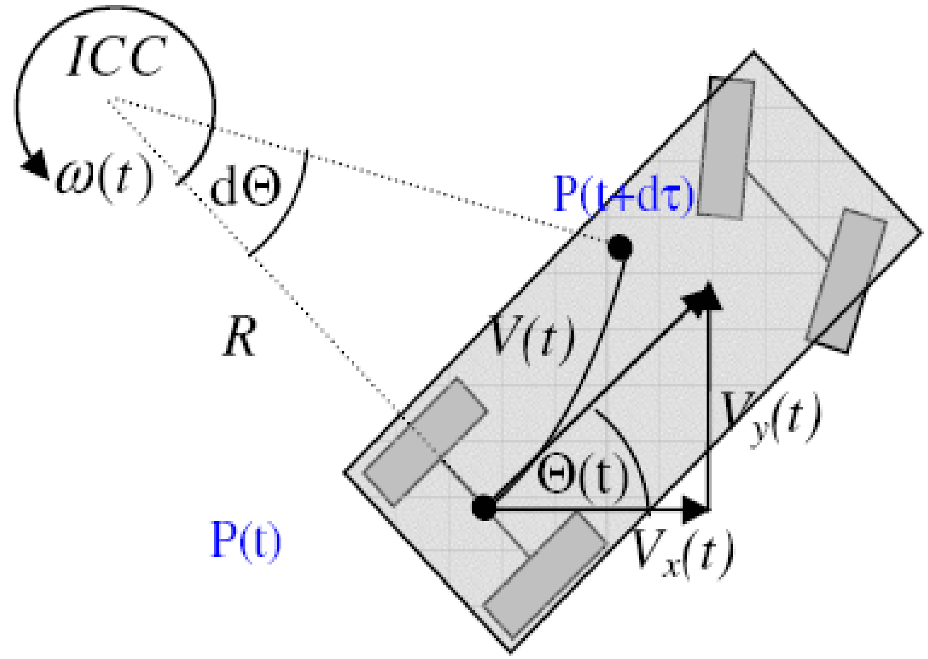
- New pose: (x, y, θ) after time Δt.



Odometry for Differential Drive

Suppose that a differential drive robot is rotating around the point ICC with an angular velocity **ω(t)**.

During the infinite short time ***dt*** the robot will travel the distance from the point **P(t)** to **P(t+dt)** with a linear velocity **V(t)**.

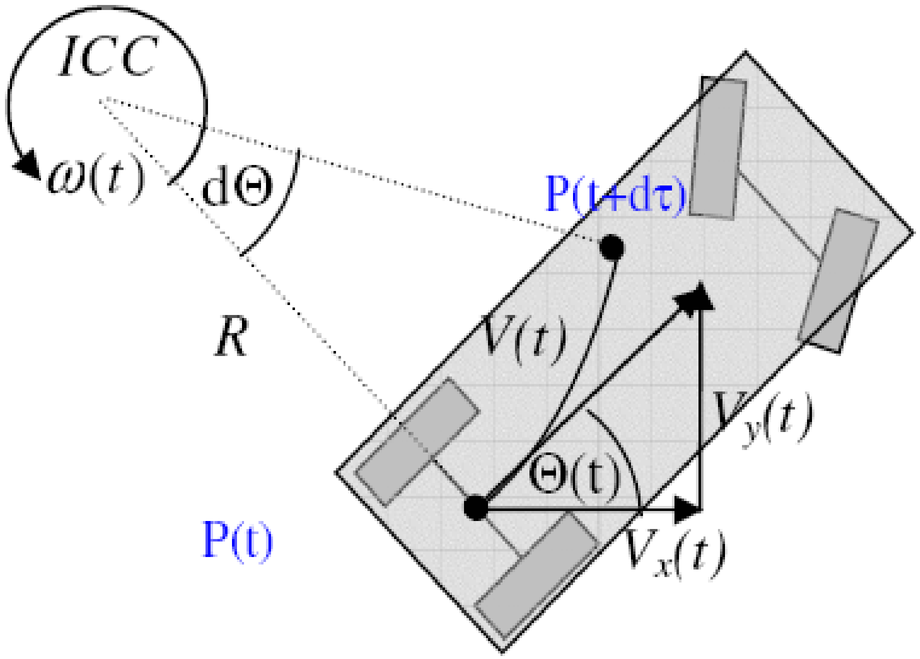


V(t) has two perpendicular components, one along the X axis - $\mathbf{V_x(t)}$, and the other along the Y axis - $\mathbf{V_y(t)}$.

For **infinite short time** we can assume that the robot is moving along a **straight line tangent** in the point P(t) to the real trajectory of the robot.

Odometry for Differential Drive

Based on the two components of the velocity V(t), the traveled distance in each direction can be calculated:



$$dx = V_x(t).dt$$

$$dy = V_y(t).dt$$

where

$$V_x(t) = V(t).\cos[\theta(t)]$$

$$V_y(t) = V(t).\sin[\theta(t)]$$

Similarly, the angle of the rotation can be obtained:

$$d\theta = \omega(t).dt$$

Odometry for Differential Drive

$$dx = V_x(t).dt$$

$$dy = V_y(t).dt$$

$$d\theta = \omega(t).dt$$

Integrating the above equations in the time we obtain:

$$x(t) = \int_0^t V_x(t)dt + x_o$$

$$y(t) = \int_0^t V_y(t)dt + y_o$$

$$\theta(t) = \int_0^t \omega(t)dt + \theta_o$$

where (x_o, y_o, θ_o) – is the initial pose.

