prpy: Probabilistic Robot Localization Python Library

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Pere Ridao

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CONTENTS

Probabilistic Robot Localization is Python Library containing the main algorithms explained in the **Probabilisitic Robot Localization** Book used in the **Probabilisitic Robotics** and the **Hands-on Localization** Courses of the **Intelligent Field Robotic Systems (IFRoS)** European Erasmus Mundus Master.

Note: This documentation is still under construction.

API:

1.1 Pose Representation

1.1.1 Pose 3DOF

class Pose3D.**Pose3D**(*input_array*)

Bases: ndarray

Definition of a robot pose in 3 DOF (x, y, yaw). The class inherits from a ndarray. This class extends the ndarray with the $oplus$ and $ominus$ operators and the corresponding Jacobians.

oplus(*BxC*)

Given a Pose3D object *AxB* (the self object) and a Pose3D object *BxC*, it returns the Pose3D object *AxC*.

$$\mathbf{^A x_B} = \begin{bmatrix} ^A x_B & ^A y_B & ^A \psi_B \end{bmatrix}^T$$
$$\mathbf{^B x_C} = \begin{bmatrix} ^B x_C & ^B y_C & ^B \psi_C \end{bmatrix}^T$$

The operation is defined as:

$$\mathbf{^A x_C} = \mathbf{^A x_B} \oplus \mathbf{^B x_C} = \begin{bmatrix} ^A x_B +^B x_C \cos(^A \psi_B) -^B y_C \sin(^A \psi_B) \\ ^A y_B +^B x_C \sin(^A \psi_B) +^B y_C \cos(^A \psi_B) \\ ^A \psi_B +^B \psi_C \end{bmatrix} \tag{1.1}$$

Parameters

BxC – C-Frame pose expressed in B-Frame coordinates

Returns

C-Frame pose expressed in A-Frame coordinates

J_1oplus(*BxC*)

Jacobian of the pose compounding operation (eq. (1.1)) with respect to the first pose:

$$J_{1\oplus} = \frac{\partial ^A x_B \oplus^B x_C}{\partial ^A x_B} = \begin{bmatrix} 1 & 0 & -^B x_C \sin(^A \psi_B) -^B y_C \cos(^A \psi_B) \\ 0 & 1 & ^B x_C \cos(^A \psi_B) -^B y_C \sin(^A \psi_B) \\ 0 & 0 & 1 \end{bmatrix} \tag{1.2}$$
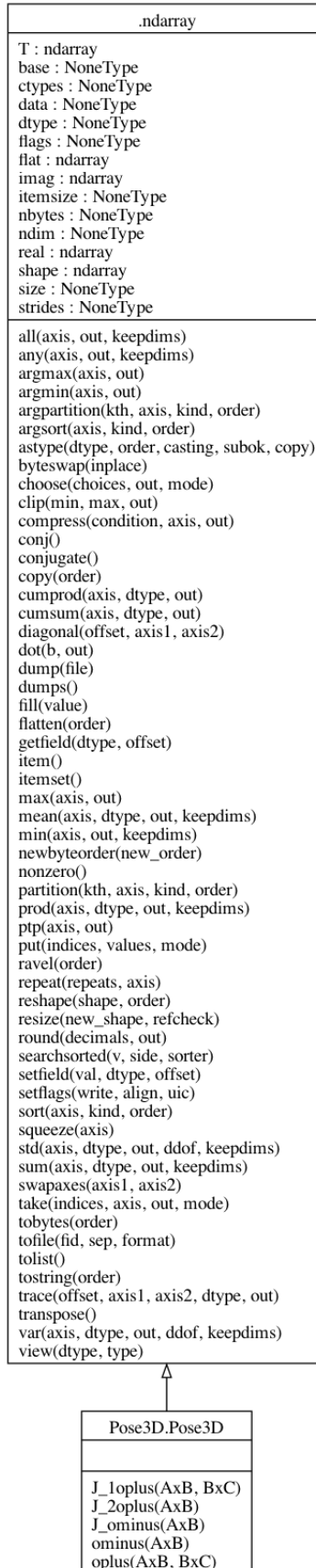
The method returns a numerical matrix containing the evaluation of the Jacobian for the pose *AxB* (the self object) and the 2nd posepose *BxC*.

