

Basic Parameters 1:

robot trajectory: **a_clock** (starting from upper left corner(0, 0) and goes clockwise)

map landmarks: **a_map** (randomly generated, used in the paper)

range of observation: double r_obs = 2;

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(0.0, 0.0, 0.0) priorNoise = Sigmas(0.2, 0.2, 0.01) // 20cm x, y, 0.01 rad bearing
- measurement measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range

example1.pdf:

-- only measurement factors, no map factors

Blue ellipses are estimated landmark uncertainty

example2.pdf:

-- only measurement factors, no map factors, **smaller prior of posex0**

pose(x0) prior(0.0, 0.0, 0.0) priorNoise = Sigmas(0.02, 0.02, 0.01) // 2cm x, y, 0.01 rad bearing

Blue ellipses are estimated landmark uncertainty

example3.pdf:

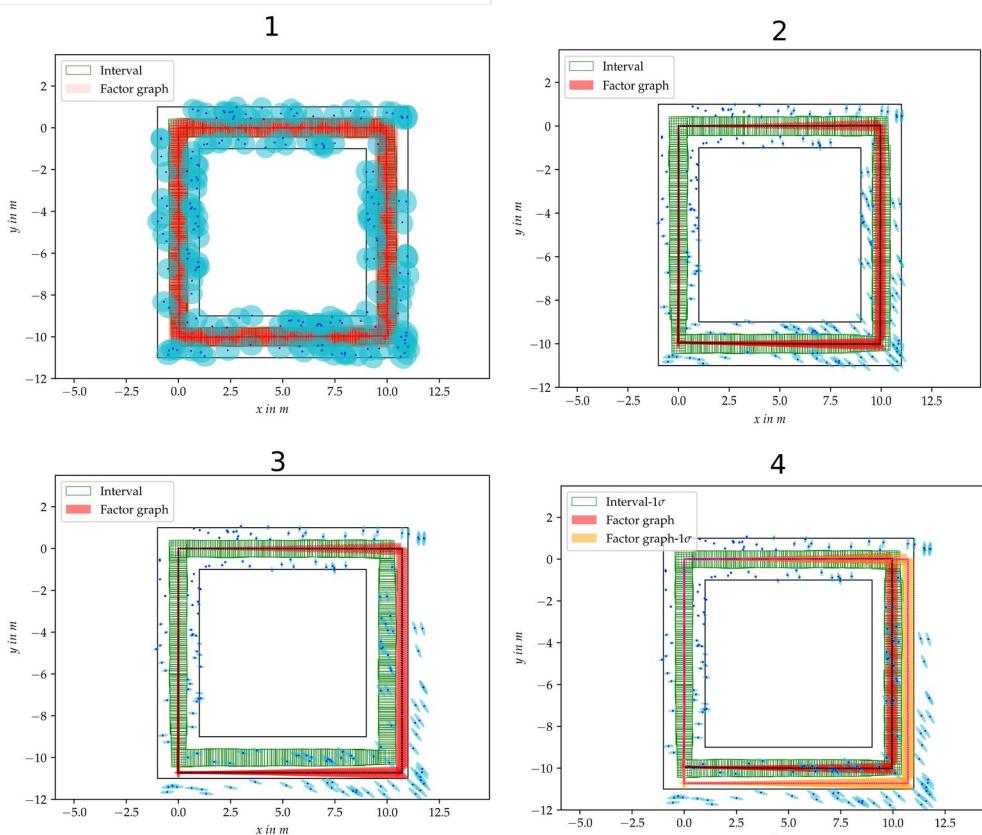
-- only measurement factors with systematic error(range + 1sigma), no map factors, smaller prior of posex0

Blue ellipses are estimated landmark uncertainty

example4.pdf:

-- comparison of example 2 and 3

Blue ellipses are estimated landmark uncertainty for Factor graph-1sigma



Basic Parameters 2: (change map landmarks)

robot trajectory: **a_clock** (starting from upper left corner(0, 0) and goes clockwise)

map landmarks: **b_map**(comparison group, also randomly generated)

range of observation: double r_obs = 2;

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(0.0, 0.0, 0.0) priorNoise = Sigmas(0.02, 0.02, 0.01) // 2cm x, y, 0.01 rad bearing
- measurement measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range

Results very similar to those in Basic Parameters 1, which implies little influence of the distribution of landmarks in the same geometry(square corridor)

example5.pdf:

