Terrestrial Multi-sensor Systems

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Terrestrial Multisensor Systems | Institute of Engineering Geodesy | University of Stuttgart (uni-stuttgart.de)
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Introduction into multi-sensor systems

Definition

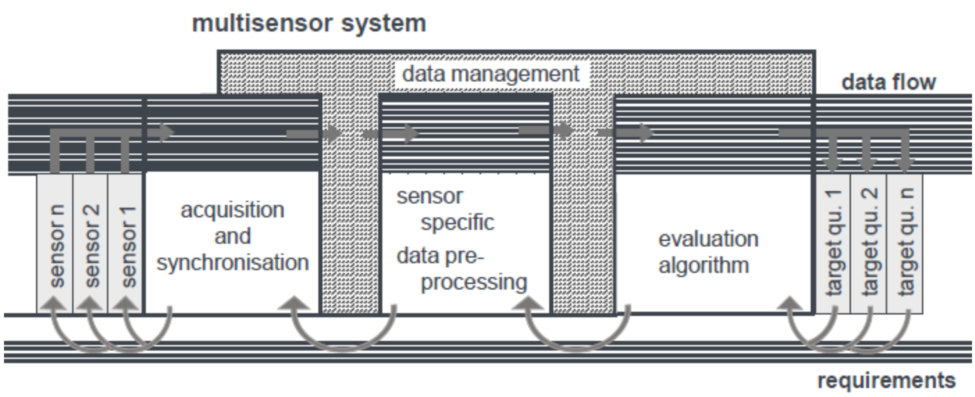
- system: group of related things that work with each other
- sensor: device that measures a physical quantity and converts it into a signal which can be read by an observer or an instrument
- multisensor system: integration of several sensors in one system
- terrestrial: restriction on land-based applications(not airborne or marine applications)
- data acquisition
  - restricted on acquisition of geometry related quantities like co-ordinates, distances, angles
  - additionally measurement quantities that contain time and geometry should be included e.g. accelerations and yaw rates
- Classification of multisensor systems

Sensor	Space-distributed sensor	Redundant sensor	Complementary sensor
	similar sensors at different measurement sites	different sensors acquire the same measurement quantity	different sensors acquire different measurement quantities
Measurement	space-distributed measurement values	redundant measurement (control is possible)	combination of measurement quantities is required to calculate the target quantity
Example	Co-ordinate measurement using GPS on a dam of a reservoir	Kinematic measurement of co-ordinates of a car using GPS as well as an inertial measurement system	Distance and angle measurement using a tachymeter to determine co-ordinates

  - Hybrid measurement systems
    - hybrid = hermaphrodite, mixed, compound of various / different inputs
    - Compound of different sensors, that acquire measurement values by different measurement principles
  - Multisensor systems according to 2) and 3) may be called hybrid too

Design

- Structure of a multisensor system



  - Data acquisition and synchronization

        - generation of raw measurement values, e.g. ba (sensor-internal) analogue/digital conversion
            - digital value of the original measurement values like current, voltage, resistance, inductivity, capacity, frequecy
        - temporal allocation of the measurement values of different sensors to one another and possibly to an external time scale
            - synchronized digital original measurement values
    - data pre-processing
        - determination of a conversion function(transfer function) from original measurement quantity to final measurement quantity
            - conversion of voltage change into length variation
            - frequently linear function(scale and offset)
        - addition of corrction and reductions
            - correction of drift effects or consideration of an addition constant
            - reduction of measurement quantities to the ellipsoid
            - result final measurement quantity and value in required unit
    - Evaluation algorithm
        - Determination of the target quantities
            - e.g. co-ordinates of a vehicle trajectory based on GPS and gyroscope measurements using a KALMAN-Filter
            - Sometimes data pre-processing and evaluation may be carried through in one step or iteratively: e.g. the determination of drift effects for inertial sensors
    - Data management / data base (optional)
        - Alternative to the direct hand over of data between the acquisition, pre-processing and evaluation modules
        - Reasons: perpetuation of evidence, recycle ability, modularity !
        - Demand: interfaces have to be defined and documented in a unique way
    - Visualization (optional)
        - Understanding and interpretation is simplified for the user (and the developer)
- Delimitation of multisensor systems
    - 3 variants
        - only data acquisition and synchronisation
        - additionally data pre-processing
        - additionally determination of target quantities

- The application and hence the required quality of the target quantities assign the structure of the multisensor system up to the required sensors.
- Typical quality criteria are accuracy, reliability / correctness, availability and integrity.

- Procedures to design and implement a multisensor system
  - Modular way
    - The converted measurement values are combined; the sensors work independently
    - Flexibility; the system may be re-configured on the base of new requirements (applications)
  - Integral way
    - The different sensors are coupled directly (on measurement level); interactions among the sensors
    - Increase of quality with respect to a specific application
    - Design and test of different sensor combinations is difficult to implement

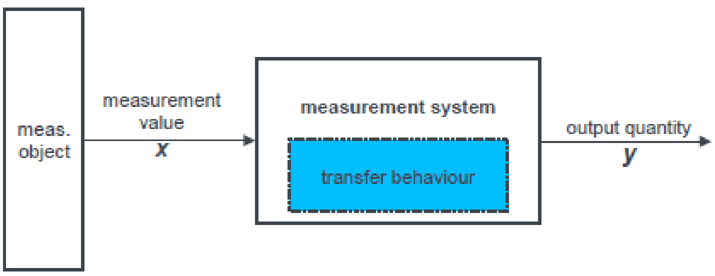
Examples

- Car Positioning - GPS-receiver, odometer, optical speed and distance sensor, gyroscope
- Construction Machine Guidance - excavator controlled by total station
- Land Machine Guidance
- Mobile Mapping System
- UVA (Unmanned Aerial Vehicle)
- Survey Boat
- Unmanned Martime Vehicles
- In-Door Navigation
- Monitoring (slope)

Data acquisition

Review of geodetic data acquisition methods

- Task of a Measurement System



- Input quantities are transferred in a certain way to output quantities
- Constant transfer behaviour
- measurement / output quantity = product of measurement value(X) and unit quantity of respective normal N: $Y = x * N$

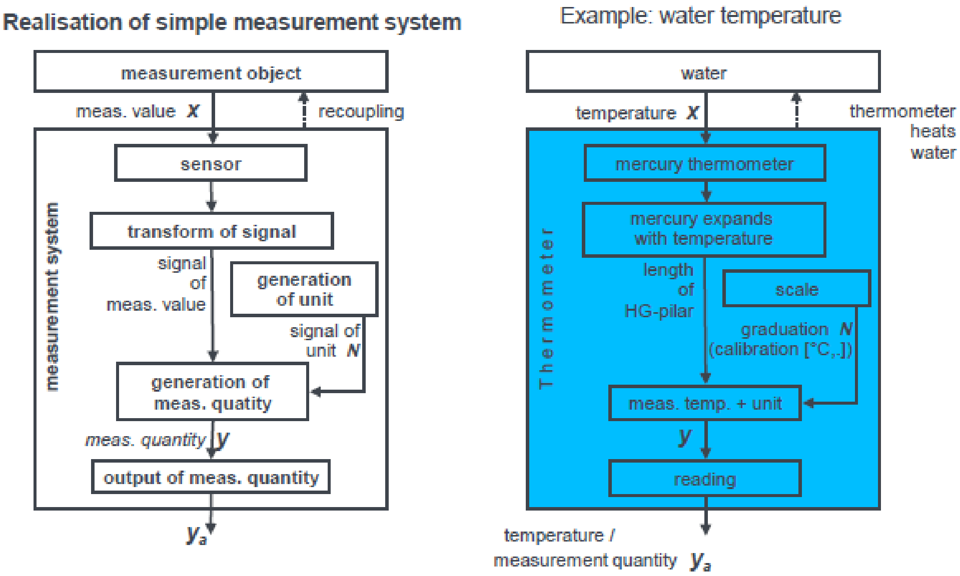
- Different Measurement Methods
  - direct vs. indirect
    - Direct measurement procedure
      - Direct comparison with normal; e.g. distance measurement by comparison with meter normal
    - Indirect measurement procedure
      - Measured value is derived from another physical quantity; e.g. pressure measurement using masses of weights put upon
  - Through the measurement process information about the measured value is transmitted using signals.
  - analog vs. digital

	Analog	Digital
Number of possible measurement values	infinite	Discrete
Output	scale	Digits
Storage/registration	High effort	Low effort
Stability/noise immunity	low	High
Post processing	Very high effort	Low effort

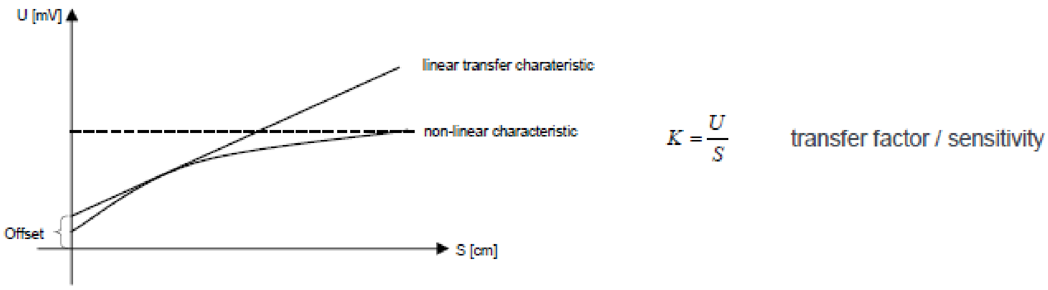
  - Analogue measurement procedure
    - Direct assignment of measured values of the measurement quantity to the physical quantity of the signal.
  - Digital measurement procedure
    - Processing and/or output of digits of the measured value; measured value of measured quantity is determined by counting (transmission of logical 0 and 1)

Analog data acquisition

- Any measurement quantity is transformed to an electric signal; as voltage (U[V]), current (I[A]), ohmic(R[Ω]) inductivity (L[Henry/H=Ωs]), capacity (C[Farad/F=As/V]), frequency (f[Hz])
- the sensor and the transformer generate the electric signal together
- Principle of analog acquisition

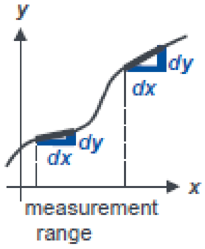


- Characteristics of the Transfer function
    - Static characteristic curve / transfer characteristic
        - transformation of measurement quantity into signal (and vice versa)



        - in general the measurement quantity is acquired in the linear part of the curve
        - Sources of error
            - non-linearity
            - offset/ Bias
            - hysteresis: sensitivity depends on direction of measured value variation
        - Static sensitivity E
            - Change of y if x is changing $E = \frac{dy}{dx}$
                - Sensitivity = transfer factor
                - dy: change of output signal
                - dx: change of input signal
            - Change of E for measurement range possible
                - start, end sensitivity (E_a, E_e)

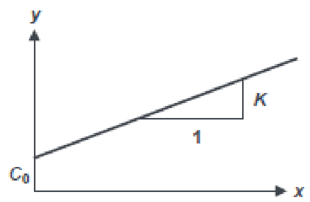
- average sensitivity (E_m)
- Indication for each single value $(E_i, i = 1, \ldots, n)$



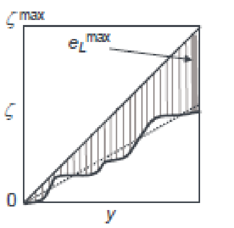
- Linear transfer characteristic
  - measurement value is simple determinable

$$\boxed{y = C_0 + K \cdot x}$$

- x … Input
- y … Output
- K … Sensitivity of converter (transfer factor / scale)
- C_0 …Offset



  - Sensitivity K is given for defined temperature and operating voltage
  - Sensitivity Temperature coefficient is dependency of the sensitivity and the temperature
- Deviations from linearity
  - Deviation from linearity eL

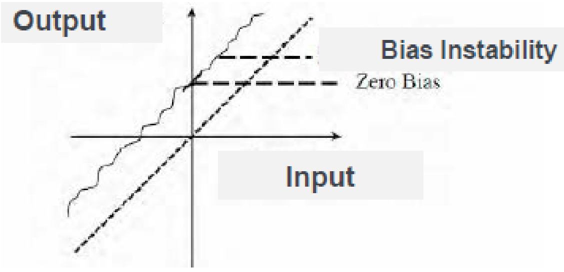


y … measured value
ζ … actual value

    - deviation from a reference line(linear transfer characteristic)
  - Used definitions
    - Reference line estimated from calibration data
      - For measurement instruments with random errors mainly
    - Reference line estimated through theoretic end values (zero point,, max.deflection) defined
      - For measurement instruments with systematic errors mainly

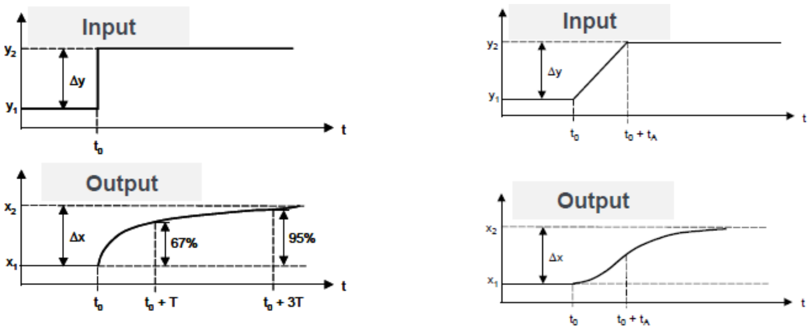
- Used specification for eL
  - Maximum deviation in [%] $e_L = \frac{e_L^{\max}}{\zeta^{\max}} \cdot 100$
- Remark
  - eL is often used instead of an error limit (for instruments with assumed linear transfer characterstic)

- Offset/ Bia

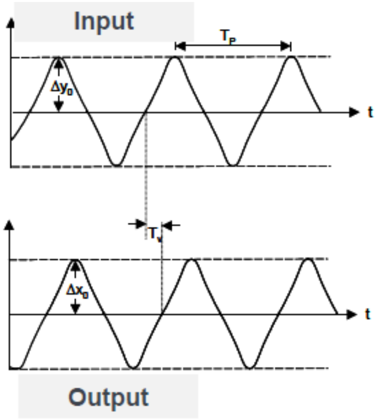


  - Zero Bias/ Initial Bias/ Turn on Bias (constant)
  - Bias Instability/ In Run Bias Stability / Bias Drift/ In Run Bias Stability (change with time)
  - Zero temperature-coefficient bias / Offset Temperature Coefficient (change with temperature)
- Examples of hysteresis errors
  - Further error source: hysteresis (sensitivity depends on direction of measured value variation)

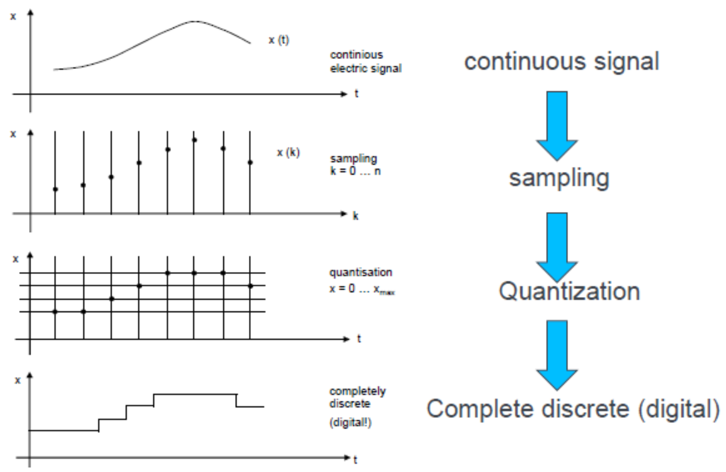
- Dynamic Characteristic
  - Reaction of the signal on temporal changes of the measurement quantity
  - of interest: Impulse of measurement quantity; e.g. switch on of measurement system