Parameters

BxC – 2nd pose

Returns

Evaluation of the $J_{1\oplus}$ Jacobian of the pose compounding operation with respect to the first pose (eq. (1.2))

```
                          .ndarray

        T : ndarray
        base : NoneType
        ctypes : NoneType
        data : NoneType
        dtype : NoneType
        flags : NoneType
        flat : ndarray
        imag : ndarray
        itemsize : NoneType
        nbytes : NoneType
        ndim : NoneType
        real : ndarray
        shape : ndarray
        size : NoneType
        strides : NoneType

        all(axis, out, keepdims)
        any(axis, out, keepdims)
        argmax(axis, out)
        argmin(axis, out)
        argpartition(kth, axis, kind, order)
        argsort(axis, kind, order)
        astype(dtype, order, casting, subok, copy)
        byteswap(inplace)
        choose(choices, out, mode)
        clip(min, max, out)
        compress(condition, axis, out)
        conj()
        conjugate()
        copy(order)
        cumprod(axis, dtype, out)
        cumsum(axis, dtype, out)
        diagonal(offset, axis1, axis2)
        dot(b, out)
        dump(file)
        dumps()
        fill(value)
        flatten(order)
        getfield(dtype, offset)
        item()
        itemset()
        max(axis, out)
        mean(axis, dtype, out, keepdims)
        min(axis, out, keepdims)
        newbyteorder(new_order)
        nonzero()
        partition(kth, axis, kind, order)
        prod(axis, dtype, out, keepdims)
        ptp(axis, out)
        put(indices, values, mode)
        ravel(order)
        repeat(repeats, axis)
        reshape(shape, order)
        resize(new_shape, refcheck)
        round(decimals, out)
        searchsorted(v, side, sorter)
        setfield(val, dtype, offset)
        setflags(write, align, uic)
        sort(axis, kind, order)
        squeeze(axis)
        std(axis, dtype, out, ddof, keepdims)
        sum(axis, dtype, out, keepdims)
        swapaxes(axis1, axis2)
        take(indices, axis, out, mode)
        tobytes(order)
        tofile(fid, sep, format)
        tolist()
        tostring(order)
        trace(offset, axis1, axis2, dtype, out)
        transpose()
        var(axis, dtype, out, ddof, keepdims)
        view(dtype, type)


                        Pose3D.Pose3D


        J_1oplus(AxB, BxC)
        J_2oplus(AxB)
        J_ominus(AxB)
        ominus(AxB)
        oplus(AxB, BxC)
```

J_2oplus()

Jacobian of the pose compounding operation ((1.1)) with respect to the second pose:

$$J_{2\oplus} = \frac{\partial^A x_B \oplus^B x_C}{\partial^B x_C} = \begin{bmatrix} \cos(^A\psi_B) & -\sin(^A\psi_B) & 0 \\ \sin(^A\psi_B) & \cos(^A\psi_B) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1.3}$$

The method returns a numerical matrix containing the evaluation of the Jacobian for the 1st posepose *AxB* (the self object).

> **Returns**
>
> > Evaluation of the $J_{2\oplus}$ Jacobian of the pose compounding operation with respect to the second pose (eq. (1.3))

ominus()

Inverse pose compounding of the *AxB* pose (the self objetc):

$$^B x_A = \ominus^A x_B = \begin{bmatrix} -^A x_B \cos(^A\psi_B) -^A y_B \sin(^A\psi_B) \\ ^A x_B \sin(^A\psi_B) -^A y_B \cos(^A\psi_B) \\ -^A\psi_B \end{bmatrix} \tag{1.4}$$