-- only measurement factors, no map factors

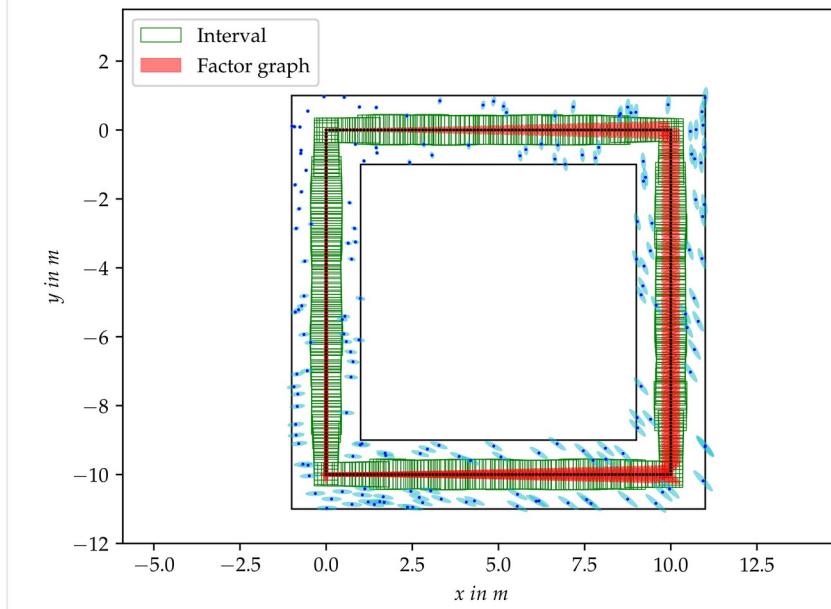
example6.pdf:

-- only measurement factors with systematic error(range + 1sigma), no map factors

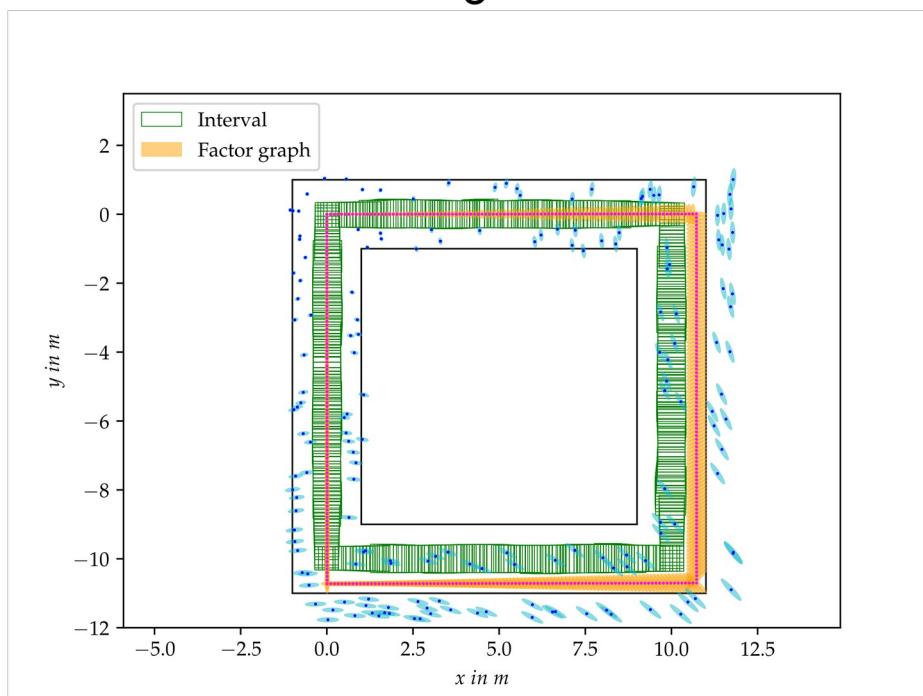
example7.pdf:

-- comparison of example 5 and 6

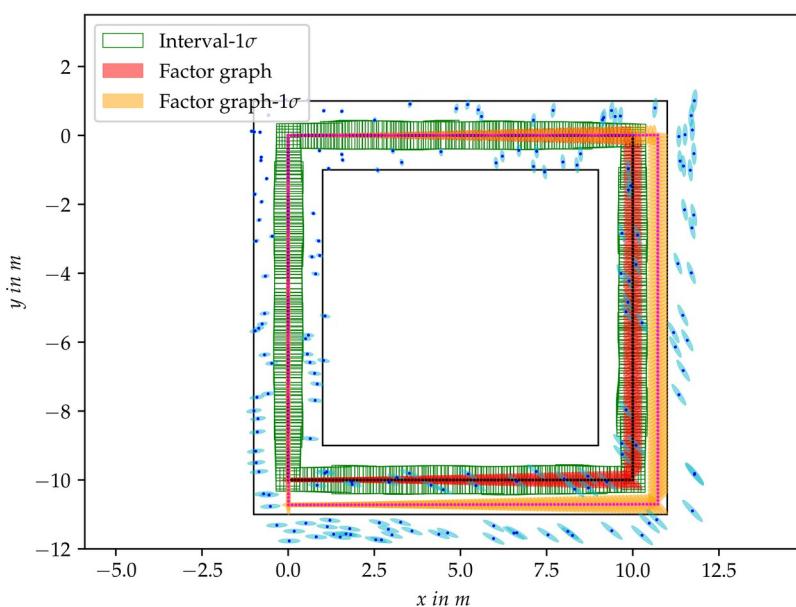
5



6



7



Basic Parameters 3: (change observation range)

