Autonomous Navigation AIC@CTL Autonomous Navigation AIC@CTU

Navigation

The art of getting from one place to another, safely and efficiently.

- The process of monitoring and controlling the movement of a craft or vehicle from one place to another.
- The activity of accurately ascertaining one's position and planning and following a route.
- As stated in [1], to navigate, one must answer the following three questions:

"Where am I?", "Where am I going?", "How do I get there?"

• The art of getting from one place to another, safely and efficiently.

Navigation

- The process of monitoring and controlling the movement of a craft or vehicle from one place to another.
- The activity of accurately ascertaining one's position and planning and following a route.
- As stated in [1], to navigate, one must answer the following three questions:

Localisation. "Where am I going?", "How do I get there?"

Tom Krajník Artificial intelligence in robotics 1 / 15 [1] Leonard, J. et al. Mobile robot localization by tracking geometric beacons. T-ROA, 1999 2 / 15 [1] Leonard, J. et al. Mobile robot localization by tracking geometric beacons. T-ROA, 1999 2/15 Tom Krajník Autonomous Navigation AIC@CTU Tom Krainík Autonomous Navigation AIC@CTU Tom Krainík Autonomous Navigation AIC@CTU Navigation

Navigation

Artificial intelligence in robotics 2019

Autonomous Navigation

Tom Krajník

FEL ČVUT

Nov 2019

- The art of getting from one place to another, safely and
- The process of monitoring and controlling the movement of a craft or vehicle from one place to another.
- The activity of accurately ascertaining one's position and planning and following a route.
- As stated in [1], to navigate, one must answer the following three questions:

Localisation.

efficiently.

Mapping,

"How do I get there?"

- The art of getting from one place to another, safely and efficiently.
- The process of monitoring and controlling the movement of a craft or vehicle from one place to another.
- The activity of accurately ascertaining one's position and planning and following a route.
- As stated in [1], to navigate, one must answer the following three questions:

Localisation.

Mapping,

Motion planning

Lecture overview

Autonomous navigation in mobile robotics can be divided by the way it uses knowledge of the environment [2]:

- 1. Map-less navigation
 - · unknown environments with known structure
 - · road following, obstacle avoidance
 - · observations translate to motion commands
- 2. Map-based navigation
 - known (un)structured environments
 - observations and map translate to motion commands
 - a typical intermediate step is localisation
- 3. Map-building-based navigation
 - observations and map translate to both commands and map update
 - (un)known, (un)structured environments
 - a typical intermediate step is localisation

[1] Leonard, J. et al. Tom Krainík

Mobile robot localization by tracking geometric beacons. T-ROA, 1999

2 / 15 [1] Leonard, J. et al. AIC@CTU

Tom Krainík

Mobile robot localization by tracking geometric beacons. T-ROA, 1999

AIC@CTU

2 / 15 [2] DeSouza, G. et al. Tom Krainík

Vision for mobile robot navigation: A survey." IEEE PAMI, 2002 Autonomous Navigation

AIC@CTU

3 / 15

Autonomous Navigation Map-less navigation

Apriori known environment structure Sensor data → motion command Design considerations often based on [3]

Pseudo-random

behaviour-based

Optical flow

Lucas-Kanade

Line detection

· RANSAC, Hough

Road segmentation

region grow, CNN

Autonomous Navigation Map-less navigation

Apriori known environment structure Sensor data → motion command Design considerations often based on [3]

Pseudo-random

behaviour-based

Optical flow

 Lucas-Kanade Line detection

· RANSAC, Hough Road segmentation

region grow, CNN



Map-less navigation

Apriori known environment structure Sensor data → motion command Design considerations often based on [3]

Pseudo-random

behaviour-based

Optical flow

 Lucas-Kanade Line detection

· RANSAC, Hough Road segmentation

region grow. CNN



Intelligence Without Representation, Al 1991

Intelligence Without Representation, Al 199

Autonomous Navigation Autonomous Navigation AIC@CTU

Map-less navigation

Apriori known environment structure Sensor data → motion command Design considerations often based on [3]