Odometry for Differential Drive

Since

$$V_x(t) = V(t).\cos[\theta(t)]$$

$$V_y(t) = V(t).\sin[\theta(t)]$$

We can rewritten the previous equations as follows:

$$x(t) = \int_0^t V(t).\cos[\theta(t)]dt + x_o$$

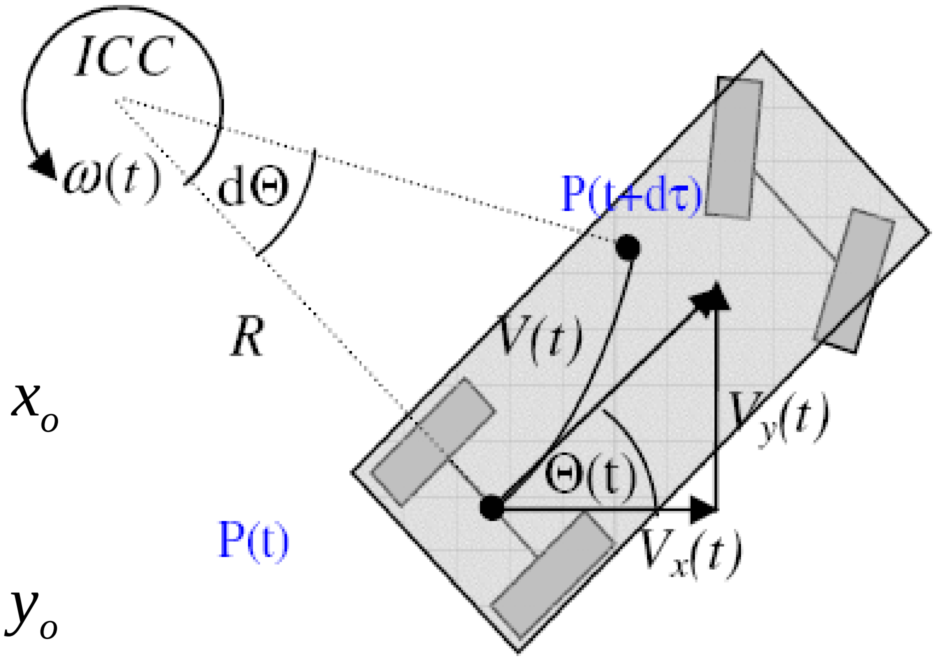
$$y(t) = \int_0^t V(t).\sin[\theta(t)]dt + y_o$$

$$\theta(t) = \int_0^t \omega_x(t)dt + \theta_o$$

These formulas are valid for all robots capable of moving in a particular direction θ*(t) at* a given velocity *V(t)*.

Odometry for Differential Drive

For the special case of **differential drive robot**, we can infer:



$$x(t) = \frac{1}{2}\int_0^t [v_L(t) + v_R(t)].\cos[\theta(t)]dt + x_o$$

$$y(t) = \frac{1}{2}\int_0^t [v_L(t) + v_R(t)].\sin[\theta(t)]dt + y_o$$

$$\theta(t) = \frac{1}{D}\int_0^t [v_R(t) - v_L(t)]dt + \theta_o$$

where D is the wheel separation; $v_L(t)$ and $v_R(t)$ are the linear velocities of the left and right wheels respectively.

Odometry for Differential Drive

For a practical realization, the previous formula can be rewritten for **discrete timing**:

$$x(k) = \frac{1}{2}\sum_{i=1}^{k}\left[v_L(i) + v_R(i)\right].\cos\left[\theta(i)\right].\Delta t + x_o$$

$$y(k) = \frac{1}{2}\sum_{i=1}^{k}\left[v_L(i) + v_R(i)\right].\sin\left[\theta(i)\right].\Delta t + y_o$$

$$\theta(k) = \frac{1}{D}\sum_{i=1}^{k}\left[v_R(i) - v_L(i)\right].\Delta t + \theta_o$$

where x(k), y(k), q(k) are the components of the pose at the **k step** of the movement and Δt is the interval (e.g. **sampling period**) between two sampling times. Depending on the expected accuracy, Δt should be properly selected.

Odometry for Differential Drive

Easier to implement on microcontrollers is the recurrent form:

$$x(k) = \frac{1}{2}\left[v_L(k) + v_R(k)\right].\cos\left[\theta(k)\right].\Delta t + x(k-1)$$

$$y(k) = \frac{1}{2}\left[v_L(k) + v_R(k)\right].\sin\left[\theta(k)\right].\Delta t + y(k-1)$$

$$\theta(k) = \frac{1}{D}\left[v_R(k) - v_L(k)\right].\Delta t + \theta(k-1)$$

Odometry for Differential Drive

The velocities $\mathbf{v_L(i)}$ **and** $\mathbf{v_R(i)}$ can be estimated based on **encoders**, even though it is easier and more precise (without time measurement) to use the **distances obtained directly from the sensors**, based on the following equation:

$$\left[v_L(k) + v_R(k)\right].\Delta t = d_L(k) + d_R(k)$$

where $d_L(k)$ and $d_R(k)$ are the distances traveled in last sampling period.

Odometry for Differential Drive

Finally the kinematics equation of differential drive can be rewritten as below:

$$x(k) = \frac{1}{2}\left[d_L(k) + d_R(k)\right].\cos\left[\theta(k)\right] + x(k-1)$$

$$y(k) = \frac{1}{2}\left[d_L(k) + d_R(k)\right].\sin\left[\theta(k)\right] + y(k-1)$$

$$\theta(k) = \frac{1}{D}\left[d_R(k) - d_L(k)\right] + \theta(k-1)$$

Outline

- Autonomous Vehicle Localization
- Local (Relative) Localization
- Global (Absolute) Localization
- Hybrid Localization
- Odometry for Differential Drive
- **Systematic and Non-Systematic Odometry Errors**
- Measurement of Odometry Errors
- Summary

Odometry Errors

Odometry is based on simple equations that are easily implemented and that utilize data from inexpensive incremental wheel encoders.

$$x(k) = \frac{1}{2}\left[d_L(k) + d_R(k)\right].\cos\left[\theta(k)\right] + x(k-1)$$

$$y(k) = \frac{1}{2}\left[d_L(k) + d_R(k)\right].\sin\left[\theta(k)\right] + y(k-1)$$

$$\theta(k) = \frac{1}{D}\left[d_R(k) - d_L(k)\right] + \theta(k-1)$$

However, odometry is also based on the assumption that wheel **revolutions can be translated into linear displacement** relative to the floor.