robot trajectory: **a_clock** (starting from upper left corner(0, 0) and goes clockwise)

map landmarks: **b_map**

range of observation: **double r_obs = 15;**

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(0.0, 0.0, 0.0) priorNoise = Sigmas(0.02, 0.02, 0.01) // 2cm x, y, 0.01 rad bearing
- measurement measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range

example8.pdf: (x5.txt lm5.txt cov_x5.txt cov_lm5.txt box5.txt)

-- only measurement factors, no map factors

example9.pdf: (x6.txt lm6.txt cov_x6.txt cov_lm6.txt box6.txt)

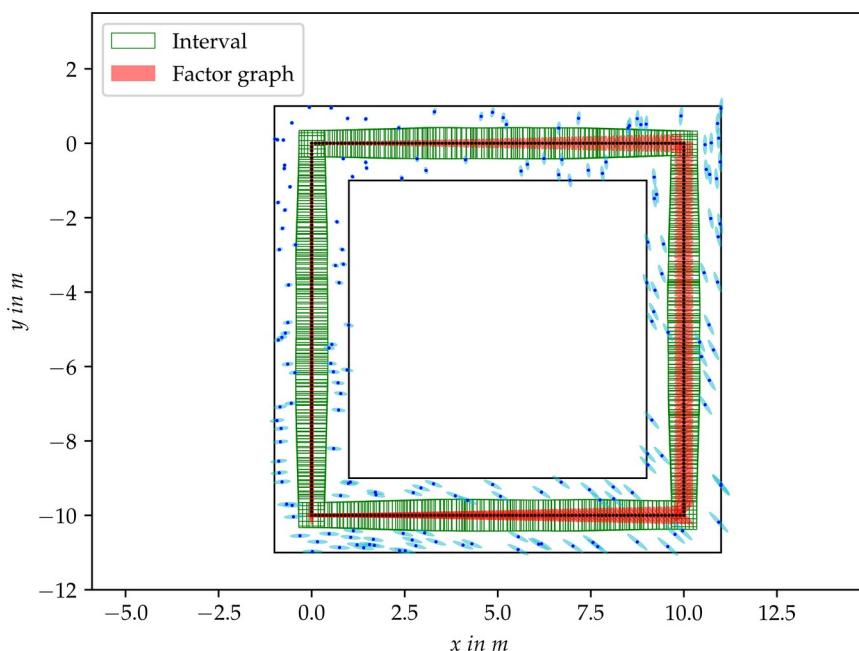
-- only measurement factors with systematic error(range + 1sigma), no map factors

example10.pdf:(x5.txt lm5.txt cov_x5.txt cov_lm5.txt x6.txt lm6.txt cov_x6.txt cov_lm6.txt box6.txt)