  - Continuous succeeding of the temporal variation; e.g. ramp or sine wave



- A/D-Conversion
  - Acquisition of analogue measurement values by digital procedure - > Analogue-to-digital-conversion
  - One disadvantage: information is reduced through discretization in time (sampling) and of signal amplitude (quantization)



  - **Sampling theorem:** A continuous function $x(t)$ (analogue signal) may be reconstructed using the entire digitally sampled values, if no frequencies larger than the Nyquist-frequency f_{vy} are contained within the analogue signal.

$$
\begin{gathered}
f_{nq}=\frac{1}{2 \cdot \Delta t} \quad \text{with } \Delta t- \text{ sampling rate} \\
\Rightarrow \Delta t_{\max } \leq \frac{1}{2 \cdot f_{\text{ral,max}}} \\
\Delta t_{\max }=\leq \frac{1}{(5-10) \cdot f_{\text{real,max}}}
\end{gathered}
$$

Problem:

$$
\text{at } \Delta t>\frac{1}{2 \cdot f_{\text{rad ,max}}} \Rightarrow \quad \text{Aliasing}
$$

Steps up to A/D-conversion

→ Suppression of Aliasing
  ⇒ Anti-aliasing filter = analogue low-pass filter to suppress high frequencies
  ⇒ Danger of aliasing is reduced or eliminated

→ Choice of a time interval for digitalisation
  ⇒ window function

→ Amplification of input signal

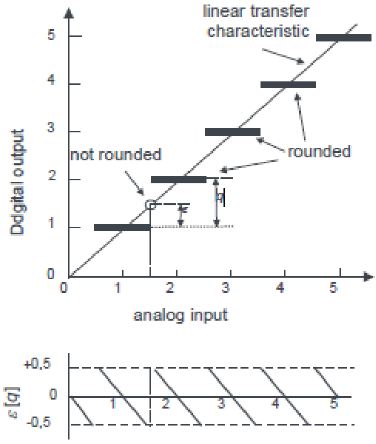
Not treated in detail in this lecture,
⇒ Signal processing.
⇒ dynamic Systems

- Quantisation Error
  - In A/D Conversion an analogue interval is assigned to a digital value

Quantisation error ε

- Assumption: uniform distribution

$$\sigma_{\varepsilon}^{2} = \frac{q^{2}}{12}$$

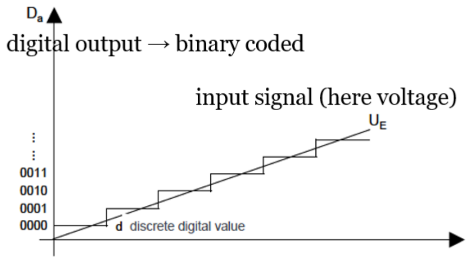


Resolution

- Analog: lowest readable interval q
- Digital: last valid and displayed digit

resoluton ≠ accuracy !

- Transfer Characteristic A/D - Converter
  - Each analog range is matched to a digital value #miss

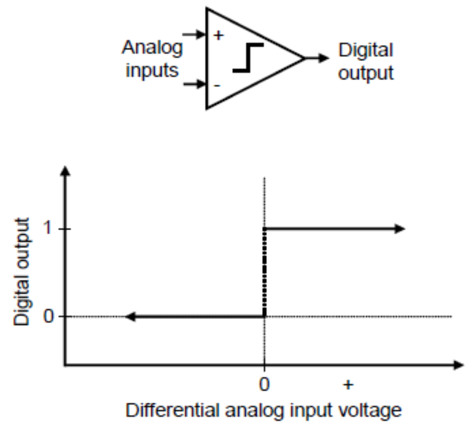


- Discretization and Resolution

	discretisation		Resolution for an measuring range of		
			± 1 V	± 5 V	± 20 V
4 Bit	16	combinations	0,125 V	0,625 V	2,5 V
8 Bit	256	combinations	0,0078 V	0,039 V	0,156 V
16 Bit	65536	combinations	30,5 µV	152 µV	610 µV

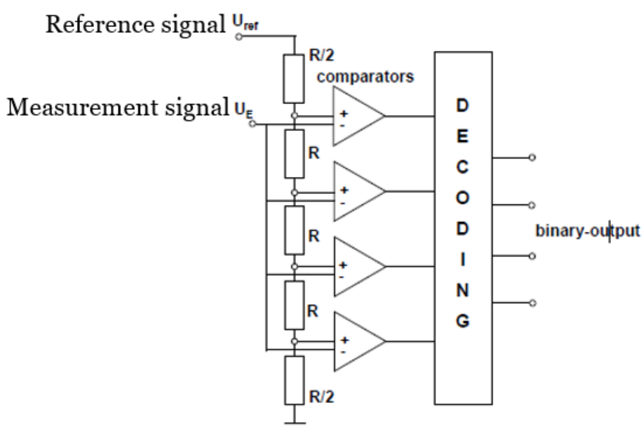
- More bits → higher resolution
- Smaller measurement range → higher resolution

- Comparator (needed for every A/D-conversion)



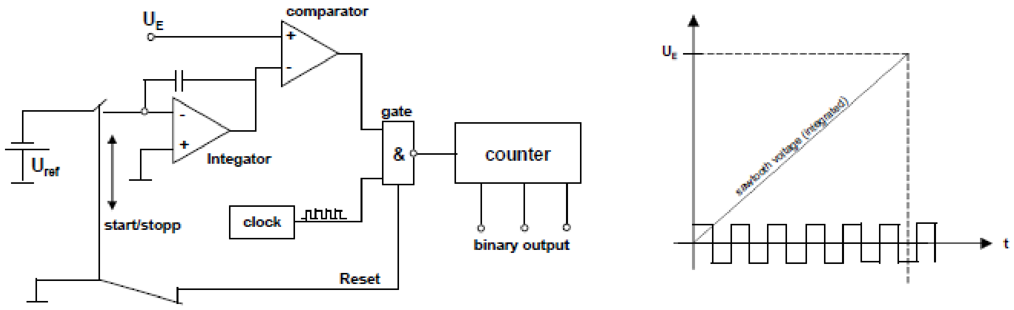
- reference signal Uref
- measurement signal UE
- e.g. Uref >U →0, Uref<U →1

- Flash-Converter / Parallel Converter



- comparison of the input signal with multiple reference signals
- n bit resolution yields to 2n–1 comparators are needed for voltage comparison, since for highest reference voltage no comparator is needed
- resolution 4~14 Bit
- advantage: very fast: < 100 ns
- diadvantage: High power loss and cost (especially for high resolution - cannot have high resolution)

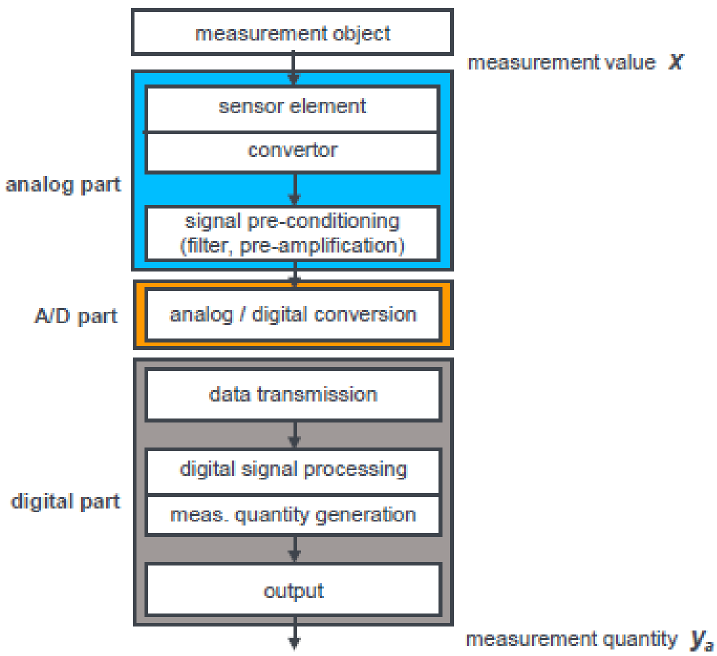
- Single Slope Integrating Convertor



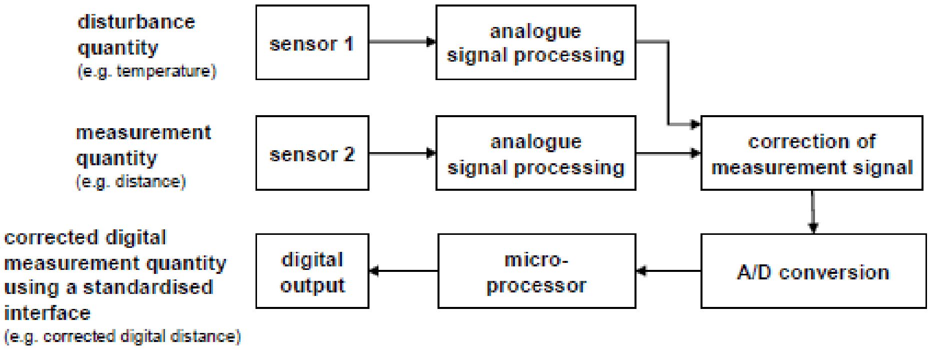
- Measurement of the time, that an integrator needs to reach the amplitude of the input signal
  - comparison of the integrated reference voltage with measured voltage (comparator)
  - counting of impulses of an oscillator/clock up to measured voltage is reached
    - much slower; higher resolution
    - high voltage for many impulses / small voltage for few impulses
  - If UE is reached
    - number of counted impulses is the digital output / measurement value
    - reset is effected (integrator restarts)

Digital data acquisition

- Measurement principle of complex sensors



- Distance measurement with tachymeter



- for sensors using digital signal processing (complex sensors)
- acquisition means for this case
  - inquiry of digital measurement values at correct point in time (time epoch)
- transformation and A/D-conversion is carried through on a microprocessor integrated into a sensor; corrections may be included
- Digital Output
  - (bi)seriel or (bi) parallel interfaces e.g. RS-232 (point to point)
  - specification in layers (specific definition, not treated in this lecture)

- TEDS - Sensors
  - General problems of sensors
    - different formats and interfaces, information about sensor, measurement quantity, unit, sensitivity is not available
  - Solution
    - transmission of sensor-specific data by the sensor itself; "Plug and Play" in data acquisition
    - TEDS-sensors / Transducer Electronic Data Sheet
  - Content of a TEDS
    - sensor type
    - Serial number and manufacturer
    - Measurement quantity and unit
    - Sensitivity (and offset)
    - Date of calibration
  - IEEE 1451 (IEEE = Institute of Electrical and Electronics Engineers)
    - Standard, that is independent of networks, systems and sensors
    - Valid for serial interfaces, bus systems as e.g. CAN bus, wireless transmission as e.g. Bluetooth, etc.

Special kinematic sensors(project related)

- Accelerometer (acceleration)

  - **Measurement Quantities (No integration):**

    measurement of acceleration: $a\left[\frac{m}{s^2}\right]$ (the unit is often given in [g]/[mg])

  - **Deviated Quantities:**

    – 1-time integration over time: measurement of velocity:

    $$v_i = v_{i-1} + a \cdot \Delta t \left[\frac{m}{s}\right].$$

    – 2-times integration over time: measurement of distances

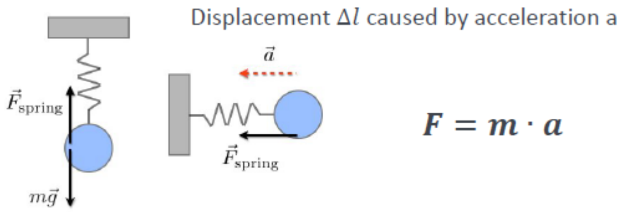
    distance increment between two epochs: $\Delta s_i = v_{i-1} \cdot \Delta t + 0.5 \cdot a \cdot \Delta t^2\ [m]$

    distance from starting point: $s_i = s_{i-1} + v_{i-1} \cdot \Delta t + 0.5 \cdot a \cdot \Delta t^2\ [m]$

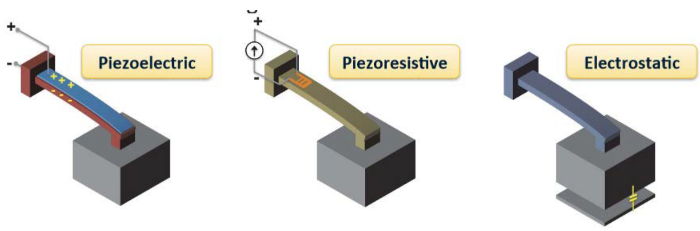
  General Problem of accelerometers: the offset of acceleration can have a be very big influence for the velocity and distance through 1-time or 2-time integration over time. E.g. offset of a is 0.1 m/s^2 →

After	1s	10s	60s	1h
Velocity errors [m/s]	0.1	1	6	360
Distance errors [m]	0.05	5	180	648000

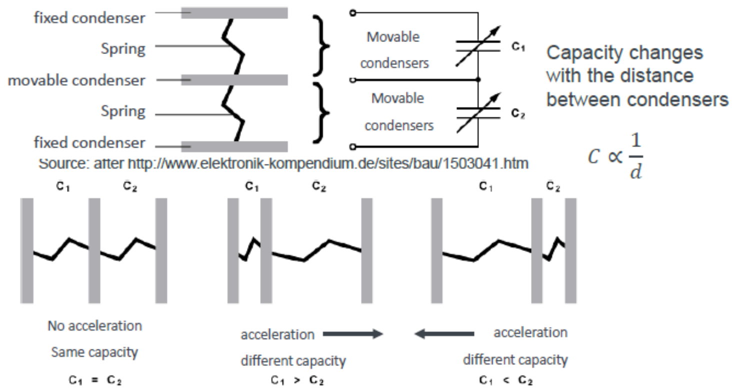
  - Basic function: $\boldsymbol{F = m \cdot a}$
  - Three measurements principles
    - Spring-mass system



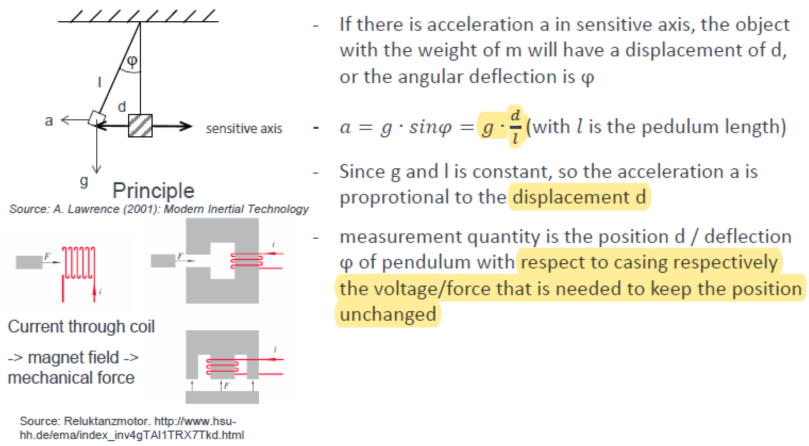
      - If there is acceleration a in sensitive axis, the object with the weight of m will have a displacement of Δl
      - Force F can be calculated with spring constant k and the displacement Δl: $F = k \cdot \Delta l$
      - So the acceleration can calculated: $a = k \cdot \Delta l / m$, a is proportional to Δl
      - If the acceleration a in measured in vertical direction, the influence of the gravity should be subtracted -$a = a - g$
      - Displacement has to be converted into electrical signal, there are different kinds of transducer



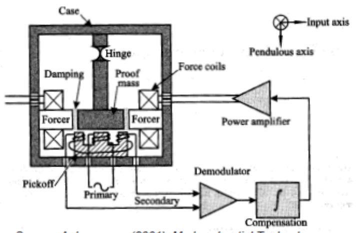
- Piezoelectric: piezoelectric material (e.g. Quarz, ceramic) will change its form because of the force, the force can be transferred to voltage, the voltage can be measured
- Piezoresistive: resistance of some materials (e.g. silicon) can change because of the force, the resistance change can be measured
- Electrostatic (capacitive): measure the change of capacity or voltage between two condensers
- Electrostatic (capacitive)