Pseudo-random

behaviour-based

Optical flow

Lucas-Kanade

Line detection

[3] Brooks

Tom Krajník

RANSAC, Hough

Road segmentation

region grow, CNN



Video location: videos/flow

Intelligence Without Representation. Al 1991

Autonomous Navigation

Map-less navigation

Apriori known environment structure Sensor data → motion command Design considerations often based on [3]

Pseudo-random

behaviour-based

Optical flow

4 / 15 [3] Brooks:

Tom Krainík

AIC@CTU

Lucas-Kanade

Line detection

RANSAC, Hough

Road segmentation

region grow, CNN



Video location: videos/line-detect

AIC@CTU

AIC@CTI

Map-less navigation

Apriori known environment structure Sensor data → motion command Design considerations often based on [3]

Pseudo-random

- behaviour-based Optical flow
- Lucas-Kanade

Line detection

Tom Krainíl

RANSAC, Hough

Road segmentation

· region grow, CNN



AIC@CTU

AIC@CTU

4 / 15 [3] Brooks:	Intelligence Without Representation. Al 1991	4 / 15

Map-less navigation

Apriori known environment structure Sensor data \rightarrow motion command Design considerations often based on [3]

Pseudo-random

behaviour-based

Optical flow

Lucas-Kanade

Line detection

[3] Brooks

Tom Krainík

RANSAC, Hough

Road segmentation

region grow, CNN



Vid. loc.: videos/road-segmentation

Autonomous Navigation

Intelligence Without Representation. Al 1991

Apriori known environment (pre-build map)

General: (observations, map) \rightarrow motion command

Topological map

- map-less + direction
- Landmark map
- image features
- Geometric map
- · CAD, polygons
- Occupancy grids

4 / 15 Filiat and Mever

AIC@CTU

qualitative nav.

Map-based navigation

Typical: (observations, map) \rightarrow position \rightarrow motion command

- 2d, 3d, OctoMap
- Memory-based

Video location: videos/lama

Autonomous Navigation Map-based navigation

Apriori known environment (pre-build map)

General: (observations, map) \rightarrow motion command

Typical: (observations, map) \rightarrow position \rightarrow motion command

Topological map

- map-less + direction
- Landmark map
- image features
- Geometric map
- · CAD, polygons
- Occupancy grids
- 2d, 3d, OctoMap
- Memory-based

Filiat and Mever

qualitative nav.



Video location: videos/repli

Map-based navigation

Autonomous Navigation

Intelligence Without Representation. Al 1991

Apriori known environment (pre-build map)

General: (observations, map) \rightarrow motion command Typical: (observations, map) \rightarrow position \rightarrow motion command

Topological map

• map-less + direction

Landmark map

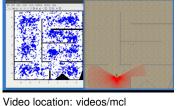
image features

Geometric map CAD, polygons

Occupancy grids

2d, 3d, OctoMap

Memory-based qualitative nav.



Map-based navigation

Autonomous Navigation

Map-based navigation in mobile robots: A review ... Cognitive Systems Research 2003

Apriori known environment (pre-build map)

(observations, map) \rightarrow motion command General: Typical: (observations, map) \rightarrow position \rightarrow motion command

Topological map

- map-less + direction
- Landmark map
- image features Geometric map
- CAD, polygons

Occupancy grids

 2d, 3d, OctoMap Memory-based qualitative nav.



Video location: videos/2dgrid

Map-based navigation

Autonomous Navigation

Map-based navigation in mobile robots: A review ... Cognitive Systems Research 2003

Apriori known environment (pre-build map)

General: (observations, map) \rightarrow motion command Typical: (observations, map) \rightarrow position \rightarrow motion command

Topological map

- map-less + direction
- Landmark map
- image features Geometric map
- CAD, polygons Occupancy grids
- 2d, 3d, OctoMap

Memory-based

qualitative nav.



Video location: videos/qualitative

Example teach-and-repeat map-based navigation

Image sequence indexed by position pics/along the learned path

Example teach-and-repeat map-based navigation

- raw distance between frames,
- · local snapshots of the environment,
- · robot traverses approximately the same distance,
- · steers according to what is sees in front of it.