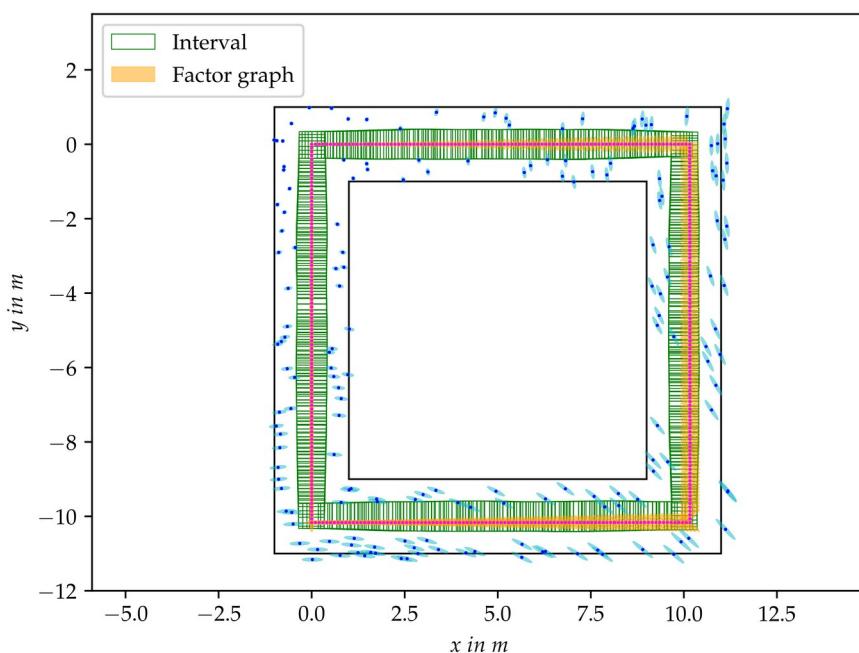
-- comparison of example 8 and 9

Results implies that more measurements would reduce the final deviation of pose estimation under influence of systematic error.

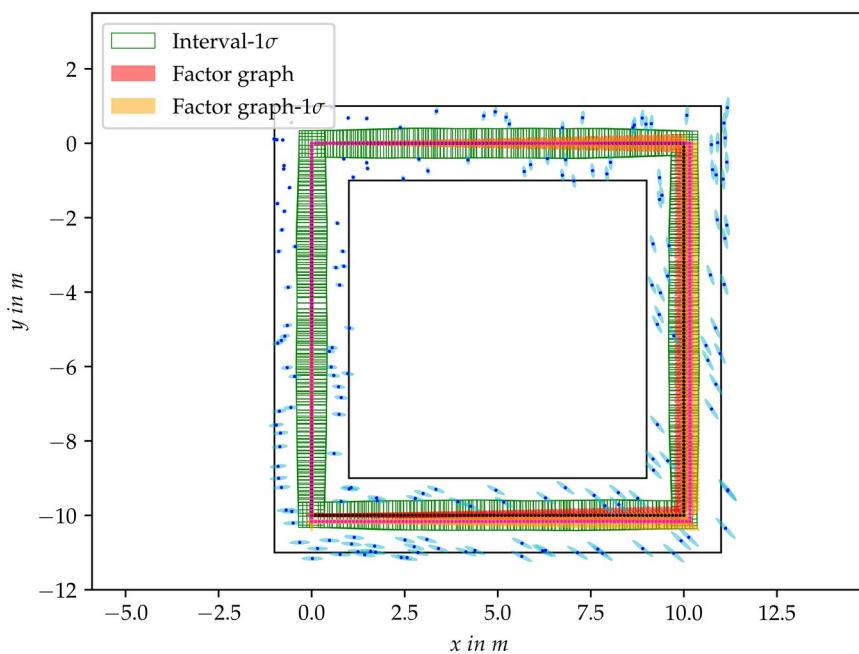
8



9



10



Basic Parameters 4: (change the running direction of robot)

robot trajectory: scenario1 **a_counterclock** (starting from upper left corner(0, 0) and goes counter-clockwise)

map landmarks: b_map

range of observation: double r_obs = 2;

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(0.0, 0.0, -M_PI_2) priorNoise = Sigmas(0.02, 0.02, 0.01) // 2cm x, y, 0.01 rad bearing
- measurement measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range

example11.pdf: (x7.txt lm7.txt cov_x7.txt cov_lm7.txt box7.txt)

-- only measurement factors, no map factors

example12.pdf: (x8.txt lm8.txt cov_x8.txt cov_lm8.txt box8.txt)

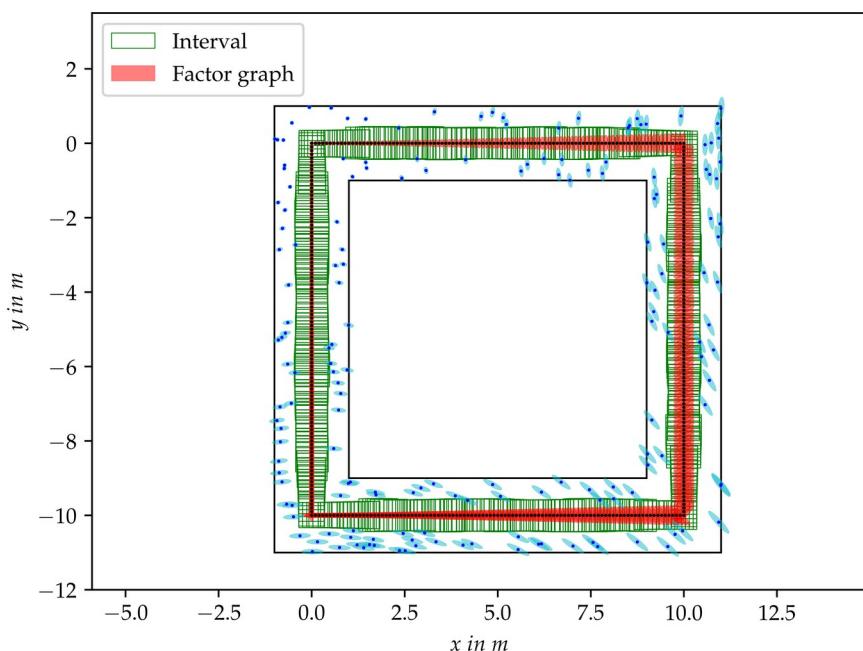
-- only measurement factors with systematic error(range + 1sigma), no map factors