> **Returns**
>
> > A-Frame pose expressed in B-Frame coordinates (eq. (1.4))

J_ominus()

Jacobian of the inverse pose compounding operation ((1.1)) with respect the pose *AxB* (the self object):

$$J_{\ominus} = \frac{\partial \ominus^A x_B}{\partial^A x_B} = \begin{bmatrix} -\cos(^A\psi_B) & -\sin(^A\psi_B) & ^A x_B \sin(^A\psi_B) -^A y_B \cos(^A\psi_B) \\ \sin(^A\psi_B) & -\cos(^A\psi_B) & ^A x_B \cos(^A\psi_B) +^A y_B \sin(^A\psi_B) \\ 0 & 0 & -1 \end{bmatrix} \tag{1.5}$$

Returns the numerical matrix containing the evaluation of the Jacobian for the pose *AxB* (the self object).

> **Returns**
>
> > Evaluation of the $J_{\ominus}$ Jacobian of the inverse pose compounding operation with respect to the pose (eq. (1.5))

1.2 Robot Simulation

class SimulatedRobot.**SimulatedRobot**(*xs0, map=[], *args*)

> Bases: object

This is the base class to simulate a robot. There are two operative frames: the world N-Frame (North East Down oriented) and the robot body frame body B-Frame. Each robot has a motion model and a measurement model. The motion model is used to simulate the robot motion and the measurement model is used to simulate the robot measurements.

All Robot simulation classes must derive from this class .

dt = 0.1

> class attribute containing sample time of the simulation

__init__(*xs0, map=[], *args*)

> > **Parameters**
> >
> > > • **xs0** – initial simulated robot state x_{s_0} used to initialize the the motion model

```
SimulatedRobot.SimulatedRobot

M : list
Qsk : NoneType
Rsk : NoneType
dt : float
k : int
nf
plt_samples : list
trajectory
usk : NoneType
vehicleAxes
vehicleFig : NoneType
vehicleIcon : VehicleIcon
visualizationInterval : int
xTraj : list
xsk : NoneType
xsk_1
yTraj : list

PlotRobot()
SetMap(map)
fs(xsk_1, uk)
```

Fig. 1: SimulatedRobot Class Diagram.

- **map** – feature map of the environment $M = [{}^N x_{F_1}^T, ..., {}^N x_{F_{nf}}^T]^T$

Constructor. First, it initializes the robot simulation defining the following attributes:

- **k** : time step

- **Qsk** : **To be defined in the derived classes**. Object attribute containing Covariance of the simulation motion model noise

- **usk** : **To be defined in the derived classes**. Object attribute containing the simulated input to the motion model

- **xsk** : **To be defined in the derived classes**. Object attribute containing the current simulated robot state

- **zsk** : **To be defined in the derived classes**. Object attribute containing the current simulated robot measurement

- **Rsk** : **To be defined in the derived classes**. Object attribute containing the observation noise covariance matrix

- **xsk** : current pose is the initial state

- **xsk_1** : previous state is the initial robot state

- **M** : position of the features in the N-Frame

- **nf** : number of features

Then, the robot animation is initialized defining the following attributes:

- **vehicleIcon** : Path file of the image of the robot to be used in the animation

- **vehicleFig** : Figure of the robot to be used in the animation

- **vehicleAxes** : Axes of the robot to be used in the animation

---

- **xTraj** : list containing the x coordinates of the robot trajectory

- **yTraj** : list containing the y coordinates of the robot trajectory

- **visualizationInterval** : time-steps interval between two consecutive frames of the animation

PlotRobot()

Updates the plot of the robot at the current pose

fs(*xsk_1*, *uk*)

Motion model used to simulate the robot motion. Computes the current robot state x_k given the previous robot state x_{k-1} and the input u_k. It also updates the object attributes xsk, xsk_1 and usk to be made them available for plotting purposes. *To be overriden in child class*.

> **Parameters**
>
> - **xsk_1** – previous robot state x_{k-1}
>
> - **uk** – model input u_{s_k}
>
> **Returns**
> current robot state x_k

SetMap(*map*)

Initializes the map of the environment.