- Pendulous accelerometer

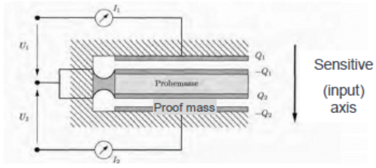


- Realisation: Q-Flex



Source: A. Lawrence (2001): Modern Inertial Technology

- hinge supports mass, hinge must lie in plane containing proof mass centre of gravity
- if proof mass is centred, voltages are identical, (pick off as differential transformer)
- if proof mass moves sideways, the voltage difference (electric signal) increases; the difference is proportional to displacement (measurement quantity)
- Voltage output is passed to an amplifier that generates current to drive two forcers to hold the proof mass in the centre



Source: J. Wendel (2011): Integrierte Navigationssysteme : Sensordatenfusion, GPS und Inertiale Navigation

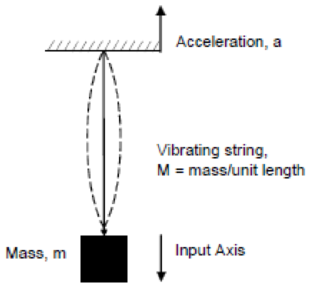
$$F = \frac{Q_1^2}{K} - \frac{Q_2^2}{K} \qquad F = \frac{(Q+\Delta q)^2}{K} - \frac{(Q-\Delta q)^2}{K} = \frac{4 \cdot \Delta q \cdot Q}{K} = m \cdot a$$

$\Delta q = I\,\Delta t$ measurement

$$a = \frac{4 \cdot I \cdot \Delta t \cdot Q}{m \cdot K}$$

Mass, weight

- Vibrating beam accelerometer



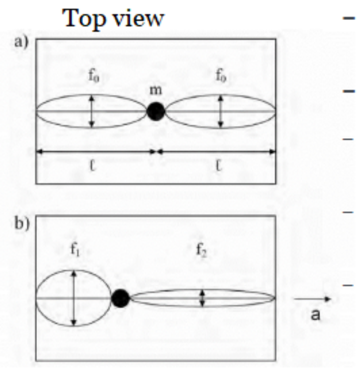
Principle

Frequency $f_0 = \frac{\sqrt{m \cdot a / M}}{2 \cdot \pi}$ with M: strings's mass per unit length

$$a \propto f^2$$

- proof mass hangs on a wire that is made to vibrate
- vibration with a given frequency (e.g. 1450 Hz for Accelerax Design)
- mostly the vibration is electronically generated by a quartz resonator
- tensile resonant frequency depends on tensile strain
- tensile strain depends on acceleration, if proof mass is fixed to wire
- the frequency difference between two points of time / epochs is the measure for acceleration

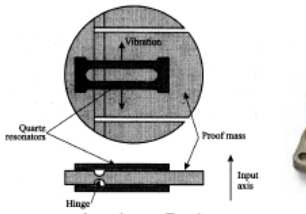
- example



$$a = \frac{2 \cdot M \cdot l^2 \cdot (f_2^2 - f_1^2)}{m}$$

Source: F., Wild-Pfeiffer (2015): Das Potential von MEMS-Inertialsensor zur Anwendung in der Geodäsie und Navigation

- two resonators: frequency of tensioned resonator increases, frequency of compressed resonator decreases
- frequency difference = measure for acceleration
- elimination of drift and temperature effects using the frequency difference
- resolution is defined by the possibility to detect small frequency differences
- proof mass: squeezed film



Accelerax Design

Above: Top View, Below: cross-section

Honeywell's ACCELEREX® resonating beam accelerometer (RBA)

Source: https://aero1.honeywell.com/inertsensor/rba500.shtml

  - offset error, systematic error

- Gyroscope (rate of rotation / angular velocity)

<u>Measurement Quantities (</u>**No integration**<u>)</u>:

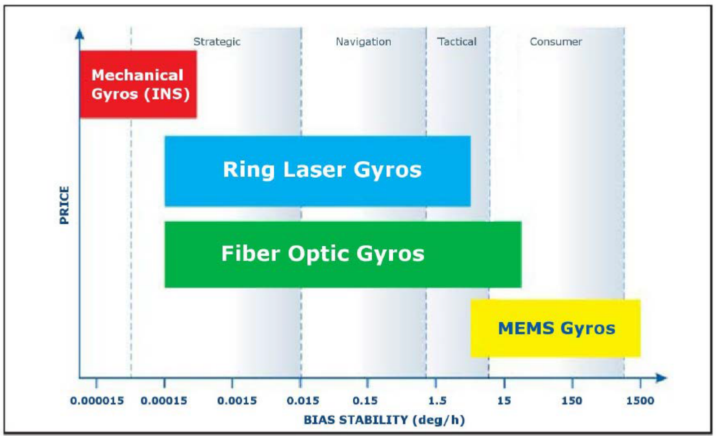
measurement of <u>rate of rotation / angular velocity</u>: $\dot{\varphi}\,[\frac{°}{s} / \frac{gon}{s} / \frac{rad}{s}]$

<u>**Deviated Quantities:**</u>

- 1-time integration over time: measurement of angles respectively differences of azimuths in horizontal case

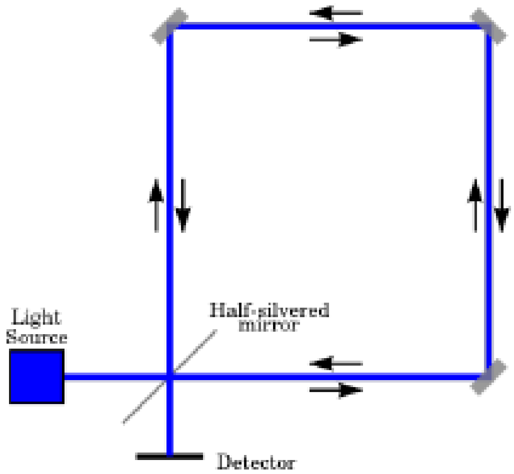
$$\varphi_i = \varphi_{i-1} + \Delta\varphi = \varphi_{i-1} + \dot{\varphi} \cdot \Delta t \;[° / gon / rad]$$

  - Measurements principles



    - Mechanical gyroscope
    - Ring Laser Gyro (RLG) - optical gyros (based on Sagnac effect)
    - Fiber Optic Gyro (FOG) - optical gyros (based on Sagnac effect)
    - Vibrating gyroscope - Focus

- MEMS (Microelectromechanical systems)
    - Advantage: small, low power consumption and low cost
- Optical Gyroscope
    - Two kinds of optical Gyroscope
        - Ring Laser Gyro (RLG)
        - Fiber Optic Gyro
    - Both of them are designed based on Sagnac effect



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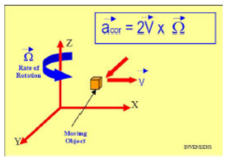
    -
        - A beam of light is split and the two beams are made to follow the same path but in opposite directions
        - Two paths have different traveling time from source to source, if the ring has rotation
    - Optical gyroscope RLG or FOG are widely used in airplane, sometime, one is main system and the other is used as back-up system
- Basic Function

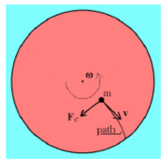
Coriolis acceleration: $a = \frac{4 \cdot v \cdot \dot{\varphi}}{k} \Rightarrow \dot{\varphi} = \frac{a \cdot k}{4 \cdot v} \qquad \dot{\varphi} \propto a$

v - amplitude of periodically variated velocity of vibration

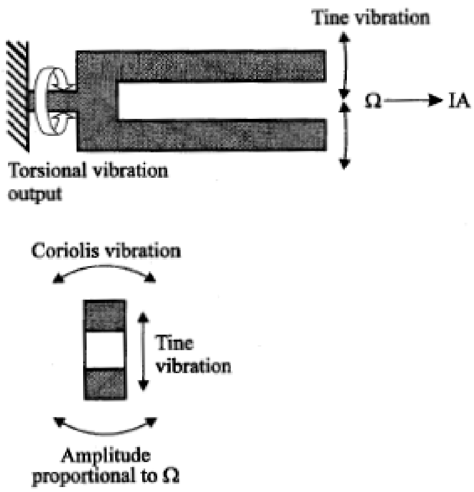
k - torsion constant

$\dot{\varphi}$ - steady speed input rate of motion

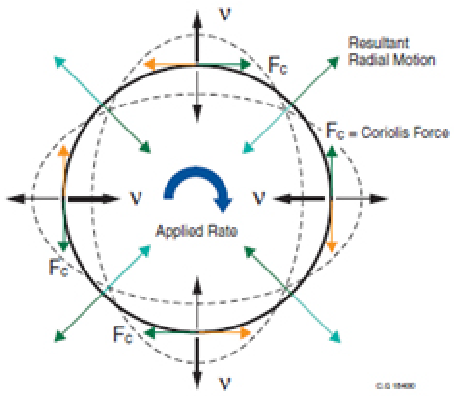




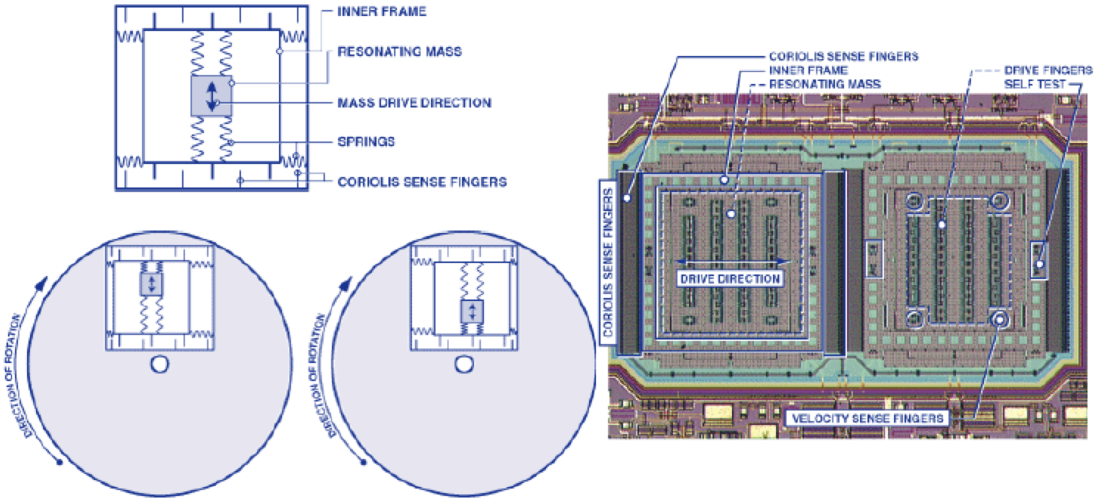
-
- Tuning Fork Gyro Principles



- two bars oscillating anti-phase (with velocity of v)
- oscillation in the plane of the bars with a periodic torque
- If the turning fork is rotated at a steady speed about its axis, the Coriolis acceleration generates a precession movement around that axis with an amplitude proportional to input rate $a = \frac{4 \cdot v \cdot \dot{\varphi}}{k}$
- Coriolis acceleration = measure for rate of motion
- change of Coriolis acceleration due to rate of motion of the vehicle
- Sensor based on Tuning Fork Gyro Principles
  - Panasonic EWTS 82
  - Micromachined silicon tuning fork gyro
- Ring-gyroscope Principles



- Spring-mass System Principles



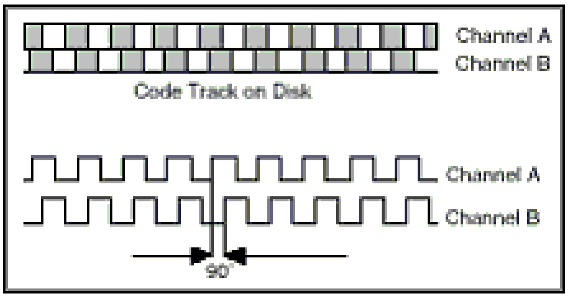
- Xsens- Motion Tracker
  - Inertial Measurement Unit (IMU) is combination of accelerometer and gyroscope, sometimes magnetometers
  - In Project IMU Motion Tracker MTi from XSENS will be used
  - Motion Tracker MTi is so called 9D-IMU: 3D Gyroscopes, 3D Accelerometers,3D Magnetometers and realized by MEMS -technique
  - Inertial Sensor Application Grades

Application Grade	Gyro Performance	Accelerometer Performance
Consumer/Commercial	>1 deg/s	>50 mg
Tactical	~1 deg/h	~1 mg
Navigation	0.01 deg/h	25 µg
Strategic	~0.001 deg/h	~1 µg

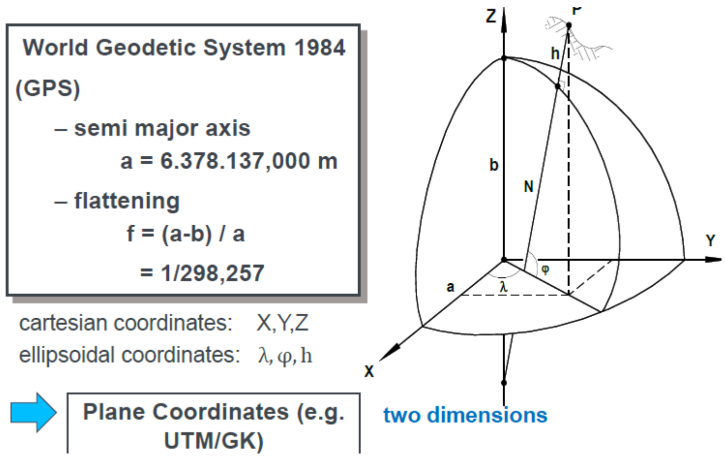
    - Strategic/ Marine grade: military ships, submarines and some spacecraft
    - Navigation grade: military aircraft
    - Tactical grade (alone use for short-term, combination with other sensors for long-term): UAV
    - Consumer grade: automotive (e.g. airbag, anti-lock braking), gaming controllers, camera stability
- Optical speed and distance sensor (distance increment)
  - Spatial-filtering velocimetry (SFV)
    - measurement information based on relative movement of ground and vehicle with sensor
    - the ground is illuminated by halogen lighting or a LED-array
    - a spatial filter (parallel-slit reticle) is moving above the immovable ground

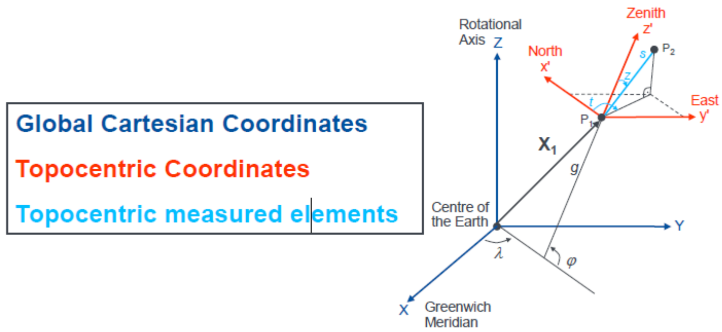
- a photo detector is mounted behind a lense and the spatial filter
- the optical image of the ground focused on the image plane sweeps over the spatial filter
- the photodetector behind the spatial filter generates an electric signal that corresponds to the periodic change of light intensity transmitted through the spatial filter
- the central frequency of the photodetector's output signal is proportional to the velocity of the target $f_0 = \frac{M}{g} \cdot v$
  - with M - image scale of objective (typical: 0.5) (constant scale realized by using double telecentric objective) g - constant of spatial filter (typical : 0.5 mm)
- distance increment per pulse: $\Delta s = g/M$ and distance: $s = N \cdot \Delta s$ with N number of pulses during a measurement period

- Odometer (distance increment)
  - Odometer / Incremental Rotary Encoder
    - Black-white-fields and quadrature encoder:



    - Two code tracks and two reading devices at the same place
    - If after rising side in channel A, the next side in channel B is going down: clockwise direction / forewords movement.
    - If after rising side in channel A, the next side in channel B is rising too: counter-clockwise direction / backwards movement.
- GNSS (absolute position)





- Low-Cost GNSS Receiver for Geodetic Applications, e.g. for monitoring, and machine control (Accuracy: mm to cm-level) is possible, if Carrier Phase measurements should be accessible!