example13.pdf:(x7.txt lm7.txt cov_x7.txt cov_lm7.txt x8.txt lm8.txt cov_x8.txt cov_lm8.txt box8.txt)

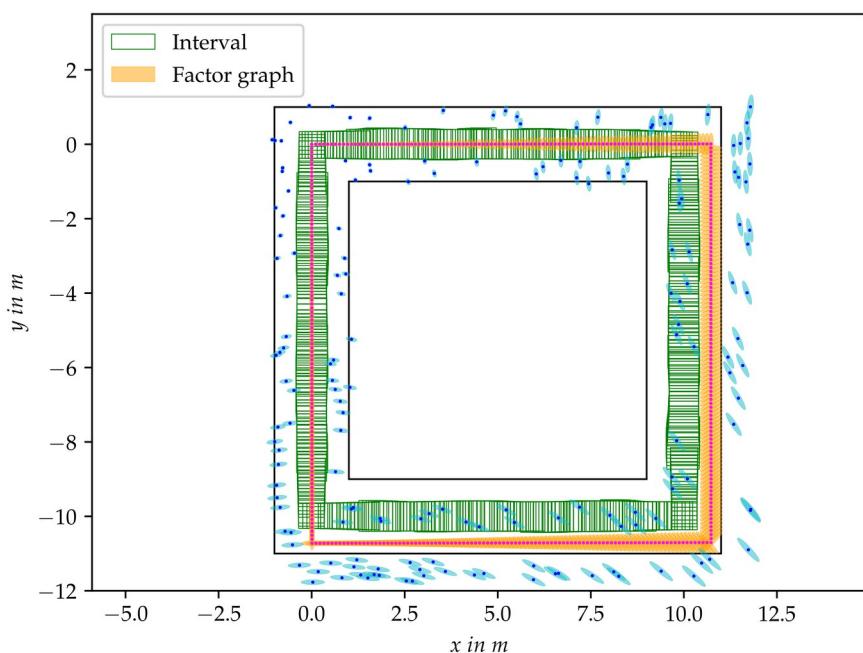
-- comparison of example 11 and 12

The only difference with Basic Parameters 2 is the opposite running direction of robot, no influence on resulting pose uncertainty ellipses. This is obvious since the measurements are the same at each pose and the graph optimizes all measurements in one go.

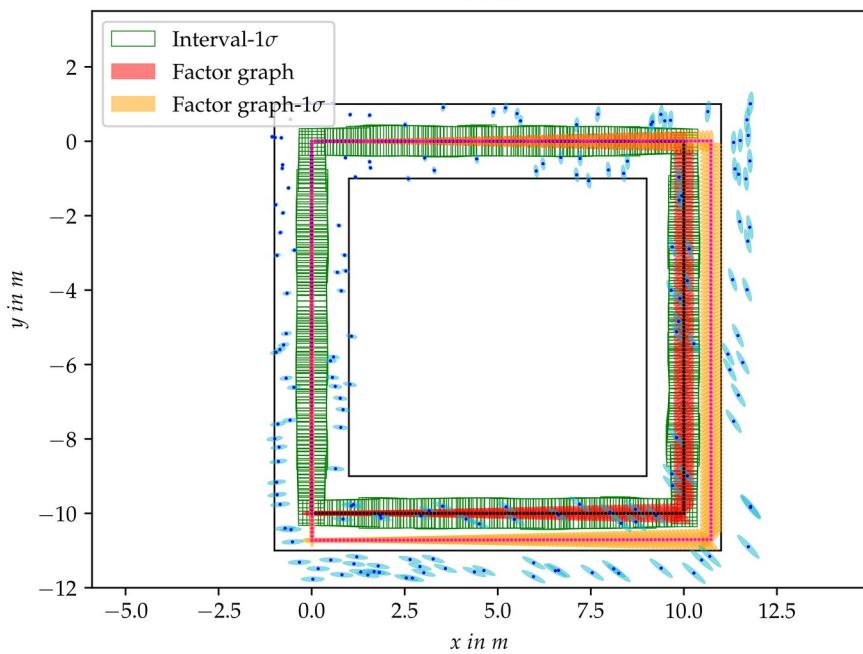
11



12



13



Basic Parameters 5: (change starting location of robot)

robot trajectory: scenario2 **b_clock** (starting from upper right corner(10, 0) and goes clockwise)

map landmarks: **b_map**

range of observation: double **r_obs** = 2;