_PlotSample(*x*, *P*, *n*)

Plots n samples of a multivariate gaussian distribution. This function is used only for testing, to plot the uncertainty through samples. :param x: mean pose of the distribution :param P: covariance of the distribution :param n: number of samples to plot

1.2.1 3 DOF Diferential Drive Robot Simulation

class DifferentialDriveSimulatedRobot.**DifferentialDriveSimulatedRobot**(*xs0*, *map=[]*, **args*)

Bases: *SimulatedRobot*

This class implements a simulated differential drive robot. It inherits from the `SimulatedRobot` class and overrides some of its methods to define the differential drive robot motion model.

__init__(*xs0*, *map=[]*, **args*)

> **Parameters**
>
> - **xs0** – initial simulated robot state $\mathbf{x_{s_0}} = [^N x_{s_0} \; ^N y_{s_0} \; ^N \psi_{s_0}]^T$ used to initialize the motion model
>
> - **map** – feature map of the environment $M = [^N x_{F_1}, ..., ^N x_{F_{n_f}}]$

Initializes the simulated differential drive robot. Overrides some of the object attributes of the parent class `SimulatedRobot` to define the differential drive robot motion model:

- **Qsk** : Object attribute containing Covariance of the simulation motion model noise.

$$Q_k = \begin{bmatrix} \sigma_{\dot{u}}^2 & 0 & 0 \\ 0 & \sigma_{\dot{v}}^2 & 0 \\ 0 & 0 & \sigma_{\dot{r}}^2 \end{bmatrix} \tag{1.6}$$

- **usk** : Object attribute containing the simulated input to the motion model containing the forward velocity u_k and the angular velocity r_k

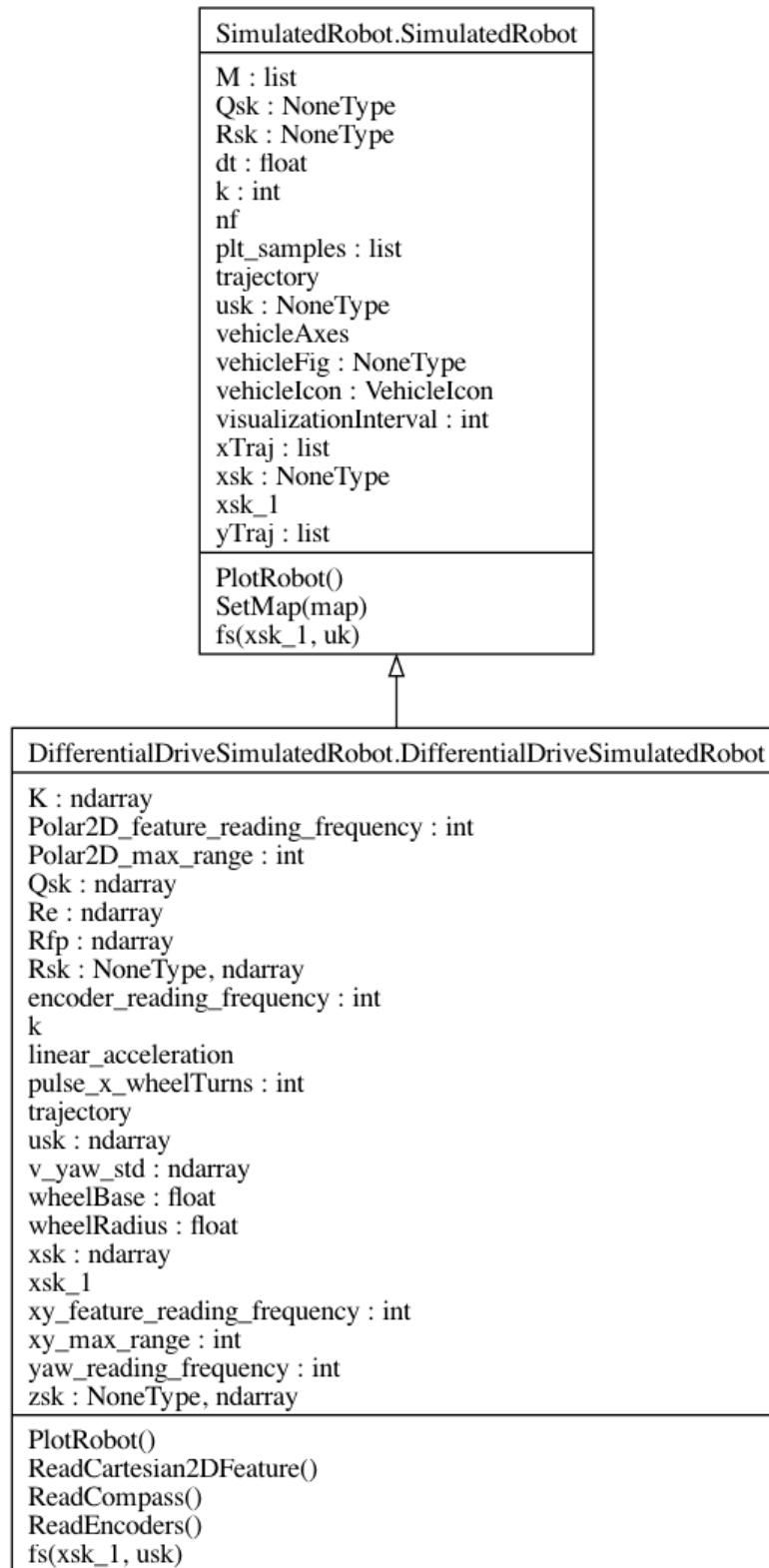$$\mathbf{u_k} = \begin{bmatrix} u_k & r_k \end{bmatrix}^{\mathbf{T}} \tag{1.7}$$