Table 1: Receiver classes, applications and accuracy levels of static positioning

receiver class	used signal	applications	accuracy	appr. costs
low cost	code or phase-smoothed code, 1 frequency	car navigaton, location based services, sailing, mass market	1 to 10 m	100 – 500 €
geodata acquisition	phase-smoothed code, 1 frequency	infrastructure planning, architecture, GIS applications	0,5 to 3 m	5 000 – 10 000 €
geodetic	code and phase, in general 2 frequencies	surveying, geodynamics	0,001 to 0,1 m	10 000 € - 30 000 €

- Trends of Positioning with Low Cost GNSS
    - Low Cost GNSS receivers are more and more cheaper, they are not limited to single-frequency, single-system
    - Carrier-phase raw measurement are accessible from some smartphones, precise positioning could possible with smartphones (sensor intergration)
    - Precise Positioning with Low-Cost GNSS for automated vehicles
- GNSS Correction Services (RTK)
    - SAPOS
    - Leica SmartNet

        - Trimble VRS Now
        - Axio-Net
        - NovAtel Correct
        - Topcon TopNETlive

Basics of computer equipment

- Real-time
    - Real-time capability means the provision of application-related results at the required point of time with the required quality (e.g. accuracy)
    - Real-time systems realize operations in a defined time interval
    - depends on its application and required quality
    - Example
        - Due to technical reasons positioning using a multi sensor system succeeds within 0,1 sec; different applications give different results for with respect to adherence of real-time
        - Monitoring survey; maximum assumed movement: 1cm/h ⇒ real-time is met
        - Guidance of construction machines: movement 8 cm in 0,1 s ⇒ real-time partly met; border area
        - Car navigation for Advanced Driver Assistance Systems (ADAS): movement 3m in 0,1 s ⇒ no real-time
    - The effect of belated (non-in-time) provision of results defines further classification of real-time!
        - Very Hard Real-time
            - Required point of time has to be kept by all means
            - Non-fulfillment leads to "catastrophic" effects e.g. accident
            - The integrity is given with % confidence level (e.g. 10-6 /10-8)
            - Applications: security-related e.g. ADAS like collision avoidance or roboter control
        - Hard Real-time
            - Required point of time has to be kept
            - Non-fulfilment leads to worthlessness of results - no accidents
            - Application examples: car navigation systems, e.g. old GPS position for navigation using a car navigation system
        - Soft Real-time
            - Fulfilment of time restrictions is not important within given statistical limits

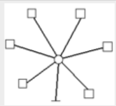
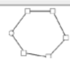
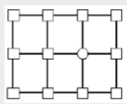
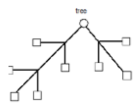
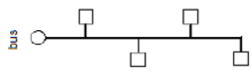
    - Non-fulfilment leads to reduced quality, but not to worthlessness of results; e.g. if 95% of a quantity is acquired within the given time limits, the result is not falsified by the remaining 5%
    - Application example: synchronisation of video conference, synchronisation of images and sound/tone; synchronisation of influence quantities (like temperature) and output quantities (like deformation quantities)
- Software - Examples for Real Time Operating Systems (RTOS)
  - Measurement acquisition systems (and programming environments) - Qualified for guidance and control tasks
    - LabView National Instruments; graphical programming (within some 10-9 s)
    - DasyLab measX GmbH & Co. KG; graphical programming
    - MatLab Mathworks; originally command line based
      - too slow compared to Labview
  - For all measurement acquisition systems exist real time variants: development in “normal” system, execution on real time system
- Hardware-Bussystems
  - Definition: bus systems are connection lines that are common to all participants of data exchange (here: connections: sensors → measurement computer).
  - Computer: the rate of transmission resp. capacity is defined by the used bus system
  - Data acquisition cards
    - in direct connection with computer bus system
    - computer bus system relevant for data transmission and synchronisation
    - principle of measurement computer e.g. of National Instruments
    - if a serial interface is used, the rate of transmission and the synchronisation accuracy is reduced
  - Approach to realtime system
    - direct hardware access in storage; e.g. graphic card - reqason: realtime system on the card
    - measurement acquisition cards work in this way: data is acquired and written into main storage in realtime, afterwards the operating system takes the data in "non-realtime-mode"
  - Coupling of realtime sub-systems
    - Combination of several realtime cards / sub-realtime systems coupled with a non-realtime operating system of the computer
    - PXI-computer (typical for National Instruments)

- Exchange of information between the cards by passing the operating system(normal oprating system is slow)
- Real-Time System Integration Bus (RTSI) of National Instruments creates this possibility incl. highly accurate synchronisation; (Programming using LabView Real-Time)

- classification

Classification		Examples	Length of connecting wire
parallel	control bus, (data or expansion bus)	ISA, PCI, VME, VXI	< 1m
	short distance bus	IEEE 488 (measurement instrument bus)	< 20 m
serial	field bus	CAN, Interbus,LON	< 1000 m
	long distance bus	LAN, WLAN, WAN, MAN, GAN	> 1000 m

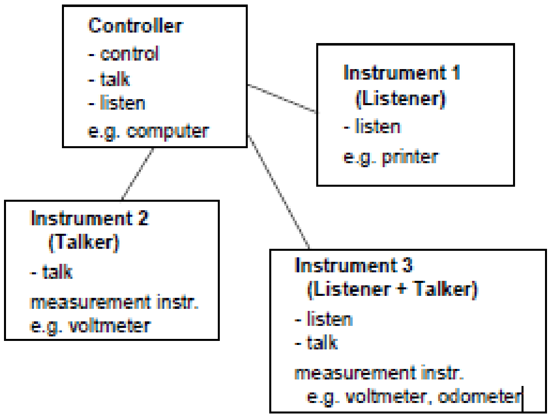
- Bustopology

Classification	**Pro**	**Con**	**Figure**
star	Disturbance effects only one connection, Use of different connections at same time	Master failure leads to total failure, High connecting effort	
Ring	Small connecting effort	Only one paticipatant may use the bus at the same time	
Network	Disturbance (almost) without effect, Use by several participants at same time	Very high connecting effort	
Tree	Low connceting effort	Number of branches defines the number of users at same time, Master failure leasds to faile in interaction of branches	
Line	Low connecting effort	Only one participant may use the bus at same time, Disturbance effects all connections	
Bus	All participats directly connected	Only one participant may use the bus at same time, Disturbance effects all conncetions	

slaves - sensors/field instruments masters - measurement computer

- disturbance
- use of different connection
- master failure
- connecting effort
- paticipant

- Example for Busssystems
  - GPIB / IEEE-488 / IEC*-Bus 625 (General Purpose Interface Bus)

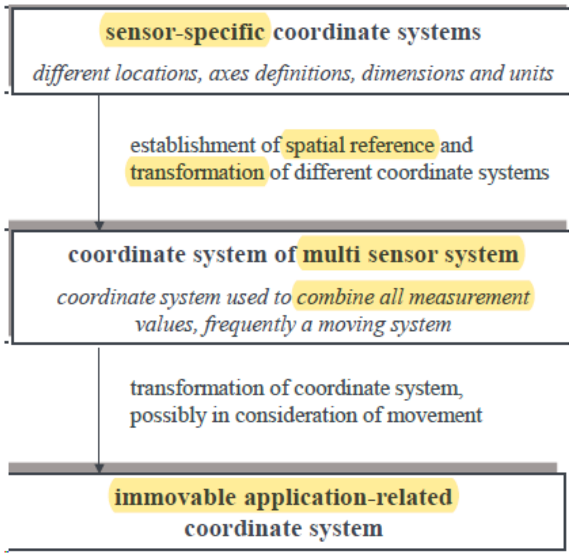


- Basics
  - combination of measurement instruments of all kind
  - development by HP
  - parallel bus, 8-Bit-Bus, short distance bus
  - interface to all PC's and all other standard computers available
  - length of connecting wire < 20m (collectively), between single instruments < 2m (prolongation using Extender up to 1000m possible, telephone network allows further transmission)
  - data rate: up to 1 Mbit/sec
  - bus topology: between line and star everything is allowed; ring is not allowed; bus as the rule
  - maximum 15 instruments
  - advantage: simple programming
- "Listen" may be done by several instruments (receive commands / data)
- "Talk" may be done by one instrument only at the same time (send commands / data)
- "Control" means assignment of "Listener" and "Talker"
- the controller is not required, e.g. if a defined assignment is realized: odometer (Talker) transmits to printer (Listener)
- Functionality
  - slowest instruments defines the maximum transfer rate and velocity
  - data transfer using the handshake procedure
  - VXI is a combination of GPIB and VNE
- Mechanical specification
  - shape of the connector of the instruments (connecting wires, data wires, bus management)

    - GPIB cable is defined too
    - If instruments do not have an IEEE-488 interface, an adapter has to be used: the GPIBIC, e.g. for computers with RS-232 interface
- CAN-Bus (Controller Area Network)
  - Basics
    - developed an implemented for cars by Bosch; meanwhile generally used in automation
    - field bus, serial bus
    - low-priced cabling (characteristic for field buses in general)
    - sensor / actuator bus:
      - direct communication with sensors, actuators, drives, input and output units
    - real-time capability, meaning ensured reaction time ≤ 10ms (for 50 km/h = 0,14 m)
    - length of connecting wire: 40m to 1km, prolongation by repeater possible
    - data rate depends on bus length: 1 Mbit/sec for 40m; 50 Kbit/sec for 1km
    - maximum 32 instruments
    - bus topology: bus or ring (or star)
  - Functionality
    - CAN-participants are masters with different priority (multi-master characteristic)
      - master / slave distinction eliminated
    - access via CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance)
    - message with highest priority will be transmitted
    - communication technology is event-based; each participant is responsible for is own data transmission to all participants/nodes
  - Most important characteristic
    - fault tolerant protocol
    - a node detect, if it is faulty and eliminates itself from the network

Data processing

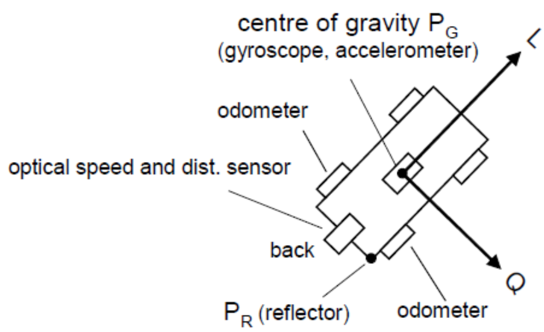
Coordinate systems



- Source Quantities
- Every sensor delivers results in sensor-specific coordinate system

Tachymeter	Local astronomic 3d or 2d system	immovable
(PD)GPS	3D geocentric system	immovable
Gyroscope, odometer	(here) 2D horizontal system, in vehicle plane	moving
Accelerometer, optical speed and distance sensor, odometer	1D-system, in drive direction	moving

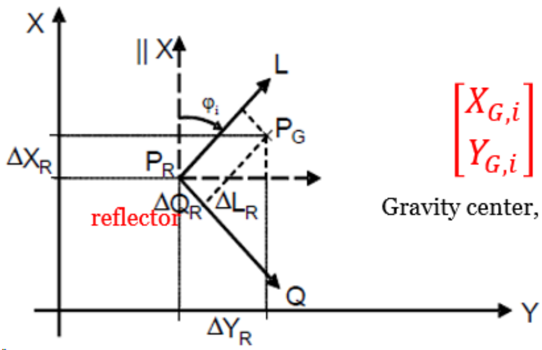
  - different location on the moving object
  - different definition of coordinate axes
  - different dimensions and units
- example



  - sensor
    - Tachymeter: local astronomic 3D- or 2D-system, immovable
    - (PD)GPS: 3D geocentric system, immovable

- Gyroscope, odometer: (here) 2D horizontal system, in vehicle plane, moving
- Accelerometer, optical speed and distance sensor, odometer: 1D-system, in drive direction, moving

- 1. Step: Combination within vehicle system (L,Q)
    - Gyroscope, odometer measures: ϕ°,Δφ → Δφ
    - Accelerometer, odometer, opt. speed a. dist. sensor: a,v,Δs → Δs
    - Tachymeter / GPS: X ,Yϕ L,Q, with φ as azimuth / grid bearing
    - correction
        - no corretection(with assumption)
            - Rotation is approximately identical for all positions of the moving vehicle
            - Acceleartion and driven distance identical at back and centre of gravity
        - need correction
            - Tachymeter or (PD)GPS gives position in global / superior system for reflector res. antenna
- Reduction of reflector / antenna position on centre of gravity



reflecter

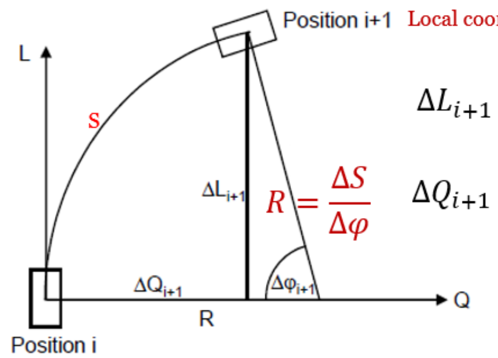
ΔL, ΔQ change every time

$$\begin{bmatrix} X_{G,i} \\ Y_{G,i} \end{bmatrix} = \begin{bmatrix} X_{R,i} \\ Y_{R,i} \end{bmatrix} + \begin{bmatrix} cos\varphi_i - sin\varphi_i \\ sin\varphi_i - cos\varphi_i \end{bmatrix} \begin{bmatrix} \Delta L \\ \Delta Q \end{bmatrix}$$

Gravity center, epoch i

φ_i *current azimuth*

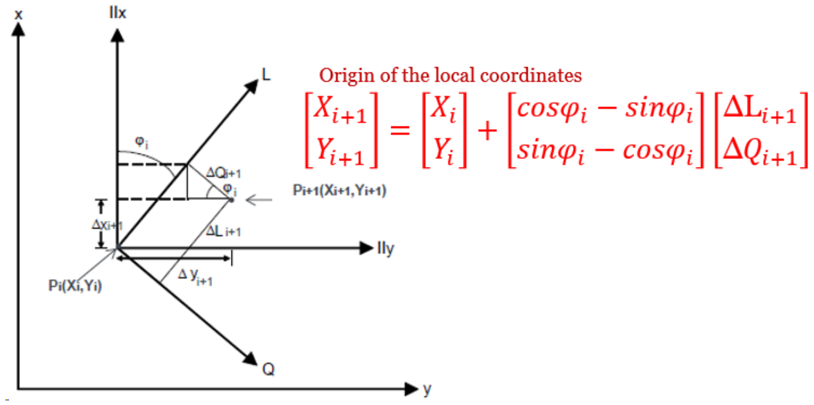
- 2. Step: Determination of coordinates in local moving system(vehicle system)



$$\Delta L_{i+1} = R \cdot \sin \Delta\varphi_{i+1} = \frac{\Delta s_{i+1}}{\Delta\varphi_{i+1}} \cdot \sin \Delta\varphi_{i+1}$$

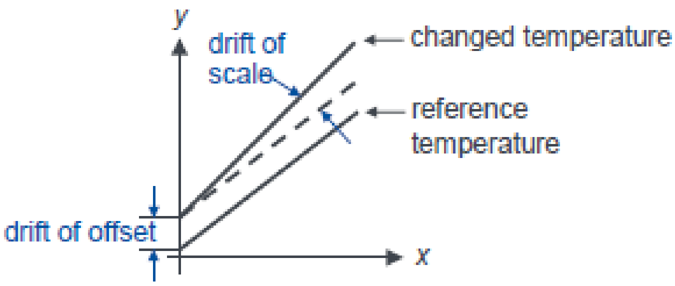
$$\Delta Q_{i+1} = R - R \cos \Delta\varphi_{i+1} = \frac{\Delta s_{i+1}}{\Delta\varphi_{i+1}} \cdot (1 - \cos \Delta\varphi_{i+1})$$