This assumption is only of **limited validity**.

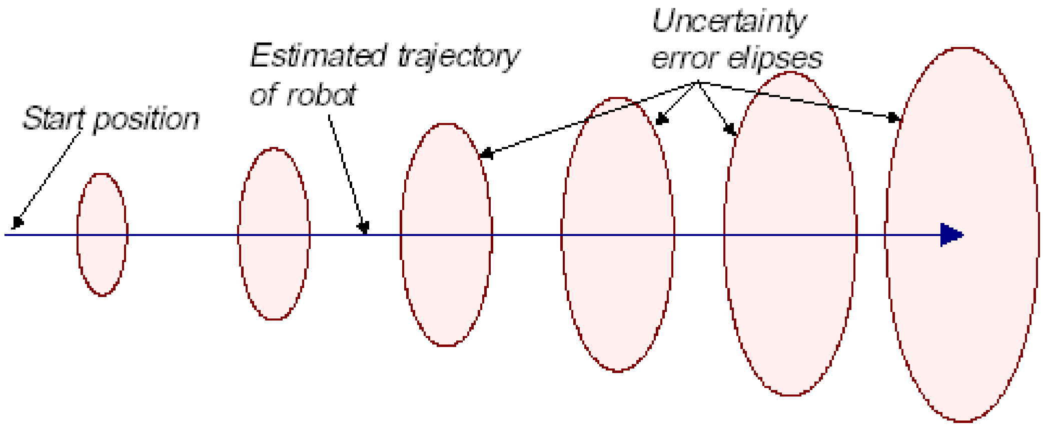
Odometry Errors

Each computed robot position is surrounded by a characteristic "**error ellipse**," which indicates a region of uncertainty for the robot's actual position.

$$x(k) = \frac{1}{2}\left[d_L(k) + d_R(k)\right].\cos\left[\theta(k)\right] + x(k-1)$$

$$y(k) = \frac{1}{2}\left[d_L(k) + d_R(k)\right].\sin\left[\theta(k)\right] + y(k-1)$$

$$\theta(k) = \frac{1}{D}\left[d_R(k) - d_L(k)\right] + \theta(k-1)$$



Accumulated odometry errors

Growing "error ellipses" indicate the **growing position uncertainty** with odometry.

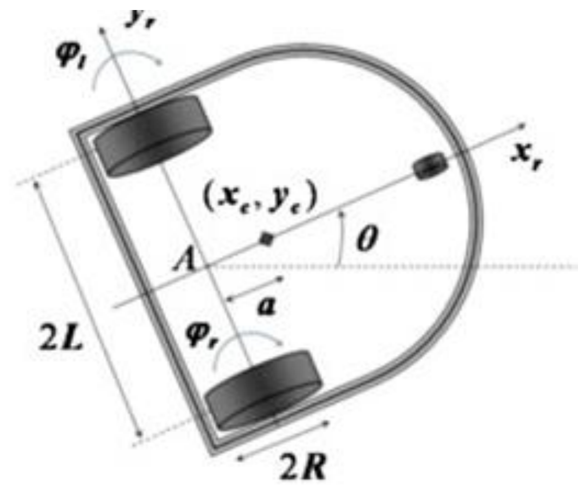
Odometry Errors

Odometry Errors

- **Systematic Errors**
- **Non-Systematic Errors**

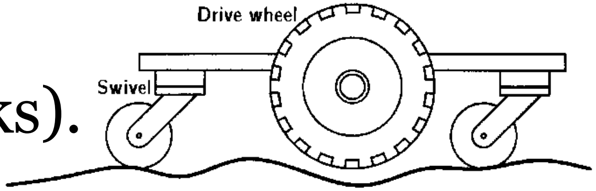
Odometry Errors

- **Systematic Errors:**
  - ◇ Unequal wheel diameters.
  - ◇ Average of actual wheel diameters differs from nominal wheel diameter.
  - ◇ Actual wheelbase differs from nominal wheelbase.
  - ◇ Misalignment of wheels.
  - ◇ Finite encoder resolution.
  - ◇ Finite encoder sampling rate.

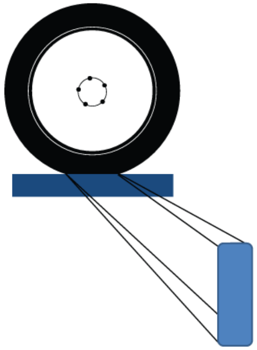


Odometry Errors

- **Non-Systematic Errors:**
  - ◇ Travel over uneven floors (bumps or cracks).



  - ◇ Travel over unexpected objects on the floor.
  - ◇ Wheel-slippage due to:
    - – slippery floors
    - – overacceleration
    - – fast turning (skidding)
    - – external forces (interaction with external bodies)
    - – internal forces (castor wheels)
    - – non-point wheel contact with the floor.



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Measurement of Odometry Errors

- **Measurement of Systematic Odometry Errors**
  - ◇ The error due to **unequal wheel diameters**, defined as:

    $$E_d = D_R / D_L$$

    where D_R and D_L are the actual wheel diameters of the right and left wheel, respectively.

  - ◇ The error due to **uncertainty about the effective wheelbase**, defined as:

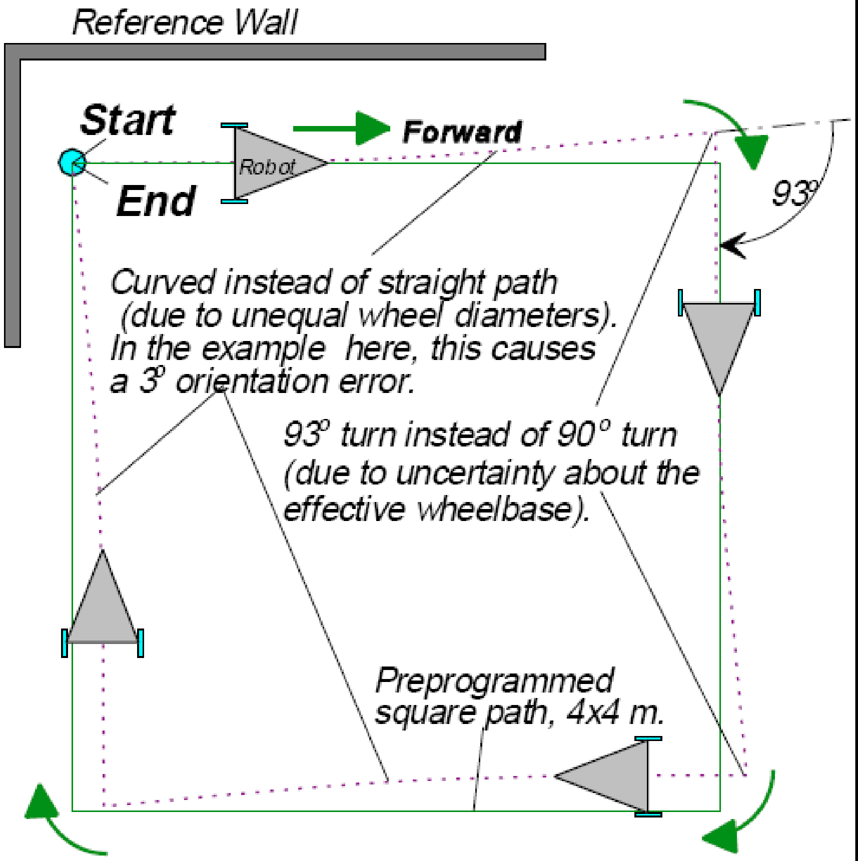
    $$E_b = b_{\text{actual}} / b_{\text{nominal}}$$

    where b is the wheelbase of the vehicle, ideally measured as the distance between the two contact points between the wheels and the floor.

Measurement of Odometry Errors

- **Measurement of Systematic Odometry Errors**
  - ◊ **Bidirectional square-path experiment or University of Michigan Benchmark (UMBmark)**

UMBmark requires that the square path experiment be performed in both clockwise and counterclockwise direction.

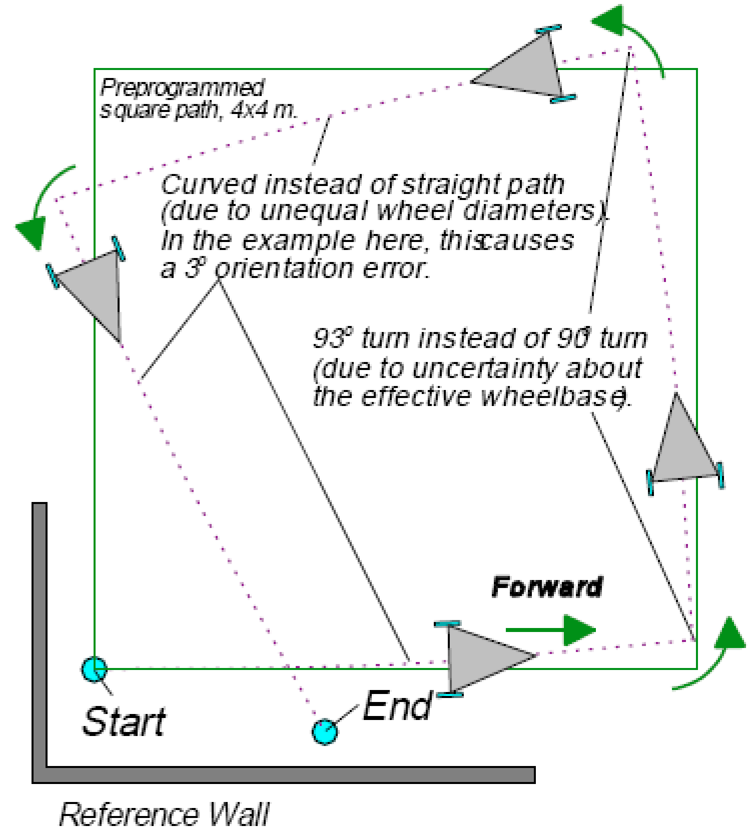


The effect of the **two dominant systematic dead-reckoning errors E_b and E_d**. Note how both errors may cancel each other out when the test is performed in only one direction.

Measurement of Odometry Errors

- **Measurement of Systematic Odometry Errors**
  - ◇ **UMBmark**

    After conducting the UMBmark experiment, one may wish to derive a single numeric value that expresses the odometric accuracy (with respect to systematic errors) of the tested vehicle.



two dominant systematic dead-reckoning errors E_b and E_d : when the square path is performed in the opposite direction one may find that the errors add up.

Measurement of Odometry Errors

- **Measurement of Systematic Odometry Errors**
  - ◇ **UMBmark**

Let $\in x, \in y, \in\theta$ represent the return position errors caused by odometry.

$$\in x = x_{abs} - x_{calc}$$

$$\in y = y_{abs} - y_{calc}$$

$$\in \theta = \theta_{abs} - \theta_{calc}$$

x_{abs}, y_{abs} & θ_{abs} = absolute position and orientation of the robot;

x_{calc}, y_{calc} & θ_{calc} = position and orientation of the robot as computed from odometry.