SimulatedRobot.SimulatedRobot

M : list
Qsk : NoneType
Rsk : NoneType
dt : float
k : int
nf
plt_samples : list
trajectory
usk : NoneType
vehicleAxes
vehicleFig : NoneType
vehicleIcon : VehicleIcon
visualizationInterval : int
xTraj : list
xsk : NoneType
xsk_1
yTraj : list

PlotRobot()
SetMap(map)
fs(xsk_1, uk)

DifferentialDriveSimulatedRobot.DifferentialDriveSimulatedRobot

K : ndarray
Polar2D_feature_reading_frequency : int
Polar2D_max_range : int
Qsk : ndarray
Re : ndarray
Rfp : ndarray
Rsk : NoneType, ndarray
encoder_reading_frequency : int
k
linear_acceleration
pulse_x_wheelTurns : int
trajectory
usk : ndarray
v_yaw_std : ndarray
wheelBase : float
wheelRadius : float
xsk : ndarray
xsk_1
xy_feature_reading_frequency : int
xy_max_range : int
yaw_reading_frequency : int
zsk : NoneType, ndarray

PlotRobot()
ReadCartesian2DFeature()
ReadCompass()
ReadEncoders()
fs(xsk_1, usk)

Fig. 2: DifferentialDriveSimulatedRobot Class Diagram.

- **xsk** : Object attribute containing the current simulated robot state

$$x_k = \begin{bmatrix} {}^N x_k & {}^N y_k & {}^N \theta_k & {}^B u_k & {}^B v_k & {}^B r_k \end{bmatrix}^T \tag{1.8}$$

where ${}^N x_k$, ${}^N y_k$ and ${}^N \theta_k$ are the robot position and orientation in the world N-Frame, and ${}^B u_k$, ${}^B v_k$ and ${}^B r_k$ are the robot linear and angular velocities in the robot B-Frame.

- **zsk** : Object attribute containing $z_{s_k} = [n_L \, n_R]^T$ observation vector containing number of pulses read from the left and right wheel encoders.