- 3. Step: Transformation of local coordinates(change) into superior coordinate system



Corrections for the sensors(project related)

- Drift is slow change of y for non changing x



- linear or non-linear
- drift of offset: stability of offset
- drift of scale: stability of sensitivity
- main causes
  - temperature
  - irreversible mechanisms inside the sensor with time
- manufacturer information
  - relation to disturbance quantity
    - time-related drift
    - drift per temperature change
  - validation: within given conditions of service
- In General
  - scale(linear) (mk, mb) for gyroscope, accelerometer
  - offset for gyroscope, accelerometer $(\dot{\varphi}_{off}, a_{off})$
  - non-linearity, e.g. periodical behaviour
  - deviations due to external influences, e.g. temperature

- error models

$$\dot{\varphi}_{\mathrm{cor}} = (1 + \mathrm{m_k}) \cdot \dot{\varphi} + \dot{\varphi}_{\mathrm{off}}$$
$$\mathrm{a_{cor}} = (1 + \mathrm{m_b}) \cdot \mathrm{a} + \mathrm{a_{off}}$$

$\dot{\varphi}, a$ - original measured quantities (e.g. in mV)

- scale and offset
  - variant in time
  - dependent on temperature
- calibration "on-the-fly" (resp. "on-the-drive")
  - using given values of high-precise sensor that deliver coordinates in immovable coordinate system, tachymeter, GPS
    - in general consideration of offset only(scale varications without importance)
- offset
  - rate of rotation(for e.g. Gyroscope)

$$\underset{\text{gyro}}{\dot{\varphi}\Delta t} = \underset{\text{Measurement(orientation change)}}{\varphi_{measurement}}$$

$$\Delta\varphi_{given} = \arctan\left(\frac{Y_{i+1} - Y_i}{X_{i+1} - X_i}\right) - \arctan\left(\frac{Y_i - Y_{i-1}}{X_i - X_{i-1}}\right)$$

e.g. from GNSS/tychymeter

$$\dot{\varphi}_{\text{off}} = \dot{\varphi}_{given} - \dot{\varphi}_{measurement} = \frac{\Delta\varphi_{\text{given}}}{\Delta t} - \dot{\varphi}_{measurement}$$

GPS has error ->Take Δt as long as possible – take longer baseline to decrease effect

$$\overline{\varphi_{\dot{o}ff}} = \frac{1}{n}\sum \varphi_{\dot{o}ff}$$ Measure for relibility

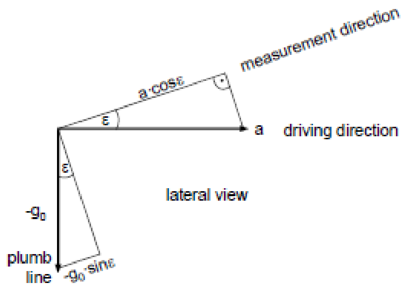
$$\Delta\varphi_{cor} = \Delta\varphi_{measurement} + \dot{\varphi}_{\text{off}}\Delta t$$

- acceleration(for e.g. accelerometer)

$$\Delta S_{\text{given}} = \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2 + (Z_{i+1} - Z_i)^2}$$
$$\Delta S_{\text{given}} = V_{i-1}\Delta t + \tfrac{1}{2} a_{\text{given}} \Delta t^2$$
$$a_{\text{given}} = 2\left(\frac{\Delta S_{\text{given}}}{\Delta t^2}\right) - \frac{V_{i-1}}{\Delta t}$$
$$a_{\text{off}} = a_{\text{given}} - a_{\text{measurement}}$$
$$\overline{a_{\text{off}}} = \tfrac{1}{n}\sum a_{\text{off}}$$
$$\Delta S_{\text{corr}} = \Delta S_{\text{measurement}} + \tfrac{1}{2}\overline{a_{\text{off}}}\Delta t^2$$

- Misalignment Errors
  - Accelerometer inclined by an angle ε - occurs for inclined ground too

(occurs for inclined ground too)



$$a_m = a\cdot\cos\varepsilon + g_0\cdot\sin\varepsilon \qquad g_0 = 9.81\frac{m}{s^2}$$

(measured = influence of acceleration –influence of gravity)

$$\varepsilon \quad small \quad \Rightarrow \cos\varepsilon = 1; \sin\varepsilon = \varepsilon$$

$$a_m = a + g_0\cdot\varepsilon$$

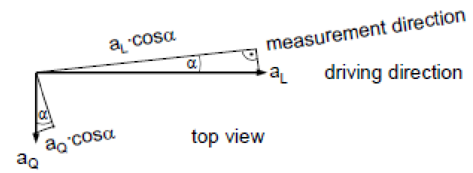
$$a = a_m - \underbrace{g_0\cdot\varepsilon}_{\text{num.examples / correction}} \qquad \varepsilon = 1\,gon \rightarrow g_0\cdot\varepsilon = 0{,}15\frac{m}{s^2}$$

$$\varepsilon = 1\,cgon \rightarrow g_0\cdot\varepsilon = 1{,}5\cdot10^{-3}\frac{m}{s^2}$$

Instrumental resolution: $\overbrace{3\cdot10^{-3}\frac{m}{s^2}}^{\text{Panasonic / MotionTracker}}$ $\overbrace{10^{-9}\frac{m}{s^2}}^{\text{Q-Flex}}$ $\Rightarrow$ **consideration in any case !**

- Effect may not be separated from offset
- determination together with offset!

- Accelerometer not aligned along the vehicle axis, rotation around α



$$a_m = a_L\cdot\cos\alpha \pm a_Q\cdot\sin\alpha$$

a_L - longitudinal acceleration (should be measured)

a_Q - lateral acceleration = approximately centripetal acceleration

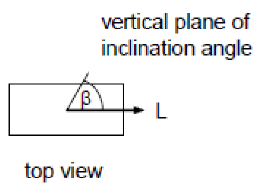
$$\alpha \quad \text{small} \quad \Rightarrow \cos\alpha = 1; \sin\alpha = \alpha$$

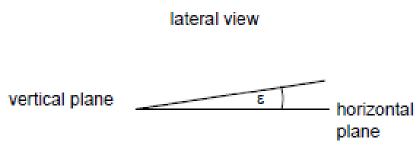
$$a_L = \frac{a_m \mp a_Q\cdot\sin\alpha}{\cos\alpha} \qquad \mathrm{a_Q} = \frac{\mathrm{v}^2}{\mathrm{R}}$$

$$a_L = a_m \mp a_Q\cdot\alpha$$

- Corrections depend on lateral acceleration and therefore on rotation angle
- Large influence, but no correction possible → good alignment required !

- Inclined Gyroscope
  - Falsification of direction measurement by error of vertical axis!





β angle between vertical plane, that contains inclination angle, and vertical plane, that contains vehicle axis L

ε inclination angle (error of vertical axis)

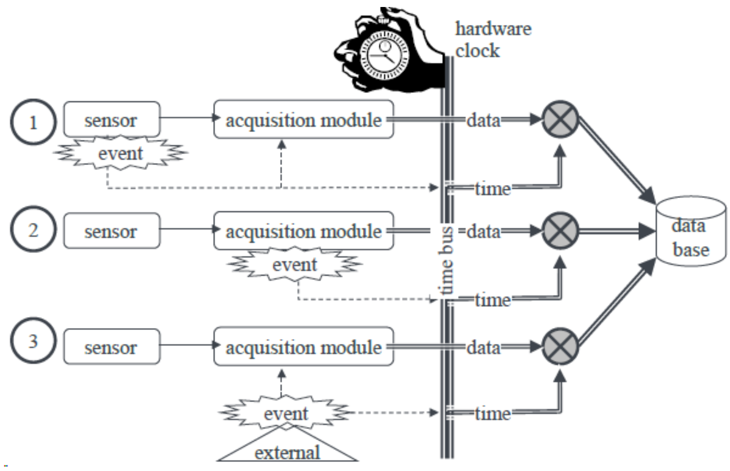
$$(\varepsilon) = \sin\beta\cdot\cot z\cdot\varepsilon$$

$z \approx 100\,gon$; since always approximately horizontal = constant influence

- maximum effect, if β equals 100 or 300 gon, meaning inclination in direction normal to vehicle axis L
- Effect may not be separated from offset

Synchronization

- Event-based acquisition and synchronisation



- Two Acquisition Methods
  - Equidistant sampling rate
    - Central generated trigger beat, that is the base for acquisition of measurement values
    - Advantage: many processing algorithms need measurement values at identical points of time and equidistant as well
    - Disadvantage: exactly identical points of time are not attainable, because the sensors have different reaction times and the transmission time of the signals varies (see bus system, operating systems)
  - Event-based acquistion
    - An event is responsible for measurement value acquisition, the respective time central registered
    - Events may be defined
      - by the sensor itself; e.g. a pps-signal of a GPS-receiver or a light barrier
      - or by a software module, that controls the sensor
      - or externally, e.g. by manual acquisition or driving through a light barrier
    - Advantage: the sensor delivers as much measurement values as is given by its measurement frequency (raw sampling rate of sensor), and the central reference time delivers an accurate synchronisation
    - Disadvantage: measurement values are not equidistant resulting in a more complex evaluation

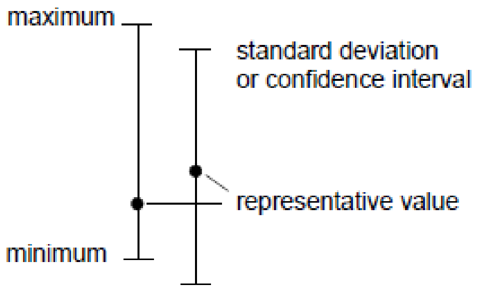
- Synchronisation
  - Relative
    - assignment of point of time of individual sensors to one time scale
    - a central clock cares for synchronisation; use of so-called time bus,
      - example: National Instrument RTSI-Bus (Real Time System Integration)
    - for space-distributes systems: clocks synchronised for beginn of measurements or central clock via wireless (DCF-77 signal or GPS-pps-signal): accuracy: some $\mathrm{ns} \triangleq 10^{-9}\ \mathrm{s}$
  - Absolute: accuracy: approximately $10^{-9}\ \mathrm{s}$
    - assignment of time scale of the measurement system to an absolute time scale
    - examples
      - GPS-time using GPS-pps-signal
      - UTC using DCF 77 time signal

Data reduction for visualization

- problem
  - frequently the acquisition delivers to many data; e.g. with a sampling rate of 1000Hz; additionally a high number of sensors
  - Visualisation is time-consuming and confusing
- Solution
  - Presentation of pooled information for a defined time period using a representative value and parameters for the behaviour in the time period
- Representative value
  - Mean value
  - Weighted Mean
  - Median
- Description of behaviour in time period
  - Interval through minimum and maximum value
  - Dispersion through standard deviation
  - Probability interval (= confidence interval) for mean or single value using significance level

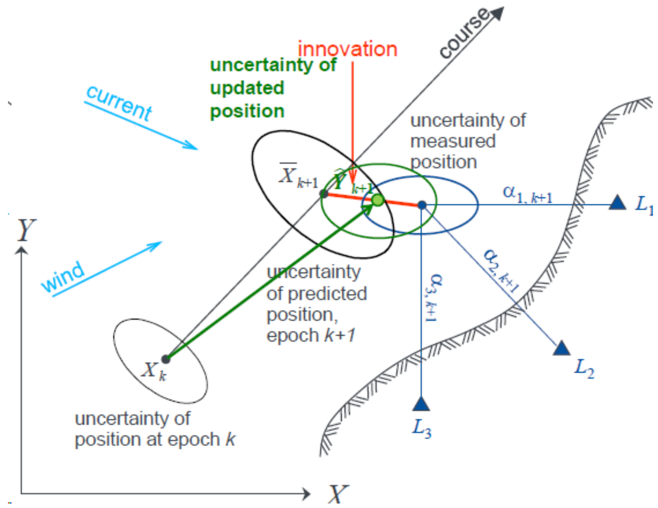
$$\begin{aligned} &\text{Mean: } C_U / C_o = \bar{l} \pm \sigma \cdot_l Y_{1-\frac{\alpha}{2}} / s_{\bar{l}} \cdot t_{f,1-\frac{\alpha}{2}} \\ &\text{single value } : C_U / C_o = l \pm \sigma_l \cdot Y_{1-\frac{\alpha}{2}} / s_l \cdot t_{f-1-\frac{\alpha}{2}} \end{aligned}$$

- Graphical representation in boxplots



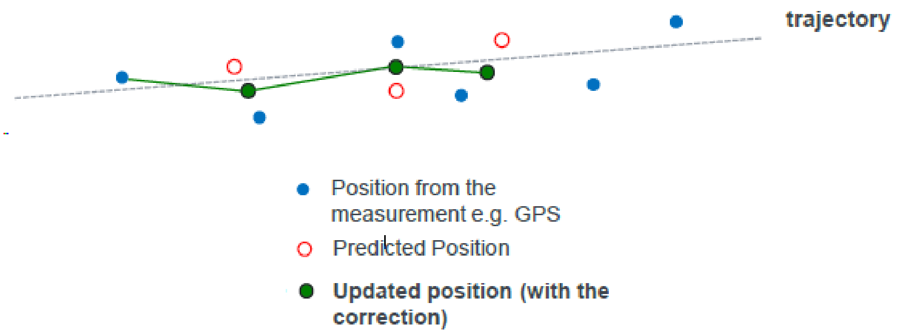
Data evaluation(project related)

- Kalman Filter Principle
  - Example: ship

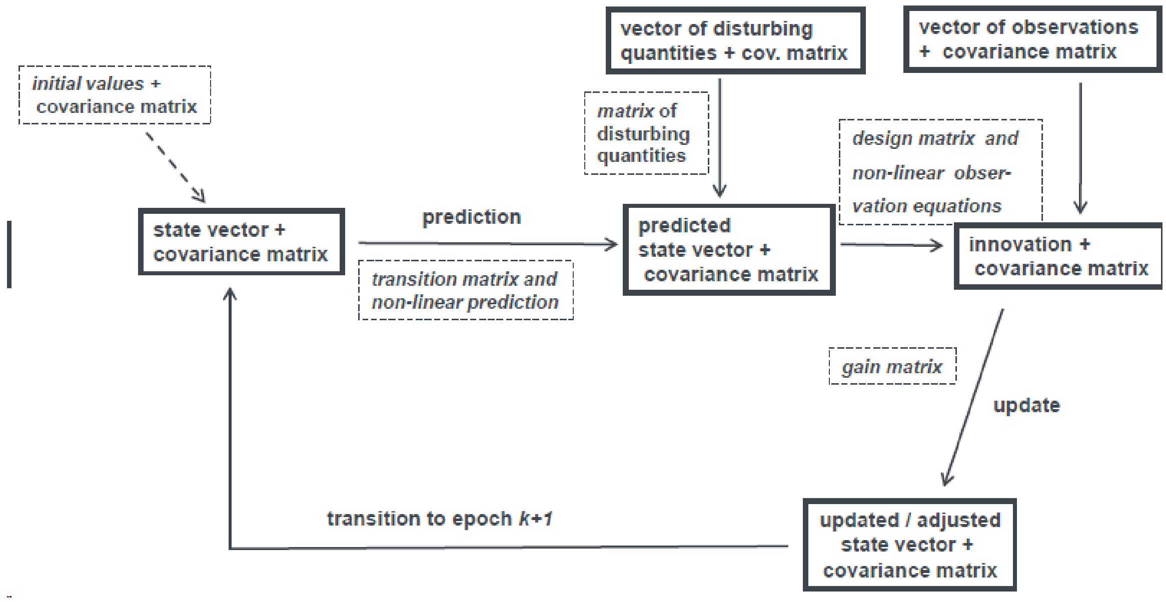


- Assumption concerning course and velocity ⇒ dead reckoning
- Kalman filter: prediction through system equation
- Disturbance quantities, only stochastically
- predicted position
- Measurement equation delivers measured position
- Kalman filter combines system and measurement equation optimally ⇒ maximum accuracy