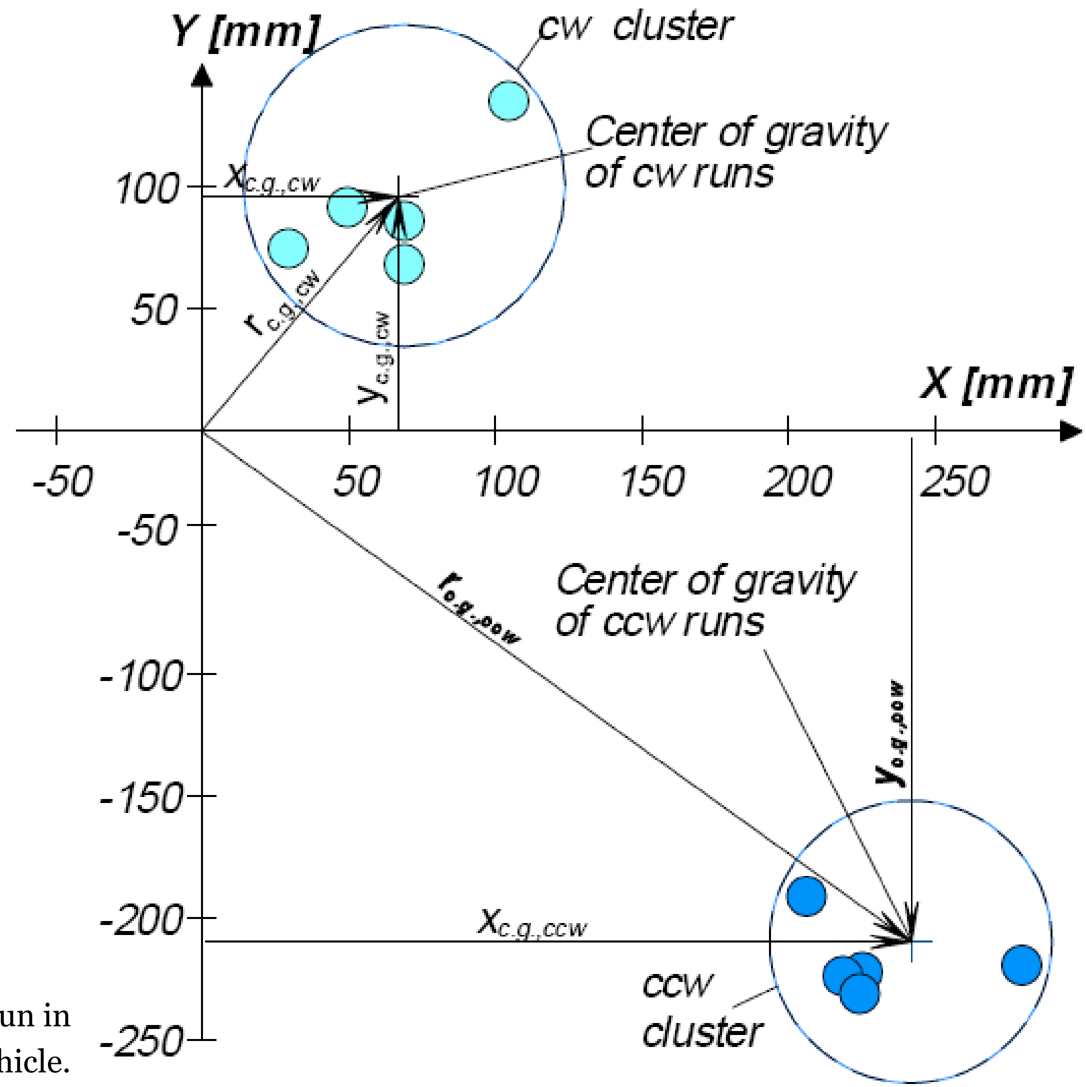
Measurement of Odometry Errors

- **Measurement of Systematic Odometry Errors**
  - ◇ **UMBmark**

    After 5 runs, the coordinates of the two centers of gravity are computed from the results:

$$x_{c.g.,cw/ccw} = \frac{1}{5}\sum_{i=1}^{5} \in x_{i,cw/ccw}$$

$$y_{c.g.,cw/ccw} = \frac{1}{5}\sum_{i=1}^{5} \in y_{i,cw/ccw}$$



Typical results from running UMBmark (a square path run in both cw and ccw directions) with an uncalibrated vehicle.