- **Rsk** : Object attribute containing $R_{s_k} = diag(\sigma_L^2, \sigma_R^2)$ covariance matrix of the noise of the read pulses`.

- **wheelBase** : Object attribute containing the distance between the wheels of the robot ($w = 0.5$ m)

- **wheelRadius** : Object attribute containing the radius of the wheels of the robot ($R = 0.1$ m)

- **pulses_x_wheelTurn** : Object attribute containing the number of pulses per wheel turn ($pulseXwheelTurn = 1024$ pulses)

- **Polar2D_max_range** : Object attribute containing the maximum Polar2D range ($Polar2D_max_range = 50$ m) at which the robot can detect features.

- **Polar2D_feature_reading_frequency** : Object attribute containing the frequency of Polar2D feature readings (50 tics -sample times-)

- **Rfp** : Object attribute containing the covariance of the simulated Polar2D feature noise ($R_{fp} = diag(\sigma_\rho^2, \sigma_\phi^2)$)

Check the parent class `prpy.SimulatedRobot` to know the rest of the object attributes.

fs(*xsk_1*, *usk*)

Motion model used to simulate the robot motion. Computes the current robot state x_k given the previous robot state x_{k-1} and the input u_k:

$$\begin{aligned}
\eta_{s_{k-1}} &= \begin{bmatrix} x_{s_{k-1}} & y_{s_{k-1}} & \theta_{s_{k-1}} \end{bmatrix}^T \\
\nu_{s_{k-1}} &= \begin{bmatrix} u_{s_{k-1}} & v_{s_{k-1}} & r_{s_{k-1}} \end{bmatrix}^T \\
x_{s_{k-1}} &= \begin{bmatrix} \eta_{s_{k-1}}^T & \nu_{s_{k-1}}^T \end{bmatrix}^T \\
u_{s_k} &= \nu_d = \begin{bmatrix} u_d & r_d \end{bmatrix}^T \\
w_{s_k} &= \dot{\nu}_{s_k} \\
x_{s_k} &= f_s(x_{s_{k-1}}, u_{s_k}, w_{s_k}) \\
&= \begin{bmatrix} \eta_{s_{k-1}} \oplus (\nu_{s_{k-1}}\Delta t + \frac{1}{2}w_{s_k}\Delta t^2) \\ \nu_{s_{k-1}} + K(\nu_d - \nu_{s_{k-1}}) + w_{s_k}\Delta t \end{bmatrix} \quad ; \quad K = diag(k_1, k_2, k_3) \quad k_i > 0
\end{aligned} \tag{1.9}$$

Where $\eta_{s_{k-1}}$ is the previous 3 DOF robot pose (x,y,yaw) and $\nu_{s_{k-1}}$ is the previous robot velocity (velocity in the direction of x and y B-Frame axis of the robot and the angular velocity). u_{s_k} is the input to the motion model contaning the desired robot velocity in the x direction (u_d) and the desired angular velocity around the z axis (r_d). w_{s_k} is the motion model noise representing an acceleration perturbation in the robot axis. The w_{s_k} acceleration is the responsible for the slight velocity variation in the simulated robot motion. K is a diagonal matrix containing the gains used to drive the simulated velocity towards the desired input velocity.

Finally, the class updates the object attributes xsk, xsk_1 and usk to made them available for plotting purposes.

To be completed by the student.

Parameters

- **xsk_1** – previous robot state $x_{s_{k-1}} = \begin{bmatrix} \eta_{s_{k-1}}^T & \nu_{s_{k-1}}^T \end{bmatrix}^T$

- **usk** – model input $u_{s_k} = \nu_d = \begin{bmatrix} u_d & r_d \end{bmatrix}^T$

Returns

current robot state x_{s_k}

ReadEncoders()

Simulates the robot measurements of the left and right wheel encoders.

To be completed by the student.