- Kalman Filter Principle



- Process-Scheme: Extended Kalman Filter



- Prediction

Predicted state vector $\bar{y}_{k+1}$ $$\bar{y}_{k+1} = \boldsymbol{T} \cdot \hat{y}_k + \boldsymbol{S} \cdot \boldsymbol{w}$$

Covariance matrix of Predicted state vector $\boldsymbol{Q}_{\bar{y}\bar{y},k+1}$ $$Q_{\bar{y}\bar{y},k+1} = \boldsymbol{T} \cdot Q_{\hat{y}\hat{y},k} \cdot \boldsymbol{T}^{\boldsymbol{T}} + \boldsymbol{S} \cdot \boldsymbol{Q}_{\boldsymbol{ww}} \cdot \boldsymbol{S}^{\boldsymbol{T}}$$

- Integration of Measurement

Predicted measurement : $\bar{l}_{k+1}$ $$\bar{l}_{k+1} = A_{k+1} \cdot \bar{y}_{k+1}$$ linear

oder $$\bar{l}_{k+1} = \varphi(\bar{y}_{k+1})$$ nicht-linear

Covariance matrix of Predicted measurement : $Q_{\bar{l}\bar{l},k+1}$ $$Q_{\bar{l}\bar{l},k+1} = A_{k+1} \cdot Q_{\bar{y}\bar{y},k+1} \cdot A_{k+1}^T$$

Innovation vector : d_{k+1} $$d_{k+1} = \boxed{l_{k+1}} - \boxed{\bar{l}_{k+1}} = l_{k+1} - A_{k+1} \cdot \bar{y}_{k+1}$$ linear

oder $$= l_{k+1} - \varphi(\bar{y}_{k+1})$$ nicht-linear

(real) Measurement at t_{k+1}: l_{k+1}

Predicted measurement $\bar{l}_{k+1}$ from $\bar{y}_{k+1}$ by meausurement system at t_{k+1}:

Covariance matrix of Innovation vector : $Q_{dd,k+1}$ $$Q_{dd,k+1} = Q_{ll,k+1} + Q_{\bar{l}\bar{l},k+1}$$

- Compatibillity Test
  - Global Compatibility Test

$$\boxed{\begin{array}{ll} H_0: & E(\mathbf{d}_{k+1}) = \mathbf{0} \\ H_A: & E(\mathbf{d}_{k+1}) \neq \mathbf{0} \end{array}}$$

H_0: Innovation is not significant

H_A: At least one element of Innovation is significant

Test value:

$$\boxed{\mathbf{d}_{k+1}^T \cdot \mathbf{\Sigma}_{dd,k+1}^{-1} \cdot \mathbf{d}_{k+1} \leq \chi^2_{n,1-\alpha}\text{:} \quad H_0 \text{ is accepted}}$$

$$\boxed{\mathbf{d}_{k+1}^T \cdot \mathbf{\Sigma}_{dd,k+1}^{-1} \cdot \mathbf{d}_{k+1} > \chi^2_{n,1-\alpha}\text{:} \quad H_0 \text{ is rejected}}$$

- Possible Resons for the failure of Compatibilty test
  - Measurement outliers/ measurement modell is not correct

$$\mathbf{d}_{k+1} = \begin{pmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{pmatrix} = \begin{pmatrix} l_1 \\ l_2 \\ \vdots \\ l_n \end{pmatrix} - \begin{pmatrix} \bar{l}_1 \\ \bar{l}_2 \\ \vdots \\ \bar{l}_n \end{pmatrix}$$

Test Values: alle Größen bezogen auf Epoche $k+1$

$$\boxed{y_j = \frac{d_j}{\sigma_{d_j}} = \frac{d_j}{\sqrt{\Sigma_{dd,jj}}}}$$

$$\boxed{H_0: \quad y_j \sim N(0,1)}$$

Test:

$|y_j| \leq y_{1-\frac{\alpha}{2}}$: H_0 **is accepted** → not outlier

$|y_j| > y_{1-\frac{\alpha}{2}}$: H_0 **is rejected** → outlier in l_j

- System modell is not correct

$$\boxed{\begin{aligned} \hat{\mathbf{x}}_{k+1} &= \bar{\mathbf{x}}_{k+1} + \mathbf{K} \cdot \mathbf{d}_{k+1} \\ \mathbf{K} &= \mathbf{\Sigma}_{\bar{x}\bar{x},k+1} \cdot \mathbf{A}_{k+1} \cdot \mathbf{\Sigma}_{dd,k+1}^{-1} \\ \mathbf{\Sigma}_{\hat{x}\hat{x},k+1} &= \mathbf{\Sigma}_{\bar{x}\bar{x},k+1} - \mathbf{K} \cdot \mathbf{\Sigma}_{dd,k+1} \cdot \mathbf{K}^T \end{aligned}}$$

$$\widehat{\Delta \mathbf{x}}_{k+1} = \hat{\mathbf{x}}_{k+1} - \hat{\mathbf{x}}_k = \mathbf{K} \cdot \mathbf{d}_{k*1}$$

$$\rightarrow \mathbf{\Sigma}_{\widehat{\Delta x}\widehat{\Delta x},k+1} = \mathbf{K} \cdot \mathbf{\Sigma}_{dd,k+1} \cdot \mathbf{K}^T$$

(χ^2-Distribution):

$$\widehat{\Delta \mathbf{x}}_{i,k+1} \cdot \mathbf{\Sigma}_{\widehat{\Delta x}\widehat{\Delta x},k+1}^{-1} \cdot \widehat{\Delta \mathbf{x}}_{i,k+1}^T \sim \chi^2_{\text{Dimension } 1,2,3}$$

$$\widehat{\Delta \mathbf{x}}_{i,k+1} \cdot \mathbf{\Sigma}_{\widehat{\Delta x}\widehat{\Delta x},k+1}^{-1} \cdot \widehat{\Delta \mathbf{x}}_{i,k+1}^T > \chi^2_{\text{Dimension},1-\alpha}$$

➔ increase system noise.

- Error in stochastic modell

  General:

  If $\Sigma_{ll} \gg \Sigma_{ww}$, $\hat{x}_{k+1}$ from system modell

  If $\Sigma_{ll} \ll \Sigma_{ww}$, $\hat{x}_{k+1}$ from measurement modell

  - Test Σ_{ll} vs. Σ_{ww} ; Variance Compenents Estimation komponentenschätzung,
  - $\Sigma_{ll} = \begin{bmatrix} \Sigma_{\overline{xx},k+1} & 0 \\ 0 & \Sigma_{ll,k+1} \end{bmatrix}$

    → Normally Σ_{ww} will be adapted, that means e.g. increase system noise.

- Update of state vector

  Gain Matrix at t_{k+1}: K_{k+1}

  $$K_{k+1} = Q_{\overline{yy},k+1} \cdot A_{k+1}^{T} \cdot Q_{dd,k+1}^{-1}$$

  Updated state vector at t_{k+1}: $\hat{y}_{k+1}$

  $$\hat{y}_{k+1} = \overline{y}_{k+1} + K_{k+1} \cdot d_{k+1}$$

  Updated state vector

  Predicted state vector

  Contain both information of system and measurement model

  Covariance matrix of Updated state vector t_{k+1}:

  $$Q_{\hat{y}\hat{y},k+1} = Q_{\overline{yy},k+1} - K_{k+1} \cdot Q_{dd,k+1} \cdot K_{k+1}^{T}$$

  $\hat{y}_{k+1}$ and $Q_{\hat{y}\hat{y},k+1}$ as input for next epoch

- Input quantities / Observations

$$\underline{l} = \begin{pmatrix} X_{GPS} \\ Y_{GPS} \\ \Delta\varphi_{gyr} \\ \Delta\varphi_{odo} \\ \Delta s_{odo} \\ \Delta s_{sad} \\ \Delta s_{acc} \end{pmatrix} \begin{matrix} \text{in horizontal system;} \\ \text{related to centre of gravity} \\ \text{gyroscope rotation angle} \\ \text{odometer rotation angle} \\ \text{odometer distance} \\ \text{speed and distance sensor distance} \\ \text{accelerometer distance} \end{matrix}$$

$$\underline{\Sigma}_{ll} = \begin{bmatrix} \sigma^2_{X_{GPS}} & 0 & 0 & & & & 0 \\ 0 & \sigma^2_{Y_{GPS}} & 0 & 0 & & & 0 \\ 0 & 0 & \sigma^2_{\Delta\varphi_{gyr}} & 0 & & & \\ & 0 & 0 & \sigma^2_{\Delta\varphi_{odo}} & 0 & & \\ & & & 0 & \sigma^2_{s_{odo}} & 0 & \\ & & & & 0 & \sigma^2_{s_{sad}} & 0 \\ 0 & 0 & & & & 0 & \sigma^2_{s_{acc}} \end{bmatrix}$$

- variances from sensor investigations (lab. 2 and 3)
- no correlation despite better knowledge

  - for any additional rotation angle or distance the respective matrices will be enlarged using exactly the same columns resp. line.

- Target quantities / State vector

straight line / circle

$$\hat{y} = \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{\varphi} \\ \hat{v} \\ \Delta\hat{\varphi} \end{bmatrix}$$

$$\Sigma_{\hat{y}\hat{y}} = \begin{bmatrix} \sigma_{\hat{x}}^2 & \sigma_{\hat{x}\hat{y}} & \sigma_{\hat{x}\hat{\varphi}} & \sigma_{\hat{x}\hat{v}} & \sigma_{\hat{x}\Delta\hat{\varphi}} \\ \sigma_{\hat{x}\hat{y}} & \sigma_{\hat{y}}^2 & \sigma_{\hat{y}\hat{\varphi}} & \sigma_{\hat{y}\hat{v}} & \sigma_{\hat{y}\Delta\hat{\varphi}} \\ \sigma_{\hat{x}\hat{\varphi}} & \sigma_{\hat{y}\hat{\varphi}} & \sigma_{\hat{\varphi}}^2 & \sigma_{\hat{\varphi}\hat{v}} & \sigma_{\hat{\varphi}\Delta\hat{\varphi}} \\ \sigma_{\hat{x}\hat{v}} & \sigma_{\hat{y}\hat{v}} & \sigma_{\hat{\varphi}\hat{v}} & \sigma_{\hat{v}}^2 & \sigma_{\Delta\hat{\varphi}\hat{v}} \\ \sigma_{\hat{x}\Delta\hat{\varphi}} & \sigma_{\hat{y}\Delta\hat{\varphi}} & \sigma_{\hat{\varphi}\Delta\hat{\varphi}} & \sigma_{\Delta\hat{\varphi}\hat{v}} & \sigma_{\Delta\hat{\varphi}}^2 \end{bmatrix}$$

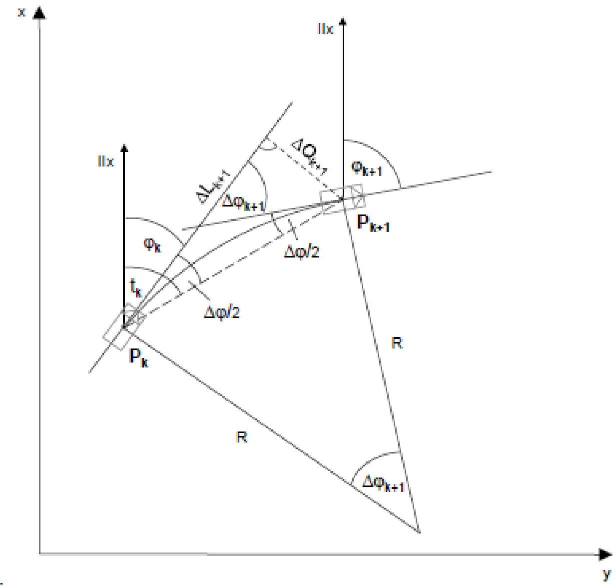
standard kinematic

$$\hat{y} = \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{v}_x \\ \hat{v}_y \end{bmatrix}$$

$$\Sigma_{\hat{y}\hat{y}} = \begin{bmatrix} \sigma_{\hat{x}}^2 & \sigma_{\hat{x}\hat{y}} & \sigma_{\hat{x}\hat{v}_x} & \sigma_{\hat{x}\hat{v}_y} \\ \sigma_{\hat{x}\hat{y}} & \sigma_{\hat{y}}^2 & \sigma_{\hat{y}\hat{v}_x} & \sigma_{\hat{y}\hat{v}_y} \\ \sigma_{\hat{x}\hat{v}_x} & \sigma_{\hat{y}\hat{v}_x} & \sigma_{\hat{v}_x}^2 & \sigma_{\hat{v}_x\hat{v}_y} \\ \sigma_{\hat{x}\hat{v}_y} & \sigma_{\hat{y}\hat{v}_y} & \sigma_{\hat{v}_x\hat{v}_y} & \sigma_{\hat{v}_y}^2 \end{bmatrix}$$

  - State vector: e.g. Coordinates of centre of gravity, velocity and azimuth / grid bearing as well as the respective covariance matrices for each epoch
  - initial values from GPS, from GPS using e.g. the first two/ three to five values, or from measured values

- Circle Drive
  - Prediction (non-linear)



$$\bar{X}_{k+1} = \hat{X}_k + \cos\hat{\varphi}_k\, \Delta L_{k+1} - \sin\hat{\varphi}_k\, \Delta Q_{k+1}$$
$$\bar{Y}_{k+1} = \hat{Y}_k + \sin\hat{\varphi}_k\, \Delta L_{k+1} + \cos\hat{\varphi}_k\, \Delta Q_{k+1}$$

$$\Delta L_{k+1} = R \cdot \sin\left(\Delta\bar{\varphi}_{k+1}\right)$$
$$\Delta Q_{k+1} = R \cdot \left(1 - \cos\left(\Delta\bar{\varphi}_{k+1}\right)\right)$$

$$\bar{X}_{k+1} = \hat{X}_k + \frac{v_{k+1}\cdot\Delta t}{\Delta\varphi_{k+1}} \cdot (\sin(\hat{\varphi}_k + \Delta\varphi_{k+1}) - \sin\hat{\varphi}_k)$$
$$\bar{Y}_{k+1} = \hat{Y}_k + \frac{v_{k+1}\cdot\Delta t}{\Delta\varphi_{k+1}} \cdot (\cos\hat{\varphi}_k - \cos(\hat{\varphi}_k + \Delta\varphi_{k+1}))$$
$$\bar{\varphi}_{k+1} = \hat{\varphi}_k + \Delta\bar{\varphi}_{k+1}$$
$$\bar{v}_{k+1} = \hat{v}_k$$
$$\Delta\bar{\varphi}_{k+1} = \Delta\hat{\varphi}_k$$

  - Prediction (linear)