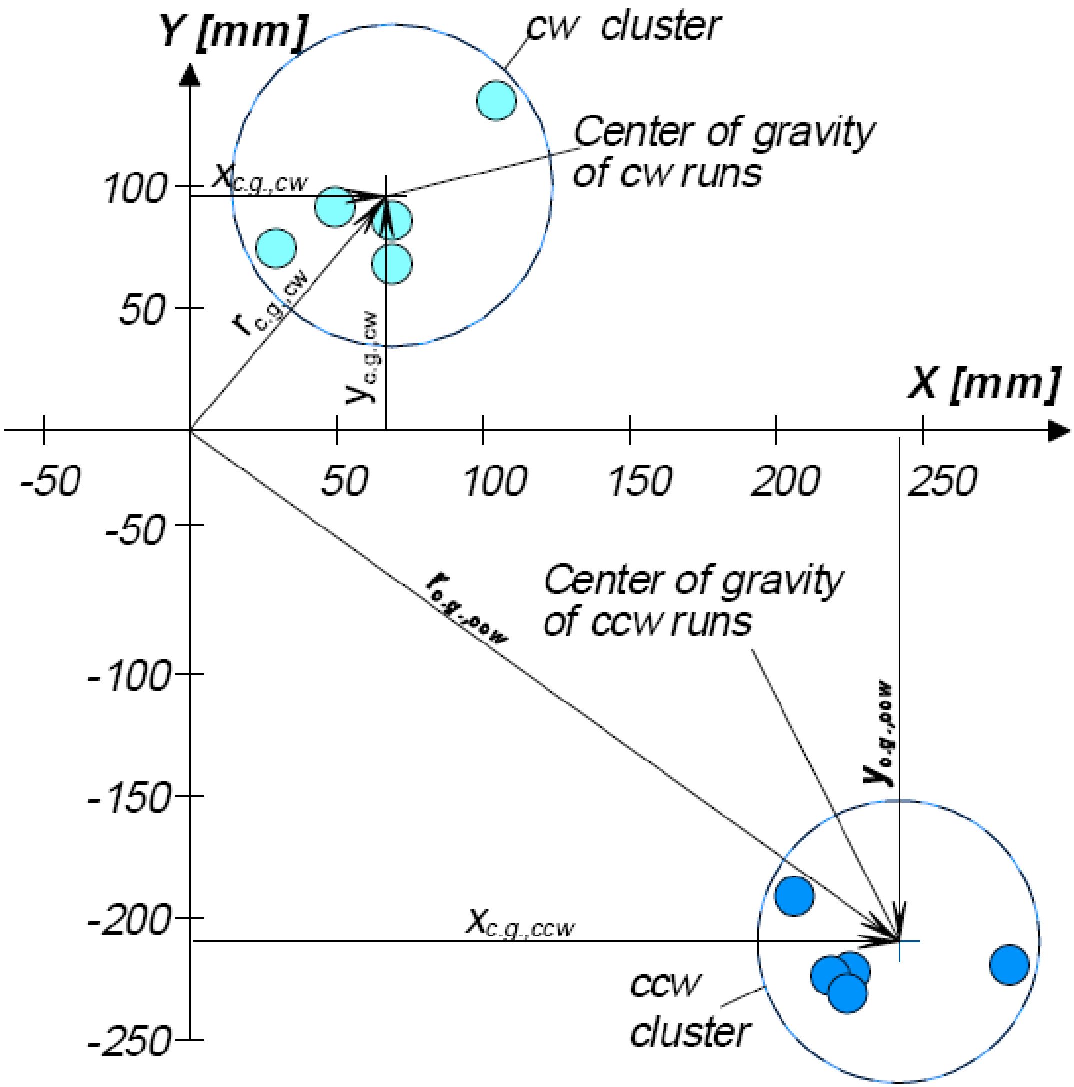
Measurement of Odometry Errors

- **Measurement of Systematic Odometry Errors**
  - ◇ **UMBmark**

    The **absolute offsets** of the two centers of gravity from the origin are given by:

$$r_{c.g.,cw} = \sqrt{\left(x_{c.g.,cw}\right)^2 + \left(y_{c.g.,cw}\right)^2}$$

$$r_{c.g.,ccw} = \sqrt{\left(x_{c.g.,ccw}\right)^2 + \left(y_{c.g.,ccw}\right)^2}$$



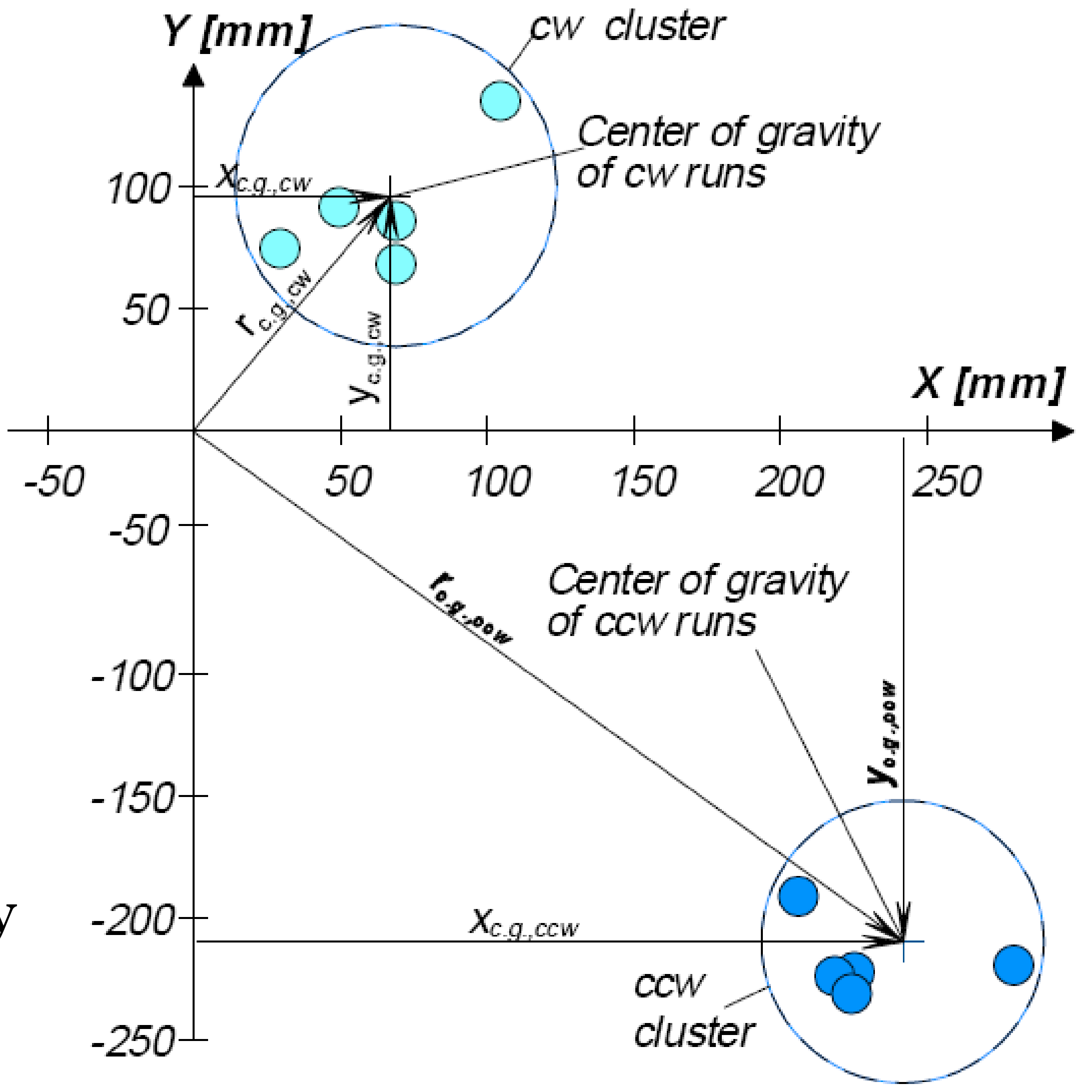
Measurement of Odometry Errors

- **Measurement of Systematic Odometry Errors**
  - ◇ **UMBmark**

    Finally, the "**measure of odometric accuracy for systematic errors**" is:

$$E_{\max, syst} = \max\left(r_{c.g.,cw}; r_{c.g.,ccw}\right)$$

The reason for not using the **average** is that for practical applications one needs to worry about the **largest possible** odometry error.