Return zsk,Rsk

$zk = [n_L \ n_R]^T$ observation vector containing number of pulses read from the left and right wheel encoders. $R_{s_k} = diag(\sigma_L^2, \sigma_R^2)$ covariance matrix of the read pulses.

ReadCompass()

Simulates the compass reading of the robot.

Returns

yaw and the covariance of its noise R_yaw

ReadCartesian2DFeature()

Simulates the reading of 2D cartesian features. The features are placed in the map in cartesian coordinates.

Returns

zsk: [[x1 y1],…,[xn yn]]

Cartesian position of the feature observations.

Rsk: block_diag(R_1,…,R_n), where R_i=[[r_xx r_xy],[r_xy r_yy]] is the

2x2 i-th feature observation covariance. Covariance of the Cartesian feature observations. Note the features are uncorrelated among them. They are independent. However, the x and y coordinates of each feature are correlated.

PlotRobot()

Updates the plot of the robot at the current pose

1.3 Robot Localization

1.3.1 Robot Localization

class Localization.**Localization**(*index*, *kSteps*, *robot*, *x0*, **args*)

Bases: `object`

Localization base class. Implements the localization algorithm.

__init__(*index*, *kSteps*, *robot*, *x0*, **args*)

Constructor of the DRLocalization class.

Parameters

- **index** – Logging index structure (`prpy.Index`)

- **kSteps** – Number of time steps to simulate

- **robot** – Simulation robot object (`prpy.Robot`)

- **args** – Rest of arguments to be passed to the parent constructor

```
Localization.Localization
```
```
index
k : int
kSteps
log_x : ndarray
log_xs : ndarray
plot_xy_estimation : bool
robot
trajectory
xTraj : list
xk
xk_1
yTraj : list
```
```
GetInput()
LocalizationLoop(x0, usk)
Localize(xk_1, uk)
Log(xsk, xk)
PlotTrajectory()
PlotXY()
```

- **x0** – Initial Robot pose in the N-Frame

GetInput()

Gets the input from the robot. To be overidden by the child class.

> **Return uk**
> input variable

Localize(*xk_1*, *uk*)

Single Localization iteration invoked from `prpy.DRLocalization.Localization()`. Given the previous robot pose, the function reads the inout and computes the current pose.

> **Parameters**
> **xk_1** – previous robot pose

> **Return xk**
> current robot pose

LocalizationLoop(*x0*, *usk*)

Given an initial robot pose x_0 and the input to the `prpy.SimulatedRobot` this method calls iteratively `prpy.DRLocalization.Localize()` for k steps, solving the robot localization problem.

> **Parameters**
> **x0** – initial robot pose

Log(*xsk*, *xk*)

Logs the results for later plotting.

> **Parameters**
>
> - **xsk** – ground truth robot pose from the simulation
>
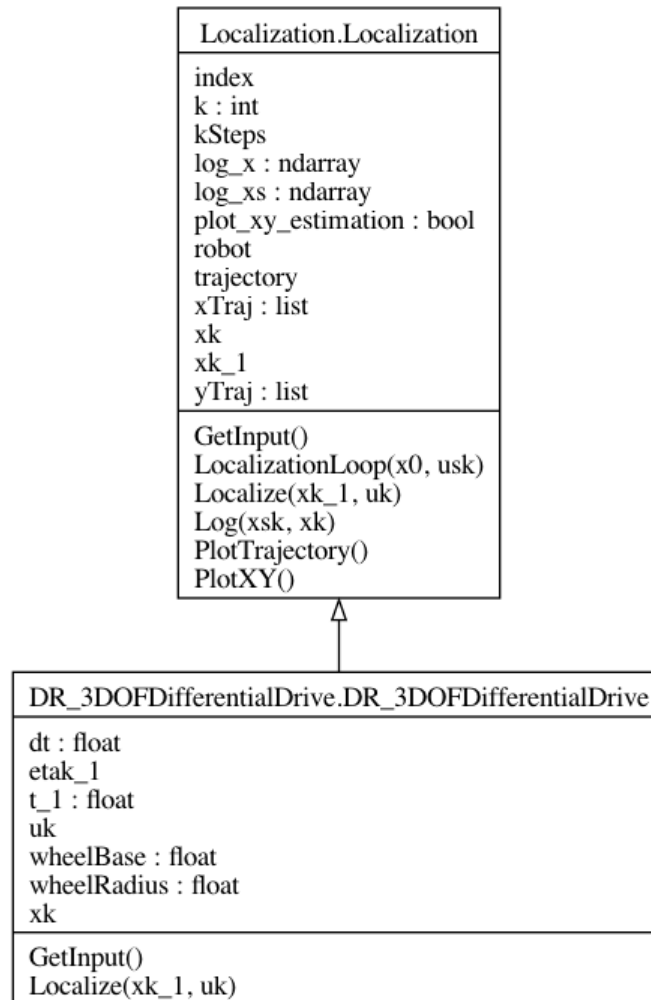> - **xk** – estimated robot pose