Tom Krajník

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

6 / 15 Krajnik, Majer et al.:

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

Autonomous Navigation

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

Example teach-and-repeat map-based navigation

Images stored in a prior map

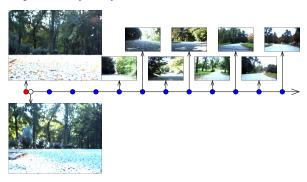


Image perceived by the robot during autonomous navigation

Example teach-and-repeat map-based navigation

Images stored in a prior map

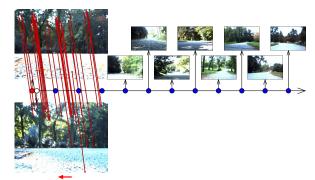


Image perceived by the robot during autonomous navigation

Example teach-and-repeat map-based navigation

Image perceived by the robot during autonomous navigation

Example teach-and-repeat map-based navigation

Images stored in a prior map

Images stored in a prior map

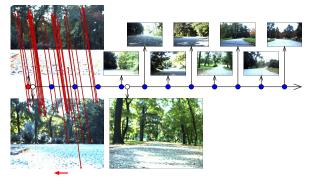


Image perceived by the robot during autonomous navigation

Krajnik, Majer et al.

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

7 / 15 Krajnik, Majer et al.:

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

7 / 15 Krajnik, Majer et al.:

Navigation without localisation: reliable teach and repeat based on In IROS, 2018 Autonomous Navigation

Example teach-and-repeat map-based navigation

Images stored in a prior map

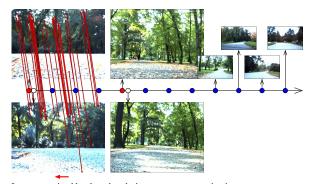


Image perceived by the robot during autonomous navigation

Example teach-and-repeat map-based navigation

Images stored in a prior map

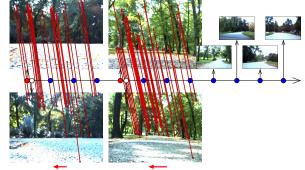


Image perceived by the robot during autonomous navigation

Example teach-and-repeat map-based navigation

Images stored in a prior map

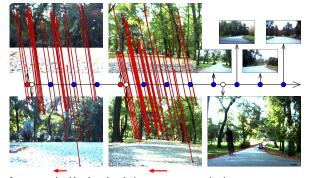


Image perceived by the robot during autonomous navigation

Autonomous Navigation Autonomous Navigation Autonomous Navigation

Example teach-and-repeat map-based navigation

Images stored in a prior map

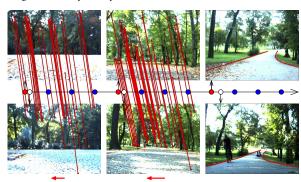


Image perceived by the robot during autonomous navigation

Example teach-and-repeat map-based navigation

Images stored in a prior map

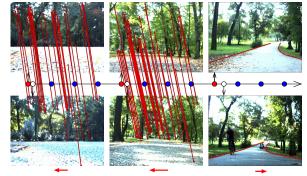
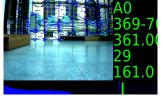


Image perceived by the robot during autonomous navigation

Example teach-and-repeat map-based navigation

Autonomous navigation along a polygonal path Discrete motion model

- Move forwards.
- · get features from map,
- get features from image,
- establish matches,
- steer by histogram voting,
- stop and turn when odometry exceeds segment length.



Video location: videos/navigate

Krajnik, Majer et al. Tom Krainík

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

AIC@CTU

7 / 15 Krajnik, Majer et al.:

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

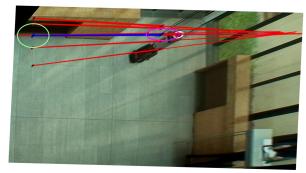
Navigation without localisation: reliable teach and repeat based on In IROS, 2018

Autonomous Navigation

Example map-based navigation - discrete error model

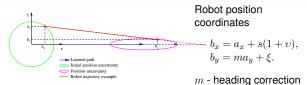
Video location: videos/segment

Example map-based navigation - discrete error model



Video location: videos/segment

Example map-based navigation - discrete error model



Krajnik, Faigl et al.: Tom Krainík

Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010

9 / 15 Krajnik, Faigl et al. AIC@CTU

Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010

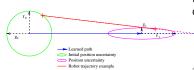
AIC@CTU

9 / 15 Krajnik, Faigl et al.:

Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010

AIC@CTU

Example map-based navigation - discrete error model



Robot position coordinates

$$b_x = a_x + s(1+v),$$

$$b_y = ma_y + \xi.$$

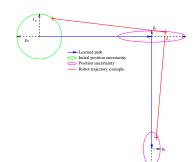
m - heading correction ξ, υ - errors (odo+cam)

Position error ellipse axes

$$f_{i+1} = g_i + v,$$

$$g_{i+1} = mf_i + \xi$$

Example map-based navigation - discrete error model



Robot position coordinates

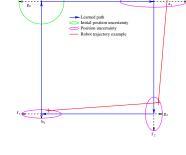
$$b_x = a_x + s(1 + v),$$

$$b_y = ma_y + \xi.$$

m - heading correction ξ, v - errors (odo+cam)

Position error ellipse axes $f_{i+1} = g_i + v,$

 $g_{i+1} = mf_i + \xi$



Example map-based navigation - discrete error model

Robot position coordinates

 ξ, υ - errors (odo+cam)

$$b_x = a_x + s(1 + v),$$

$$b_y = ma_y + \xi.$$

m - heading correction ξ, v - errors (odo+cam)

Position error ellipse axes

$$f_{i+1} = g_i + v,$$

$$g_{i+1} = mf_i + \xi$$

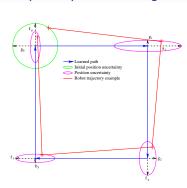
Convergence
$$f = (\xi + v)/(1 - m)$$

$$f_{\infty} = (\xi + v)/(1 - m)$$

 f_{∞} , g_{∞} finite if $||m|| < 1$.

Autonomous Navigation Autonomous Navigation AIC@CTU

Example map-based navigation - discrete error model



Robot position coordinates

$$b_x = a_x + s(1 + v),$$

$$b_y = ma_y + \xi.$$

m - heading correction ξ, υ - errors (odo+cam)

Position error ellipse axes

$$f_{i+1} = g_i + \upsilon,$$

$$g_{i+1} = mf_i + \xi$$

Convergence

$$f_{\infty} = (\xi + v)/(1 - m)$$

 f_{∞} , g_{∞} finite if $||m|| < 1$.

Example map-based navigation - discrete error model Robot position vector

$$\left(\begin{array}{c}b_x\\b_y\end{array}\right)=\left(\begin{array}{cc}1&0\\0&m\end{array}\right)\left(\begin{array}{c}a_x\\a_y\end{array}\right)+\left(\begin{array}{c}s+s\upsilon\\\xi\end{array}\right)$$

Becomes

 $\mathbf{b} = \mathbf{R^T}(\mathbf{MRa} + \mathbf{s}) = \mathbf{Na} + \mathbf{t}$ for a segment with arbitrary azimuth R

Position error covariance matrix $\mathbf{A_{i+1}} = \mathbf{N_i} \mathbf{A_i} \mathbf{N_i^T} + \mathbf{T_i}$

Convergence

 $\mathbf{A}_{\infty} = \breve{\mathbf{N}} \mathbf{A}_{\infty} \breve{\mathbf{N}} + \breve{\mathbf{T}}$ (Lyapunov equation) \mathbf{A}_{∞} exists and is finite iff $\breve{\mathbf{N}} = \prod_{i=1}^{n} \mathbf{N_i} = \prod_{n=1}^{n} \mathbf{R_i^T N_i R_i}$

Robot position coordinates

$$b_x = a_x + s(1 + v),$$

$$b_y = ma_y + \xi.$$

m - heading correction ξ, v - errors (odo+cam)

Position error ellipse axes

$$f_{i+1} = g_i + v,$$

$$g_{i+1} = mf_i + \xi$$

Convergence

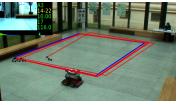
$$f_{\infty} = (\xi + v)/(1 - m)$$

 f_{∞} , g_{∞} finite if $||m|| < 1$.