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(10.0, 0.0, -M_PI_2) priorNoise = Sigmas(0.02, 0.02, 0.01) // 2cm x, y, 0.01 rad bearing
- measurement measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range

example14.pdf: (x9.txt lm9.txt cov_x9.txt cov_lm9.txt box9.txt)

-- only measurement factors, no map factors

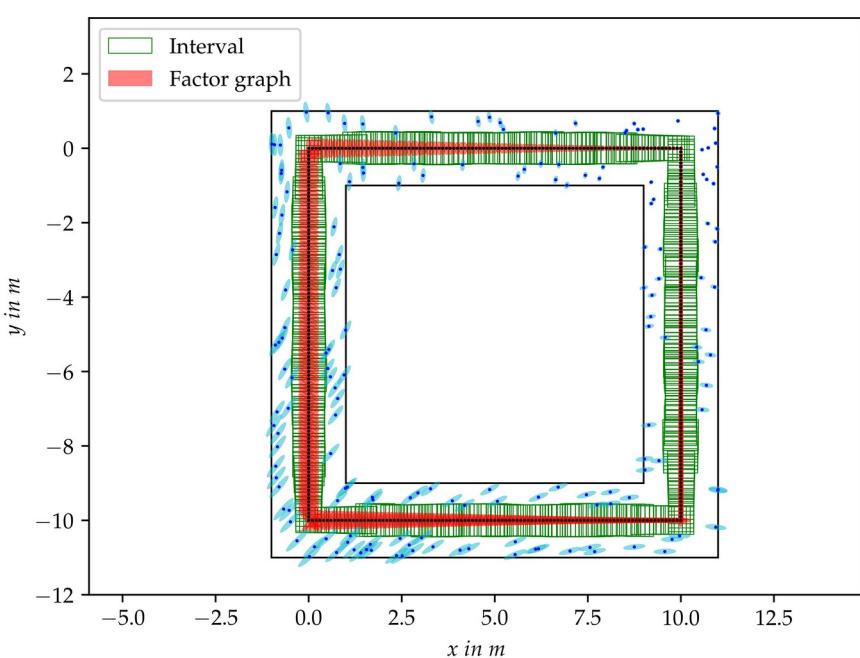
example15.pdf: (x10.txt lm10.txt cov_x10.txt cov_lm10.txt box10.txt)

-- only measurement factors with systematic error(range + 1sigma), no map factors

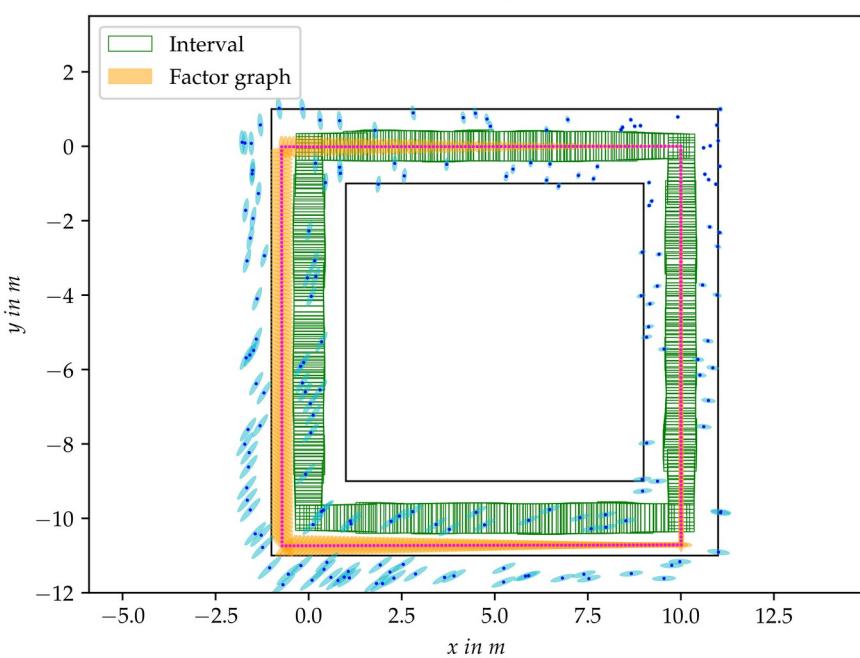
example16.pdf:(x9.txt lm9.txt cov_x9.txt cov_lm9.txt x10.txt lm10.txt cov_x10.txt cov_lm10.txt box10.txt)