PlotXY()

Plots, in a new figure, the ground truth (orange) and estimated (blue) trajectory of the robot at the end of the Localization Loop.

PlotTrajectory()

   Plots the estimated trajectory (blue) of the robot during the localization process.

1.3.2 Dead Reckoning

3 DOF Differential Drive Mobile Robot Example

```
┌─────────────────────────────────────┐
│      Localization.Localization       │
├─────────────────────────────────────┤
│ index                                │
│ k : int                              │
│ kSteps                               │
│ log_x : ndarray                      │
│ log_xs : ndarray                     │
│ plot_xy_estimation : bool            │
│ robot                                │
│ trajectory                           │
│ xTraj : list                         │
│ xk                                   │
│ xk_1                                 │
│ yTraj : list                         │
├─────────────────────────────────────┤
│ GetInput()                           │
│ LocalizationLoop(x0, usk)            │
│ Localize(xk_1, uk)                   │
│ Log(xsk, xk)                         │
│ PlotTrajectory()                     │
│ PlotXY()                             │
└─────────────────────────────────────┘
                  △
                  │
┌──────────────────────────────────────────────────────┐
│ DR_3DOFDifferentialDrive.DR_3DOFDifferentialDrive      │
├──────────────────────────────────────────────────────┤
│ dt : float                                             │
│ etak_1                                                 │
│ t_1 : float                                            │
│ uk                                                     │
│ wheelBase : float                                      │
│ wheelRadius : float                                    │
│ xk                                                     │
├──────────────────────────────────────────────────────┤
│ GetInput()                                             │
│ Localize(xk_1, uk)                                     │
└──────────────────────────────────────────────────────┘
```

class DR_3DOFDifferentialDrive.**DR_3DOFDifferentialDrive**(*index*, *kSteps*, *robot*, *x0*, **args*)

   Bases: *Localization*

   Dead Reckoning Localization for a Differential Drive Mobile Robot.

   __init__(*index*, *kSteps*, *robot*, *x0*, **args*)

      Constructor of the `prlab.DR_3DOFDifferentialDrive` class.

         Parameters

            args – Rest of arguments to be passed to the parent constructor

   Localize(*xk_1*, *uk*)

      Motion model for the 3DOF ($x_k = [x_k \ y_k \ \psi_k]^T$) Differential Drive Mobile robot using as input the readings of the wheel encoders ($u_k = [n_L \ n_R]^T$).

Parameters

- **xk_1** – previous robot pose estimate ($x_{k-1} = [x_{k-1}\ y_{k-1}\ \psi_{k-1}]^T$)

- **uk** – input vector ($u_k = [u_k\ v_k\ r_k]^T$)

Return xk

current robot pose estimate ($x_k = [x_k\ y_k\ \psi_k]^T$)

`GetInput()`

Get the input for the motion model. In this case, the input is the readings from both wheel encoders.

Returns

uk: input vector ($u_k = [n_L\ n_R]^T$)

INDICES AND TABLES

- genindex
- modindex
- search