Experimental evaluation:

- 1. Teach a closed path,
- 2. displace at start,
- 3. traverse n times,
- 4. measure c_i
- 5. compute ε_{acc} , ε_{acc} .

$$\begin{array}{lcl} \varepsilon_{acc} & = & \sqrt{\frac{1}{n-j} \sum_{i=j}^{n} \|\mathbf{c}_i\|^2} \\ \varepsilon_{rep} & = & \sqrt{\frac{1}{n-j} \sum_{i=j}^{n} \|\mathbf{c}_i, \mu\|^2} \\ \mu & = & \sum_{i=j}^{n} \mathbf{c}_i/(n-j) \end{array}$$



Video location: videos/converge

Krajnik, Faigl et al. Tom Krajník

Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010 Autonomous Navigation

AIC@CTU

10 / 15 Krajnik, Faigl et al.:

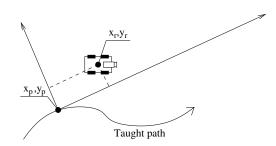
Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010 Autonomous Navigation

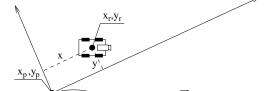
Example map-based navigation - continuous error

model

Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010 Autonomous Navigation

Example map-based navigation - continuous error model



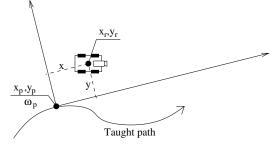


Taught path

$$\dot{x} =$$

Example map-based navigation - continuous error model

Example map-based navigation - discrete error model



$$\begin{array}{rcl}
x & = & +\omega_p y \\
\dot{y} & = & -\omega_p x
\end{array}$$

Krajnik, Faigl et al.:

Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010

AIC@CTU

12 / 15 Krajnik, Faigl et al.

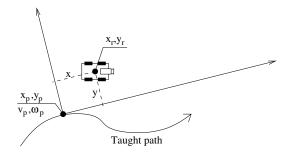
Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010

12 / 15 Krajnik, Faigl et al.: AIC@CTU

Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010

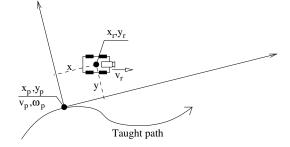
AIC@CTU

Example map-based navigation - continuous error model



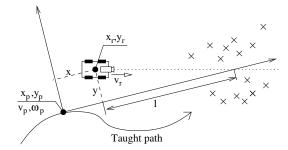
$$\dot{x} = +\omega_p y - v_p
\dot{y} = -\omega_p x$$

Example map-based navigation - continuous error model



$$\begin{array}{rcl} \dot{x} & = & +\omega_p \, y & -v_p & +v_r \\ \dot{y} & = & -\omega_p \, x \end{array}$$

Example map-based navigation - continuous error model



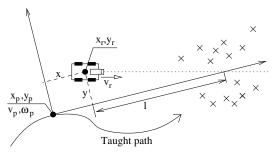
$$\dot{x} = +\omega_p y - v_p + v_r
\dot{y} = -\omega_p x - v_r y l^{-1}$$

Autonomous Navigation Autonomous Navigation Autonomous Navigation AIC@CTU

Example map-based navigation - continuous error

model

Example map-based navigation - continuous error model



$$\begin{array}{rcl} \dot{x} & = & +\omega_p \, y & -v_p & +v_r & +s_x \\ \dot{y} & = & -\omega_p \, x & & -v_r \, y \, l^{-1} & +s_y \end{array}$$

Krajnik, Faigl et al. Tom Krajník

Simple, Yet Stable Bearing only Navigation. Journal of Field Robotics, 2010

12 / 15 Krajnik, Majer et al. AIC@CTU

Navigation without localisation: reliable teach and repeat based on In IROS, 2018 Autonomous Navigation

Navigation without localisation: reliable teach and repeat based on In IROS, 2018 Autonomous Navigation

Example map-based navigation - continuous error model

$$\dot{x} = + \omega_p y - v_p + v_r + s_x$$

 $\dot{y} = - \omega_p x - v_r y l^{-1} + s_y$

Matrix form:

$$\left(\begin{array}{c} \dot{x} \\ \dot{y} \end{array} \right) = \left(\begin{array}{cc} 0 & +\omega_p \\ -\omega_p & -v_r \, l^{-1} \end{array} \right) \left(\begin{array}{c} x \\ y \end{array} \right) + \left(\begin{array}{c} s_x \\ s_y \end{array} \right),$$