Prediction of covariance matrix

$$\Sigma_{\bar{Y}_{k+1}\bar{Y}_{k+1}} = \mathbf{T} \cdot \Sigma_{\hat{Y}_k\hat{Y}_k} \cdot \mathbf{T}^{\mathrm{T}}$$

transition matrix

$$\mathbf{T} = \left(\frac{\partial \mathbf{Y_{k+1}}}{\partial \mathbf{Y_k}}\right) = \begin{pmatrix} \frac{\partial x_{k+1}}{\partial x_k} & \frac{\partial x_{k+1}}{\partial y_k} & \frac{\partial x_{k+1}}{\partial \varphi_k} & \frac{\partial x_{k+1}}{\partial v_k} & \frac{\partial x_{k+1}}{\partial \Delta\varphi_k} \\ \frac{\partial y_{k+1}}{\partial x_k} & \frac{\partial y_{k+1}}{\partial y_k} & \frac{\partial y_{k+1}}{\partial \varphi_k} & \frac{\partial y_{k+1}}{\partial v_k} & \frac{\partial y_{k+1}}{\partial \Delta\varphi_k} \\ \frac{\partial \varphi_{k+1}}{\partial x_k} & \frac{\partial \varphi_{k+1}}{\partial y_k} & \frac{\partial \varphi_{k+1}}{\partial \varphi_k} & \frac{\partial \varphi_{k+1}}{\partial v_k} & \frac{\partial \varphi_{k+1}}{\partial \Delta\varphi_k} \\ \frac{\partial v_{k+1}}{\partial x_k} & \frac{\partial v_{k+1}}{\partial y_k} & \frac{\partial v_{k+1}}{\partial \varphi_k} & \frac{\partial v_{k+1}}{\partial v_k} & \frac{\partial v_{k+1}}{\partial \Delta\varphi_k} \\ \frac{\partial \Delta\varphi_{k+1}}{\partial x_k} & \frac{\partial \Delta\varphi_{k+1}}{\partial y_k} & \frac{\partial \Delta\varphi_{k+1}}{\partial \varphi_k} & \frac{\partial \Delta\varphi_{k+1}}{\partial v_k} & \frac{\partial \Delta\varphi_{k+1}}{\partial \Delta\varphi_k} \end{pmatrix}$$

$$\mathbf{T} = \left(\frac{\partial \mathbf{Y_{k+1}}}{\partial \mathbf{Y_k}}\right) = \begin{pmatrix} 1 & 0 & \bar{v}_{k+1} \cdot \Delta t \cdot \frac{\cos(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1}) - \cos\hat{\varphi}_k}{\Delta\bar{\varphi}_{k+1}} & \Delta t \cdot \frac{\sin(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1}) - \sin\hat{\varphi}_k}{\Delta\bar{\varphi}_{k+1}} & A \\ 0 & 1 & \bar{v}_{k+1} \cdot \Delta t \cdot \frac{\sin(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1}) - \sin\hat{\varphi}_k}{\Delta\bar{\varphi}_{k+1}} & -\Delta t \cdot \frac{\cos(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1}) - \cos\hat{\varphi}_k}{\Delta\bar{\varphi}_{k+1}} & B \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Please keep in mind, that: $\bar{\varphi}_{k+1} = \hat{\varphi}_k + \Delta\bar{\varphi}_{k+1}$

$\bar{v}_{k+1} = \hat{v}_k$

$\Delta\bar{\varphi}_{k+1} = \Delta\hat{\varphi}_k$

with

$$A = \bar{v}_{k+1} \cdot \Delta t \cdot \frac{\cos(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1})}{\Delta\bar{\varphi}_{k+1}} + \bar{v}_{k+1} \cdot \Delta t \cdot \frac{\sin(\hat{\varphi}_k) - \sin(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1})}{\Delta\bar{\varphi}_{k+1}^2}$$

$$B = \bar{v}_{k+1} \cdot \Delta t \cdot \frac{\sin(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1})}{\Delta\bar{\varphi}_{k+1}} - \bar{v}_{k+1} \cdot \Delta t \cdot \frac{\cos(\hat{\varphi}_k) - \cos(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1})}{\Delta\bar{\varphi}_{k+1}^2}$$

- Acting Forces and Disturbances

No acting Forces ! $E(\mathbf{u}) = 0$,no stochastic modelling as well !

$$E(\mathbf{w}) = \mathbf{0}$$

Influence of disturbance acceleration and rotation rate to be modelled stochastically using **S**;

$$E(\mathbf{w}) = E(a, \dot{\varphi}) = \mathbf{0}$$

for this we need non-linear equations in dependence of acceleration *a*

Influence of disturbance acceleration

$$\bar{X}_{S,k+1} = \hat{X}_{S,k} + \frac{a \cdot \Delta t^2}{2 \cdot \Delta\bar{\varphi}_{k+1}} \cdot (-\sin\hat{\varphi}_k + \sin(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1}))$$

$$\bar{Y}_{S,k+1} = \hat{Y}_{S,k} + \frac{a \cdot \Delta t^2}{2 \cdot \Delta\bar{\varphi}_{k+1}} \cdot (\cos\hat{\varphi}_k - \cos(\hat{\varphi}_k + \Delta\bar{\varphi}_{k+1}))$$

$$\bar{v}_{k+1} = \hat{v}_k + a \cdot \Delta t$$

Influence of disturbance rotational rate

$$\bar{X}_{k+1} = \hat{X}_k + \frac{v_{k+1} \cdot \Delta t}{\dot{\varphi} \cdot \Delta t} \cdot (\sin(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t) - \sin\hat{\varphi}_k) = \hat{X}_k + \frac{v_{k+1}}{\dot{\varphi}} \cdot (\sin(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t) - \sin\hat{\varphi}_k)$$

$$\bar{Y}_{k+1} = \hat{Y}_k + \frac{v_{k+1} \cdot \Delta t}{\dot{\varphi} \cdot \Delta t} \cdot (\cos\hat{\varphi}_k - \cos(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t)) =_k + \frac{v_{k+1}}{\dot{\varphi}} \cdot (\cos\hat{\varphi}_k - \cos(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t))$$

$$\bar{\varphi}_{k+1} = \hat{\varphi}_k + \dot{\varphi} \cdot \Delta t$$

$$\Delta\bar{\varphi}_{k+1} = \dot{\varphi} \cdot \Delta t$$

- Disturbance Matrix

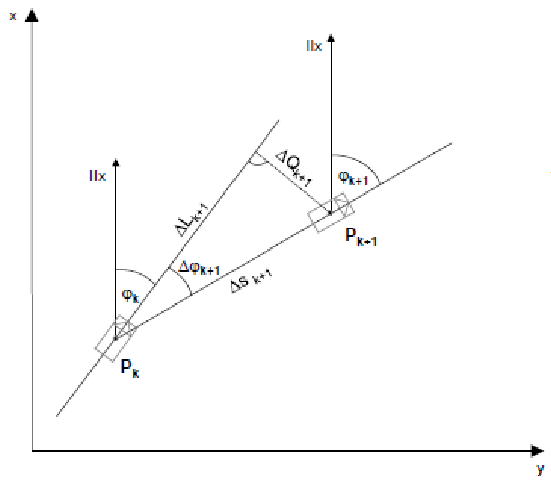
$$\mathrm{S} = \begin{pmatrix} \frac{\partial x_{k+1}}{\partial a} & \frac{\partial x_{k+1}}{\partial \dot{\phi}} \\ \frac{\partial y_{k+1}}{\partial a} & \frac{\partial y_{k+1}}{\partial \dot{\phi}} \\ \frac{\partial \varphi_{k+1}}{\partial a} & \frac{\partial \varphi_{k+1}}{\partial \dot{\phi}} \\ \frac{\partial v_{k+1}}{\partial a} & \frac{\partial v_{k+1}}{\partial \dot{\phi}} \\ \frac{\partial \Delta \varphi_{k+1}}{\partial a} & \frac{\partial \Delta \varphi_{k+1}}{\partial \dot{\phi}} \end{pmatrix} = \begin{pmatrix} \frac{\Delta t^2}{2 \cdot \Delta \bar{\varphi}_{k+1}} \cdot (-\sin \hat{\varphi}_k + \sin(\hat{\varphi}_k + \Delta \bar{\varphi}_{k+1})) & C \\ \frac{\Delta t^2}{2 \cdot \Delta \bar{\varphi}_{k+1}} \cdot (\cos \hat{\varphi}_k - \cos(\hat{\varphi}_k + \Delta \bar{\varphi}_{k+1})) & D \\ 0 & \Delta t \\ \Delta t & 0 \\ 0 & \Delta t \end{pmatrix}$$

$$C = \frac{\bar{v}_{k+1} \cdot \Delta t}{\dot{\phi}} \cdot \cos(\hat{\varphi}_k + \dot{\phi} \cdot \Delta t) - \frac{\bar{v}_{k+1}}{\dot{\varphi}^2} \cdot (-\sin(\hat{\varphi}_k) + \sin(\hat{\varphi}_k + \dot{\phi} \cdot \Delta t))$$
$$B = \frac{\bar{v}_{k+1} \cdot \Delta t}{\dot{\varphi}} \cdot \sin(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t) - \frac{\bar{v}_{k+1}}{\dot{\varphi}^2} \bar{v}_{k+1} \cdot (\cos(\hat{\varphi}_k) - \cos(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t))$$

Complete prediction $\sum_{\bar{y}k+1\bar{y}k+1} = \mathbf{T} \cdot \sum_{\hat{y}\hat{y}\hat{y}k} \cdot \mathbf{T}^{\mathrm{T}} + \mathbf{S} \cdot \sum_{\mathbf{ww}} \cdot \mathbf{S}^{\mathbf{T}}$

Variance of disturbance acceleration and rotational rate by "try and error"

- Straight Line Drive
  - prediction(non-linear)



changed:

$$\Delta L_{k+1} = \Delta \overline{s}_{k+1} \cdot \cos(\Delta \overline{\varphi}_{k+1})$$
$$\Delta Q_{k+1} = \Delta \overline{s}_{k+1} \cdot \sin(\Delta \overline{\varphi}_{k+1})$$

$$\overline{X}_{k+1} = \hat{X}_k + \cos \hat{\varphi}_k \cdot \Delta \overline{s}_{k+1} \cdot \cos(\Delta \overline{\varphi}_{k+1}) - \sin \hat{\varphi}_k \cdot \Delta \overline{s}_{k+1} \cdot \sin(\Delta \overline{\varphi}_{k+1})$$
$$\overline{X}_{k+1} = \hat{X}_k + \Delta \overline{s}_{k+1} \cdot (\cos \hat{\varphi}_k \cdot \cos(\Delta \overline{\varphi}_{k+1}) - \sin \hat{\varphi}_k \cdot \sin(\Delta \overline{\varphi}_{k+1}))$$
$$\overline{X}_{k+1} = \hat{X}_k + \overline{v}_{k+1} \cdot \Delta t \cdot \cos(\hat{\varphi}_k + \Delta \overline{\varphi}_{k+1})$$

$$\overline{Y}_{k+1} = \hat{Y}_k + \sin \hat{\varphi}_k \cdot \Delta \overline{s}_{k+1} \cdot \cos(\Delta \overline{\varphi}_{k+1}) + \cos \hat{\varphi}_k \cdot \Delta \overline{s}_{k+1} \cdot \sin(\Delta \overline{\varphi}_{k+1})$$
$$\overline{Y}_{k+1} = \hat{Y}_k + \Delta \overline{s}_{k+1} \cdot (\sin \hat{\varphi}_k \cdot \cos(\Delta \overline{\varphi}_{k+1}) + \cos \hat{\varphi}_k \cdot \sin(\Delta \overline{\varphi}_{k+1}))$$
$$\overline{Y}_{k+1} = \hat{Y}_k + \overline{v}_{k+1} \cdot \Delta t \cdot \sin(\hat{\varphi}_k + \Delta \overline{\varphi}_{k+1})$$

unchanged:

$$\overline{\varphi}_{k+1} = \hat{\varphi}_k + \Delta \overline{\varphi}_{k+1}$$
$$\overline{v}_{k+1} = \hat{v}_k$$
$$\Delta \overline{\varphi}_{k+1} = \Delta \hat{\varphi}_k$$

  - Prediction (linear) and Disturbance Matrix

Prediction of covariance matrix

$$\Sigma_{\overline{y}_{k+1}\overline{y}_{k+1}} = \mathbf{T} \cdot \Sigma_{\hat{y}_k \hat{y}_k} \cdot \mathbf{T}^{\mathrm{T}}$$

$$\mathbf{T} = \begin{pmatrix} 1 & 0 & -\overline{v}_{k+1} \cdot \Delta t \cdot \sin(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}) & \Delta t \cdot \cos(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}) & -\overline{v}_{k+1} \cdot \Delta t \cdot \sin(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}) \\ 0 & 1 & \overline{v}_{k+1} \cdot \Delta t \cdot \cos(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}) & \Delta t \cdot \sin(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}) & \overline{v}_{k+1} \cdot \Delta t \cdot \cos(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}) \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Influence of disturbance acceleration and rotational rate

$$\overline{x}_{k+1} = \hat{x}_k + a \cdot \frac{\Delta t^2}{2} \cos(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1})$$

$$\overline{y}_{k+1} = \hat{y}_k + a \cdot \frac{\Delta t^2}{2} \sin(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1})$$

$$\overline{x}_{k+1} = \hat{x}_k + \overline{v}_{k+1} \cdot \Delta t \cdot \cos(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t)$$

$$\overline{y}_{k+1} = \hat{y}_k + \overline{v}_{k+1} \cdot \Delta t \cdot \sin(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t)$$

Please keep in mind, that: $\overline{\varphi}_{k+1} = \hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}$

$\overline{v}_{k+1} = \hat{v}_k$

$\Delta\overline{\varphi}_{k+1} = \Delta\hat{\varphi}_k$

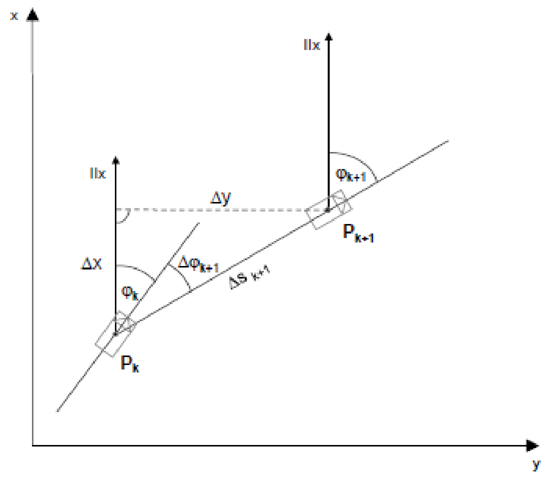
Disturbance Matrix

$$S = \begin{pmatrix} \frac{\Delta t^2}{2} \cos(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}) & -\Delta t^2 \cdot \overline{v}_{k+1} \cdot \sin(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t) \\ \frac{\Delta t^2}{2} \sin(\hat{\varphi}_k + \Delta\overline{\varphi}_{k+1}) & \Delta t^2 \cdot \overline{v}_{k+1} \cdot \cos(\hat{\varphi}_k + \dot{\varphi} \cdot \Delta t) \\ 0 & \Delta t \\ \Delta t & 0 \\ 0 & \Delta t \end{pmatrix}$$

Complete prediction

$$\Sigma_{\overline{y}_{k+1}\overline{y}_{k+1}} = \mathbf{T} \cdot \Sigma_{\hat{y}_k \hat{y}_k} \cdot \mathbf{T}^{\mathrm{T}} + \mathrm{S} \cdot \Sigma_{\mathrm{ww}} \cdot \mathrm{S}^{\mathrm{T}}$$

- Standard Kinematic Approach
  - Prediction



Linear Prediction

$$\overline{X}_{k+1} = \hat{X}_k + \Delta t \cdot \hat{v}_{x,k}$$

$$\overline{Y}_{k+1} = \hat{Y}_k + \Delta t \cdot \hat{v}_{y,k}$$

$$\overline{v}_{x,k+1} = \hat{v}_{x,k}$$

$$\overline{v}_{y,k+1} = \hat{v}_{y,k}$$

$$\Delta t \cdot \hat{v}_{x,k} = \Delta t \cdot \hat{v}_{x,k-1} + 0.5 \cdot \Delta t^2 \cdot \cos(\varphi_{k+1}) \cdot \hat{a}_k$$

$$\Delta t \cdot \hat{v}_{y,k} = \Delta t \cdot \hat{v}_{y,k-1} + 0.5 \cdot \Delta t^2 \cdot \sin(\varphi_{k+1}) \cdot \hat{a}_k$$

- Prediction and Disturbance Matrix
  - Transition Matrix

$$\mathbf{T} = \begin{pmatrix} \frac{\partial x_{k+1}}{\partial x_k} & \frac{\partial x_{k+1}}{\partial y_k} & \frac{\partial x_{k+1}}{\partial \dot{x}_k} & \frac{\partial x_{k+1}}{\partial \dot{y}_k} \\ \frac{\partial y_{k+1}}{\partial x_k} & \frac{\partial y_{k+1}}{\partial y_k} & \frac{\partial y_{k+1}}{\partial \dot{x}_k} & \frac{\partial y_{k+1}}{\partial \dot{y}_k} \\ \frac{\partial \dot{x}_{k+1}}{\partial x_k} & \frac{\partial \dot{x}_{k+1}}{\partial y_k} & \frac{\partial \dot{x}_{k+1}}{\partial x_k} & \frac{\partial \dot{x}_{k+1}}{\partial \dot{y}_k} \\ \frac{\partial \dot{y}_{k+1}}{\partial x_k} & \frac{\partial \dot{y}_{k+1}}{\partial x_k} & \frac{\partial \dot{y}_{k+1}}{\partial x_k} & \frac{\partial \dot{y}_{k+1}}{\partial x_k} \end{pmatrix} = \begin{pmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