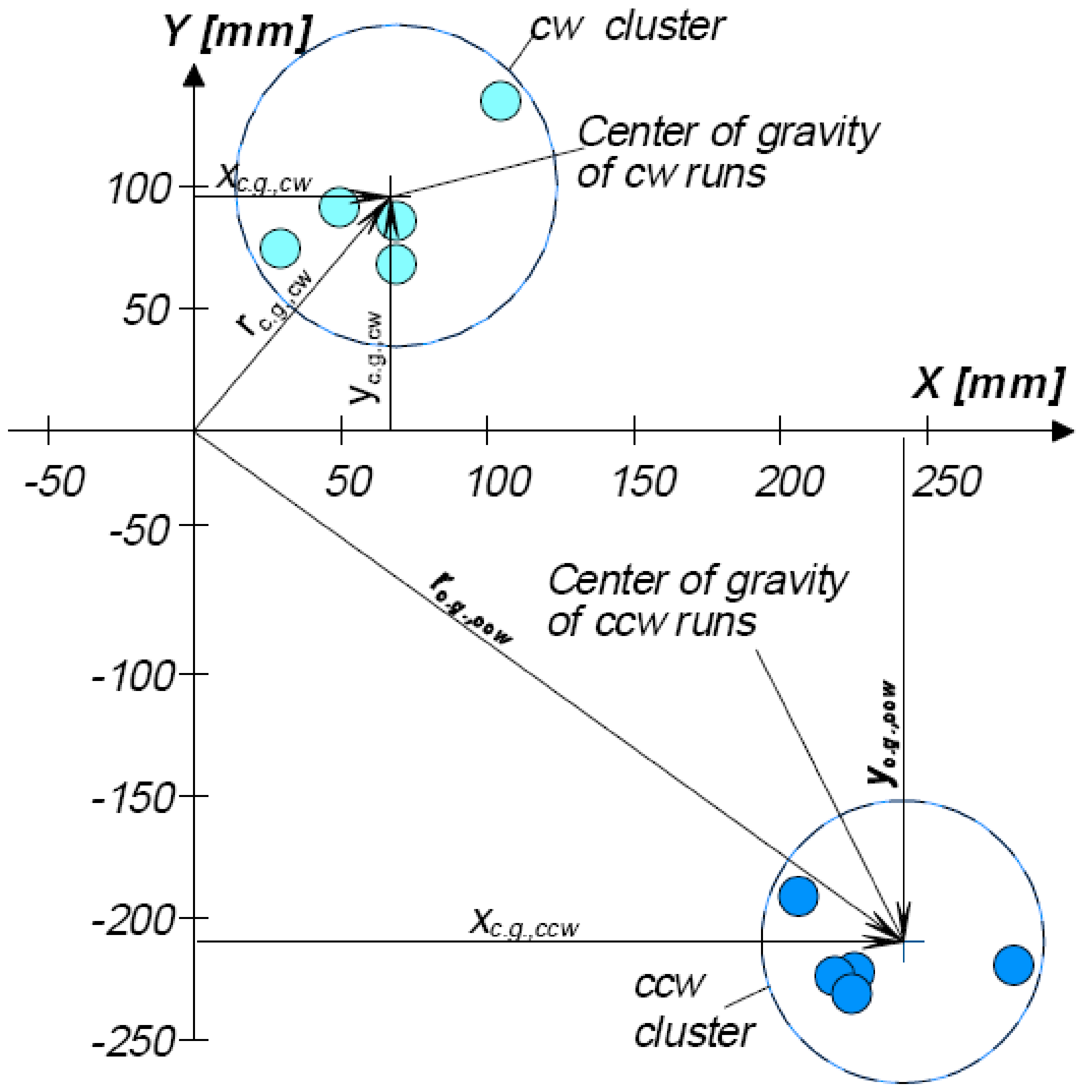


Measurement of Odometry Errors

- **Measurement of Systematic Odometry Errors**
  - ◇ **UMBmark**

$$E_{\max, syst} = \max\left(r_{c.g.,cw}; r_{c.g.,ccw}\right)$$

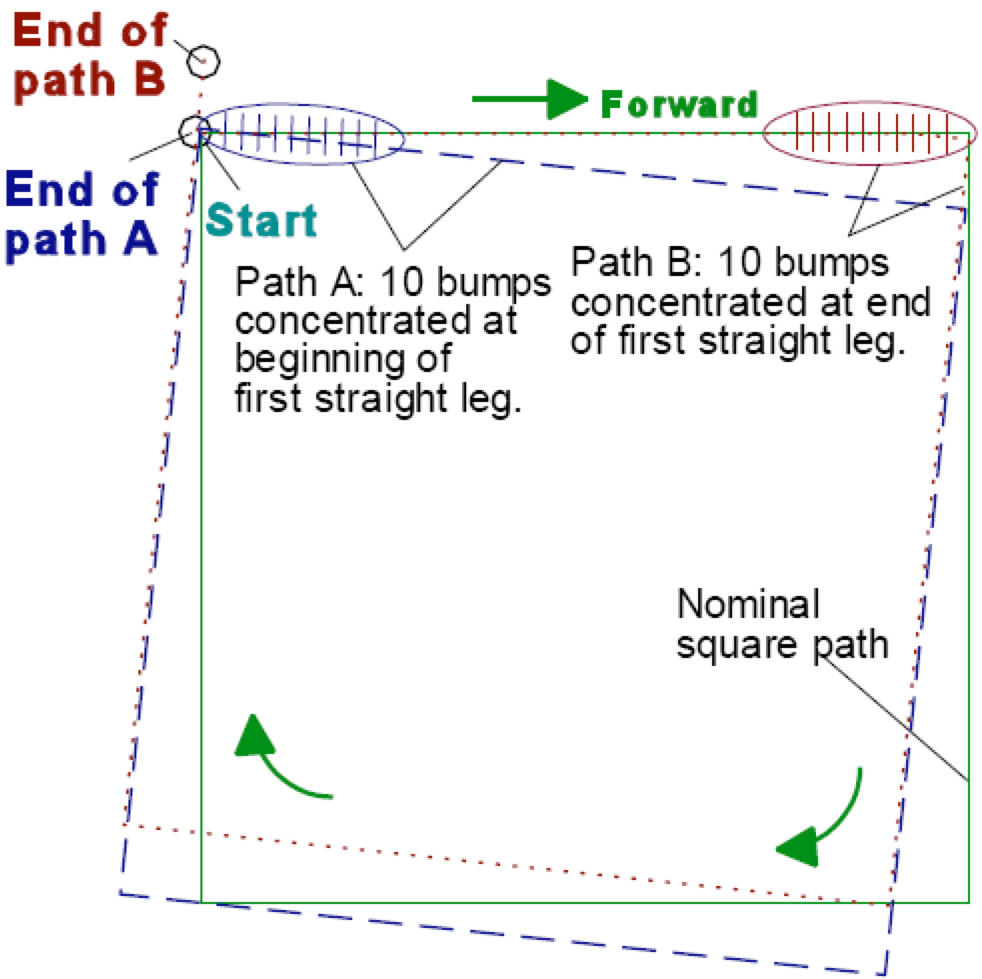
One should also note that the final orientation error $\in\theta$ is not considered explicitly in the expression for $E_{max,syst}$. This is because all systematic orientation errors are implied by the final position errors. In other words, since the square path has fixed-length sides, systematic orientation errors translate directly into position errors.