Matrix eigenvalues:

$$\lambda^2 + \lambda \frac{v_r}{I} + \omega_p^2 = 0,$$

Example map-based navigation - continuous error model

$$\dot{x} = + \omega_p y - v_p + v_r + s_s$$

 $\dot{y} = - \omega_p x - v_r y l^{-1} + s_s$

Matrix form:

$$\left(\begin{array}{c} \dot{x} \\ \dot{y} \end{array}\right) = \left(\begin{array}{cc} 0 & +\omega_p \\ -\omega_n & -v_r \, l^{-1} \end{array}\right) \left(\begin{array}{c} x \\ y \end{array}\right) + \left(\begin{array}{c} s_x \\ s_y \end{array}\right),$$

Matrix eigenvalues:

$$\lambda^2 + \lambda \frac{v_r}{l} + \omega_p^2 = 0,$$

$$v_r > 0, \quad l > 0 \implies Re(\lambda_{1,2}) < 0 \quad \text{iff} \quad \omega_p \neq 0.$$

Example map-based navigation - continuous error model

Example map-based navigation - continuous error

model

 $\dot{x} = + \omega_p y - v_p + v_r + s_x$ $= - \omega_p x - v_r y l^{-1} + s_n$

 $\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} 0 & +\omega_p \\ -\omega_p & -v_r l^{-1} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} s_x \\ s_y \end{pmatrix},$

$$\dot{x} = + \omega_p y - v_p + v_r + s_x$$

 $\dot{y} = - \omega_p x - v_r y l^{-1} + s_w$

Matrix form:

Matrix form:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} 0 & +\omega_p \\ -\omega_p & -v_r l^{-1} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} s_x \\ s_y \end{pmatrix},$$

Matrix eigenvalues:

$$\lambda^2+\lambda\frac{v_r}{l}+\omega_p^2=0,$$

$$v_r>0,\ l>0 \implies Re(\lambda_{1,2})<0 \ \text{iff} \ \omega_p\neq 0.$$

Position error decreases if path is not only a straight line.

Krajnik, Majer et al.

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

13 / 15 Krajnik, Majer et al.: Tom Krainík

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

13 / 15 Krajnik, Majer et al.:

Tom Krainík

Autonomous Navigation

Autonomous Navigation

AIC@CTU

Navigation without localisation: reliable teach and repeat based on In IROS, 2018

Example map-based navigation - continuous error model

Experimental evaluation similar to the discrete case

- 1. Teach a closed path,
- 2. displace at start,
- 3. traverse *n* times,
- 4. measure c_i ,
- 5. compute ε_{acc} , ε_{acc} .

$$\begin{array}{rcl} \varepsilon_{acc} & = & \sqrt{\frac{1}{n-j} \sum_{i=j}^{n} \left\| \mathbf{c_i} \right\|^2} \\ \varepsilon_{rep} & = & \sqrt{\frac{1}{n-j} \sum_{i=j}^{n} \left\| \mathbf{c_i}, \mu \right\|^2} \\ \mu & = & \sum_{i=j}^{n} \mathbf{c_i} / (n-j) \end{array}$$



Video location: videos/continuos

Lecture wrap up: what to remember

What to remember

- Mobile robot navigation type can be divided by the map usage, which assume different prior knowledge and thus handle the robot observations in different ways. [1]
- · Although simple, mapless navigation is commonly used in commercially-successfull systems (Roomba, Tesla etc). [2]
- Map-based navigation typically uses localisation [3], but it is not necessary for teach-and-repeat systems [4].

- [1] DeSouza et al.: Vision for mobile robot navigation: A survey. IEEE PAMI, 2002
- [2] Brooks: Intelligence without representation. Al 1991
- [3] Filiat and Meyer: Map-based navigation in mobile robots: A review... Cog.Sys. Research 2003.
- [4] Krajnik et al.: Navigation without localisation ... In IROS 2018