-- comparison of example 14 and 15

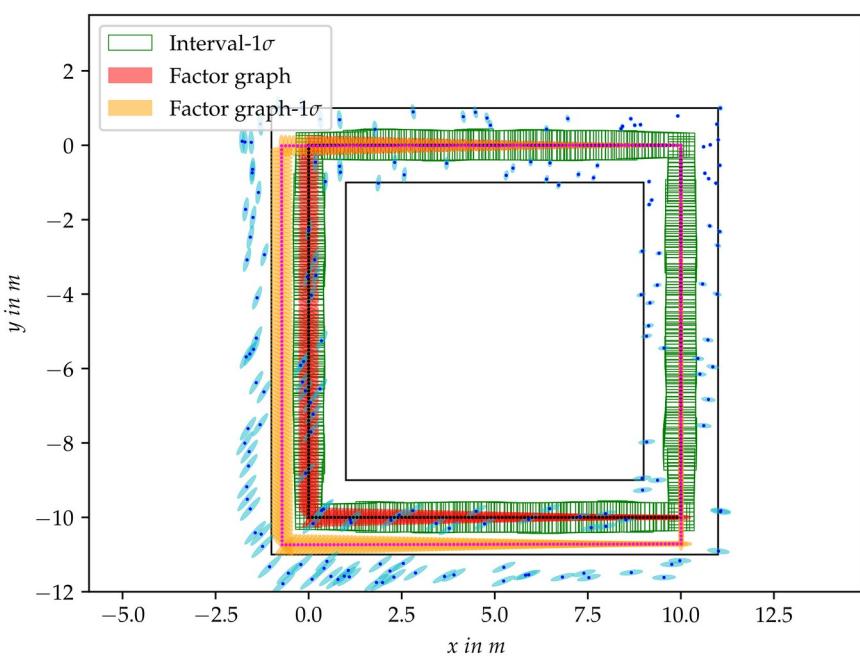
14



15



16



Basic Parameters 6: (change starting location of robot)

robot trajectory: scenario3 **c_clock** (starting from bottom right corner(10, -10) and goes clockwise)

map landmarks: b_map

range of observation: double r_obs = 2;

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(10.0, -10.0, -M_PI) priorNoise = Sigmas(0.02, 0.02, 0.01) // 2cm x, y, 0.01 rad bearing
- measurement measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range

example17.pdf: (x11.txt lm11.txt cov_x11.txt cov_lm11.txt box11.txt)

-- only measurement factors, no map factors

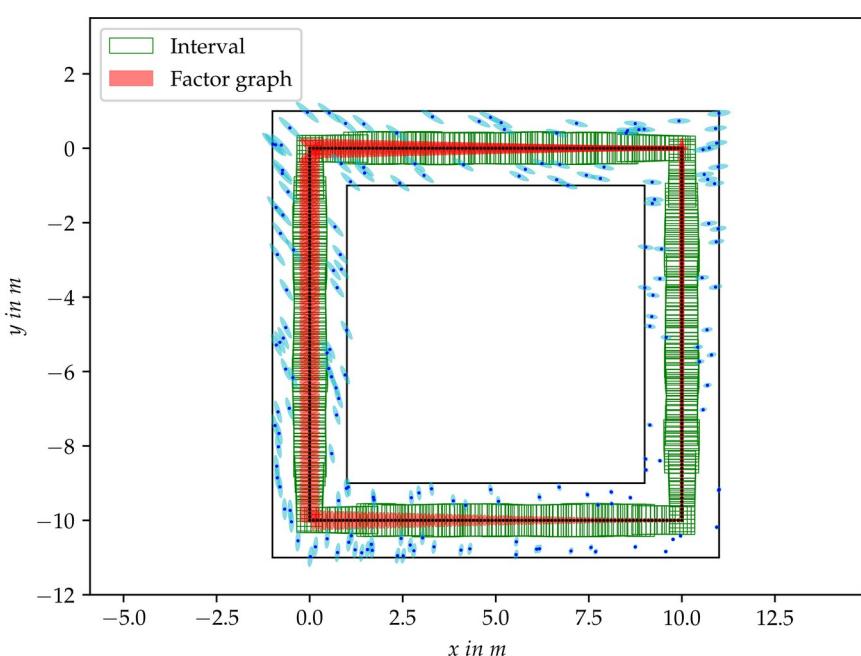
example18.pdf: (x12.txt lm12.txt cov_x12.txt cov_lm12.txt box12.txt)

-- only measurement factors with systematic error(range + 1sigma), no map factors