Measurement of Odometry Errors

- **Measurement of Non-Systematic Odometry Errors**
  - ◇ **Extended UMBmark**

    Although it is more difficult to measure small angles, measurement of $\in\theta$ is a more consistent **quantitative indicator** for comparing the performance of different robots.

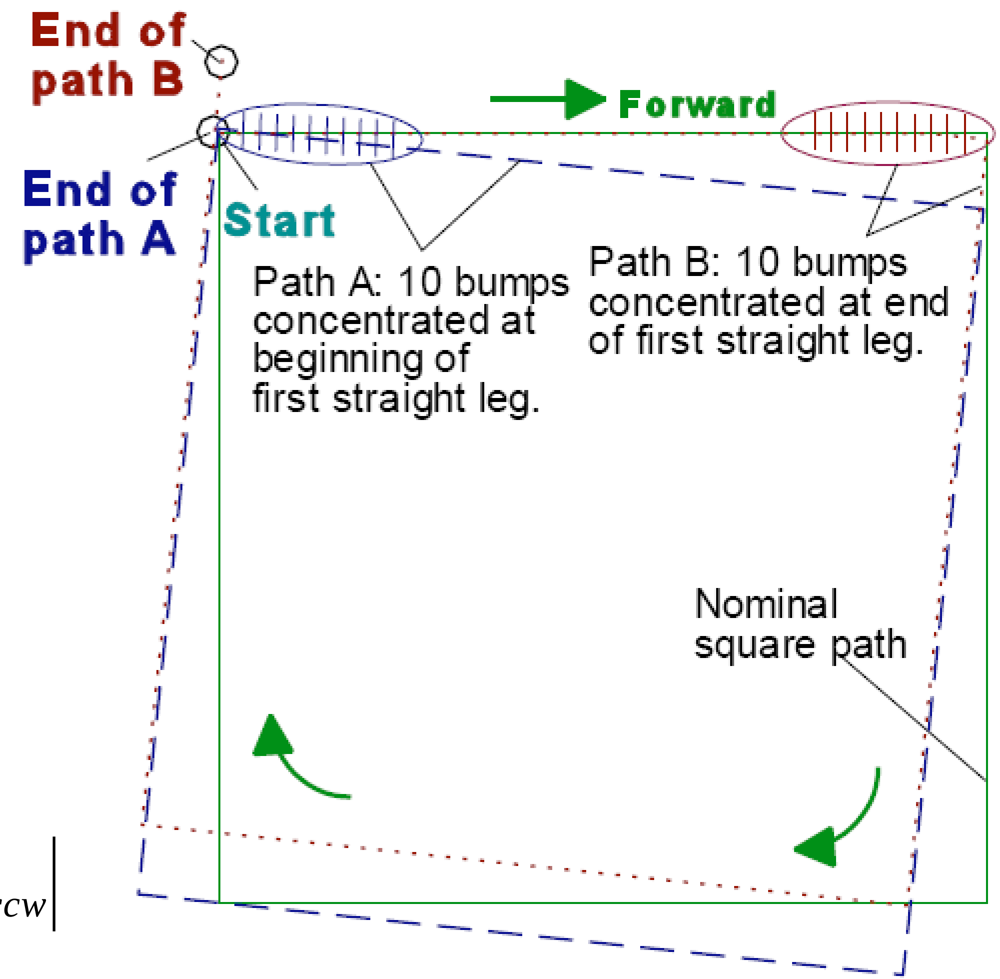


Measurement of Odometry Errors

- **Measurement of Non-Systematic Odometry Errors**
  - **Extended UMBmark**

    One can measure and express the **susceptibility** of a vehicle to non-systematic errors in terms of its average absolute orientation error defined as:

$$\in \theta^{nonsys}_{averg} = \frac{1}{5}\sum_{i=1}^{5}\left| \in \theta^{nonsys}_{i,cw} - \in \theta^{sys}_{averg,cw}\right| + \frac{1}{5}\sum_{i=1}^{5}\left| \in \theta^{nonsys}_{i,ccw} - \in \theta^{sys}_{averg,ccw}\right|$$



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Summary

- Odometry is the most widely used navigation method for mobile robot positioning.
- It is well known that odometry provides good short-term accuracy, is inexpensive, and allows very high sampling rates.
- However, the fundamental idea of odometry is the integration of incremental motion information over time, which leads inevitably to the accumulation of errors.
- In some cases, odometry is the only navigation information available; for example: when no external reference is available, when circumstances preclude the placing or selection of landmarks in the environment, or when another sensor subsystem fails to provide usable data.

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