  - Influence of disturbance acceleration

Disturbance Matrix

$$\mathbf{S} = \begin{pmatrix} \frac{\partial x}{\partial a} \\ \frac{\partial y}{\partial a} \\ \frac{\partial v_x}{\partial a} \\ \frac{\partial v_y}{\partial a} \end{pmatrix} = \begin{pmatrix} \cos(\varphi_{k+1}) \cdot 0.5\Delta t^2 \\ \sin(\varphi_{k+1}) \cdot 0.5\Delta t^2 \\ \cos(\varphi_{k+1}) \cdot \Delta t \\ \sin(\varphi_{k+1}) \cdot \Delta t \end{pmatrix}$$

Complete prediction

$$\Sigma_{\bar{\mathbf{y}}_{k+1}\bar{\mathbf{y}}_{k+1}} = \mathbf{T} \cdot \Sigma_{\hat{\mathbf{y}}_k \hat{\mathbf{y}}_k} \cdot \mathbf{T}^{\mathbf{T}} + \mathbf{S} \cdot \sigma_w^2 \cdot \mathbf{S}^{\mathbf{T}}$$

- Measurement Equations

$\mathbf{l} = \varphi(\bar{\mathbf{y}}_{k+1})$ resp. linear: $\mathbf{l} + \mathbf{v} = \mathbf{A} \cdot \bar{\mathbf{y}}_{\mathbf{k+1}}$

- for straight line and circle approach: <u>**linear**</u>

$$\begin{aligned} x_{GPS} + v &= \bar{x} \\ y_{GPS} + v &= \bar{y} \\ \Delta\varphi_{gyr} + v &= \Delta\bar{\varphi} \\ \Delta\varphi_{odo} + v &= \Delta\bar{\varphi}_k \\ s_{odo} + v &= \bar{v} \cdot \Delta t \\ s_{sad} + v &= \bar{v} \cdot \Delta t \\ s_{acc} + v &= \bar{v} \cdot \Delta t \end{aligned}$$

$$\mathbf{A} = \left(\frac{\partial \varphi(\mathbf{y})}{\partial \mathbf{y}}\right) = \begin{pmatrix} \frac{\partial x_{GPS}}{\partial \bar{x}} & 0 & 0 & 0 & 0 \\ 0 & \frac{\partial y_{GPS}}{\partial \bar{y}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{\partial \varphi_{gyr}}{\partial \Delta\bar{\varphi}} \\ 0 & 0 & 0 & 0 & \frac{\partial \varphi_{odo}}{\partial \Delta\bar{\varphi}} \\ 0 & 0 & 0 & \frac{\partial s_{odo}}{\partial \bar{s}} & 0 \\ 0 & 0 & 0 & \frac{\partial s_{sad}}{\partial \bar{s}} & 0 \\ 0 & 0 & 0 & \frac{\partial s_{acc}}{\partial \bar{s}} & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & \Delta t & 0 \end{pmatrix}$$

$$\mathbf{A}_{k+1} = \left(\frac{\partial \varphi(\mathbf{Y})}{\partial \mathbf{Y}}\right)$$

- for standard kinematic approach: non-linear

$$\begin{aligned} x_{GPS} + v &= \bar{x} \\ y_{GPS} + v &= \bar{y} \\ \Delta\varphi_{gyr} + v &= \bar{\varphi}_{k+1} - \hat{\varphi}_k = \arctan\left(\frac{\bar{y}_{k+1} - \hat{y}_k}{\bar{x}_{k+1} - \hat{x}_k}\right) - \hat{\varphi}_k \\ \Delta\varphi_{odo} + v &= \bar{\varphi}_{k+1} - \hat{\varphi}_k = \arctan\left(\frac{\bar{y}_{k+1} - \hat{y}_k}{\bar{x}_{k+1} - \hat{x}_k}\right) - \hat{\varphi}_k \\ s_{odo} + v &= \sqrt{(\bar{x}_{k+1} - \hat{x}_k)^2 + (\bar{y}_{k+1} - \hat{y}_k)^2} \\ s_{sad} + v &= \sqrt{(\bar{x}_{k+1} - \hat{x}_k)^2 + (\bar{y}_{k+1} - \hat{y}_k)^2} \\ s_{acc} + v &= \sqrt{(\bar{x}_{k+1} - \hat{x}_k)^2 + (\bar{y}_{k+1} - \hat{y}_k)^2} \end{aligned}$$

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\frac{\sin\bar{\varphi}_{k+1}}{\bar{s}_{k+1}} & \frac{\cos\bar{\varphi}_{k+1}}{\bar{s}_{k+1}} & 0 & 0 \\ -\frac{\sin\bar{\varphi}_{k+1}}{\bar{s}_{k+1}} & \frac{\cos\bar{\varphi}_{k+1}}{\bar{s}_{k+1}} & 0 & 0 \\ \cos\bar{\varphi}_{k+1} & \sin\bar{\varphi}_{k+1} & 0 & 0 \\ \cos\bar{\varphi}_{k+1} & \sin\bar{\varphi}_{k+1} & 0 & 0 \\ \cos\bar{\varphi}_{k+1} & \sin\bar{\varphi}_{k+1} & 0 & 0 \end{pmatrix}$$

$$\mathbf{A}_{k+1} = \left(\frac{\partial \varphi(\mathbf{Y})}{\partial \mathbf{Y}}\right)$$

Seminar

Data communication and transfer

- wireness
  - wifi
    - wirelessly connect devices to the internet or Ethernet networks

    - setting up to a network and transfering data
    - its range can be accessed up to 300 feet away
  - bluetooth
    - wireless technology standard
    - exchange data over short distances(<30 feet)
  - NFC(near field communication)
    - allows a device to collect and interpret data from another closely located NFC devices or tag
  - ZigBee
    - open global standard for wireless techology desighed to use low-power digital radio signals for personnal area networks
- wired
  - twisted pair cables
    - unshielded twisted pair(UTP): it does not rely on physical shielding to block interference
    - shieded twisted pair(STP): shielded with a foil jacket to cancel any external interference
  - coaxial cables
    - 75Ω - transmit video signals
    - 50Ω - transmit a data signal in a 2-way communication system
  - fiber optic cables
    - singlemode: only allows one mode of light to propagate at a time
    - multimose: multiple modes of light propagate
  - sensors with wired data transmission
    - a multisensor system contain odometer, optical speed and distance sensor, gyroscope and Ublox(GPS)
  - wired data transmission TCP/IP
    - Ethernert
      - a system for connecting a number of computer systems to form a local area network
    - USB
      - representative peripheral interface and provides a serial bus standard for connecting devices, usually a computer

Street map as a sensor

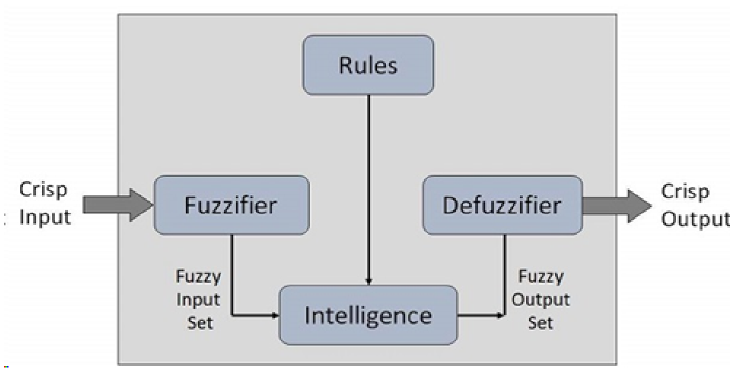
- reason
    - geographic data files(GDF)
        - definition: an international standard that is used to model , describe and transfer road network and other geographic data
        - components: detailed rules for data capture and representation & an extensive catalog of standard features, attributes and relationships
        - application: automotive navigation systems, fleet management, road traffic analysis
    - the navigation data standard(NDS)
        - definition: a standard format for automotive-grade navigation databases, jointly developed by automobile manufacturers and suppliers.
        - NDS is a registered association with the vision of providing a leading world-wide map standard for automotive grade use.
    - why and how digital street map can be a sensor?
        - digital street map is a system, to detect position and location (absolute and relative position), as well as the change of them and then send the information to other electronics as (dynamic) navigation system and traffic control center, to help planning route or managing fleet for example.
    - its accuracy as a sensor
        - absolute accuracy: depend on existing data
            - users, map companies
            - GNSS(around several meters)
        - relative accuracy(topological)
            - how roads and other features connect
- applications
    - ghosthunter
        - automatic warning system of ghost driver
        - wrong-way detection algorithm
        - warning methods
    - TransSec
        - consortium in Europe to delivering a solution to vehicle-based attracks
        - estimation of risk factors
            - suspicious movement adaptive map matching vs classic map matching
- forecast
    - chanllenges in map matching

- locating a vehicle on the road network is a crucial part of intelligent transportation systems such as route guidance and fleet management
- map-matching algorithms project raw position of the user provided by the positioninig system on the road network by comparing trajectory of the vehicle with geometry and topology of the roads.

- map matching in project GhostHunter
  - with the aid of map-matching algorithms, the determined(geometric) vehicle position is then assigned to a traffic section on a digital map. it is important that both in determining the position and in the assignment to a traffic section on a digital map integrity information is determind
- map matching in project TransSec
  - key point of TransSec
  - on-road(lane) and off-road positioning
  - navigational systems
  - curbs or pedestrain zones
  - update rate for these information is 10Hy
- map matching further solution
  - estimate the Horizontal Uncertainty Level(HUL) of GNSS fixes
    - based on the use of a high definition map that store accurate information about the road network.
    - this addictional sourse of information is crucial for autonomous navigation.
    - a particle filter is used for its ability to manage multiple hypotheses if needed.

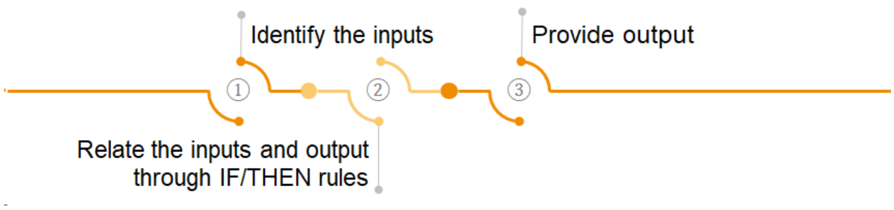
Fuzzy logic

- fuzzy logic is a method of reasoning that resembles human reasoning. It involves al intermediate possibilities between digital values YES and No and works on the level of possibilities of input to achieve the definite output.
- process



- fuzzification
  - it transforms the system inputs, which are crisp numbers, into fuzzy sets by using membership fuctions
  - Crispnumber sets:$m_A:X \rightarrow \{0,1\}$
  - Fuzzy number sets:$\mu_A:X\rightarrow[0,1]$
    - membership fuctions
      - rules for defining fuzziness represented by graphical forms.
      - used in the fuzzification and defuzzification steps of a Fuzzy logic system(FLS) to represent the degree of truth in fuzzy logic
      - map the non-fuzzy input values to fuzzy linguistic terms(to quantify a linguistic term) and vice versa.
- interference based on knowledge base
  - knowledge base
    - it stores if-then rules provided by experts
    - fuzzy rules
      - constructed to control the output variable
      - simple if-then rule with a condition and a conclution
  - inference engine
    - simulates the human reasoning process by making fuzzy inference on the inputs and if-then rules
    - after evaluating the result of each rule, these results should be combined to obtain a final result, this process is called inference.
- defuzzification
  - transform the fuzzy set obtained by the inference engine into a crisp value
  - the process of converting a fuzzy member into a crisp according to the membership function again
  - various methods for defuzzification, such as Max-membership method, weighted average method, etc.

- application
  - a carve robot system based on fuzzy inference and neural network



Input: sensor output: angle around x, y and z axis between target object and sensors			Output
Angle around x axis at time i	Angle around y axis at time j	Angle around z axis at time k	Estimated measurement error O_{ijk}
X_i	Y_j	Z_k	$\mu_X X_i + \mu_Y Y_j + \mu_Z Z_k$

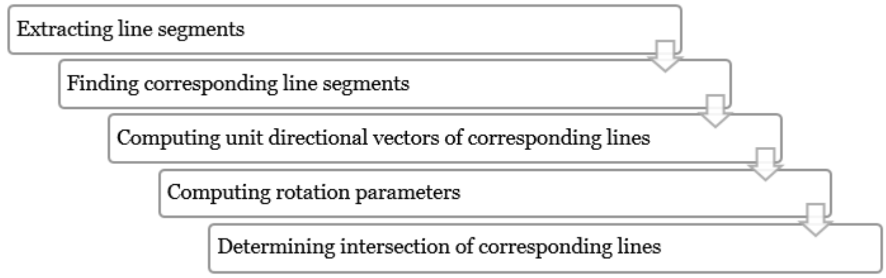
- Railway Decision Support System
  - Input
    - Delay Duration of Train 1
    - Number of Transfer Passengers
    - whether train 2 is the last train in thisdirection on this day
  - Output
    - Decision of whether the train will departure on time

Terrestrial laser scanner, a multi sensor system for registration

- A coarse-to-fine registration strategy is commonly used for LiDAR point clouds registration.
  - first used to achieve a good initial position, based on which registration is then refined utilizing the fine registration method
- TLS data resgisteration methods, coarse and fine

Methods	Main idea
Feature based methods	Feature extraction, feature matching, point cloud registration
Iterative approximation method	Euclidian distance between point clouds are continually reduced by iteration
Random sample consensus methods	Registration parameters are calculated using smallest sample set
Normal distribution transformation methods	Construct body element, generate point cloud distribution model, determine optimal matching relationship
Image assisted methods(VIS)	Extract same named feature in image, then use feature matching method
GNSS-IMU-assistent methods(Z+F)	GNSS data assisted point cloud coordinate tranformation
Standard target-assisted methods	Calculate point cloud conversion parameters using standard target information

- registration flowchart for point clouds based on line segment



Autonomous underwater vehicle

- Introduction
    - operate autonomously in a highly unstructured environment where satellite-based navigation is not directly available
    - offer a more stable platform for precision sensors than towed arrays because they are not subject to physical disturbances transmitted along the cable to the surface vessel
    - follow a path specified by the operator as closely as possible and arrive at a precise location for collection by a surface vessel
- Types of AUVs
    - Hover capable AUV
    - Intervention AUV
    - Long range AUV
    - Micro AUV
- AUV Navigation
    - For the data gathered by an AUV to be of value, the location from which the data has been acquired must be accurately known
- AUV Controlling
    - Development of this technology is focused on using intelligent controllers to provide autonomous underwater vehicles with superior control capabilities over ROVs
    - the explanation includes PID Control, Linear Quadratic Gaussian Control, Fuzzy Logic Control, Adaptive Control, and Sliding Mode Control.
- Communication
    - WLAN and radio these technologies cannot be used underwater because they are based on electromagnetic waves that do not propagate as efficiently in the water as in the air
- Applications of AUV
    - Commercial (eg. oil and gas industry)
    - Research (eg. measure the concentration of various elements or compounds, the absorption or reflection of light, and the presence of microscopic life.)
    - Environmental Monitoring (eg. oil spill, ecosystem assessment, water quality)

- Hydrography (eg. habitat mapping, deep sea mining)
- Search & Recovery (eg. drowned aircraft, sunken vessels, marine archeology)
- Military (eg.rapid environmental assessment, anti-submarine warfare)