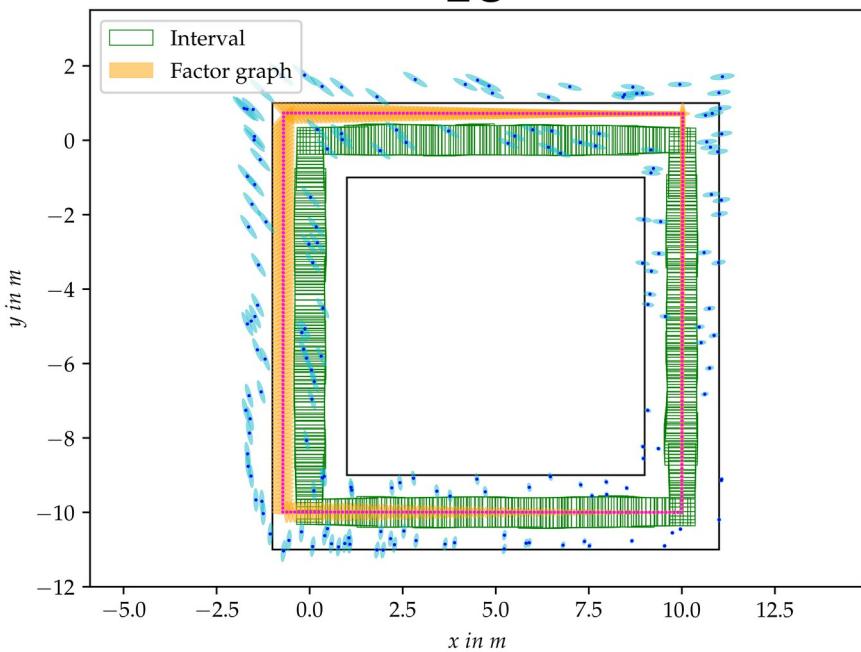
example19.pdf:(x11.txt lm11.txt cov_x11.txt cov_lm11.txt x12.txt lm12.txt cov_x12.txt cov_lm12.txt box12.txt)

-- comparison of example 17 and 18

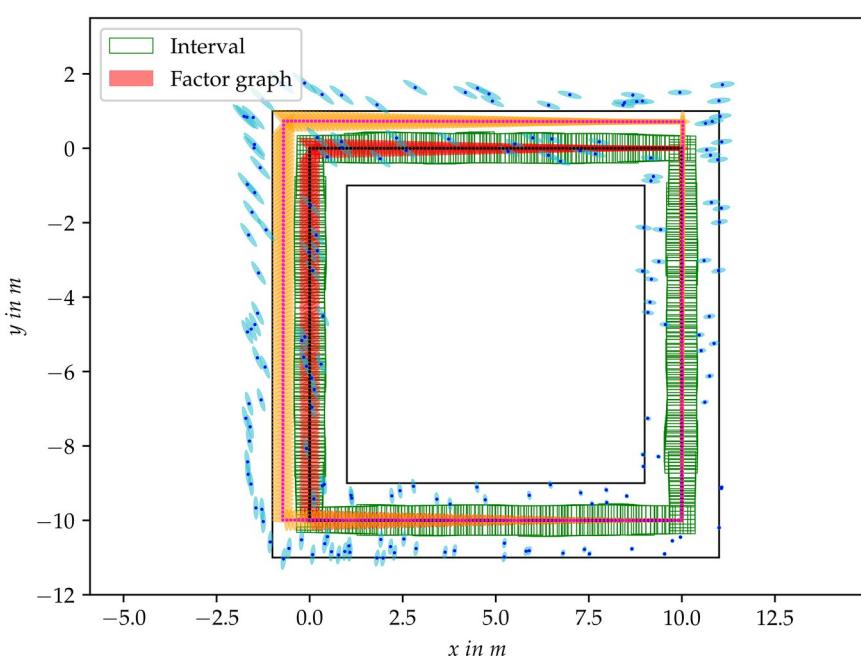
17



18



19



Basic Parameters 7: (change starting location of robot)

robot trajectory: scenario4 **d_clock** (starting from bottom left corner(0, -10) and goes clockwise)

map landmarks: **b_map**

range of observation: double **r_obs** = 2;

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(0.0, -10.0, M_PI_2) priorNoise = Sigmas(0.02, 0.02, 0.01) // 2cm x, y, 0.01 rad bearing
- measurement measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range

example20.pdf: (x13.txt lm13.txt cov_x13.txt cov_lm13.txt box13.txt)

-- only measurement factors, no map factors

example21.pdf: (x14.txt lm14.txt cov_x14.txt cov_lm14.txt box14.txt)

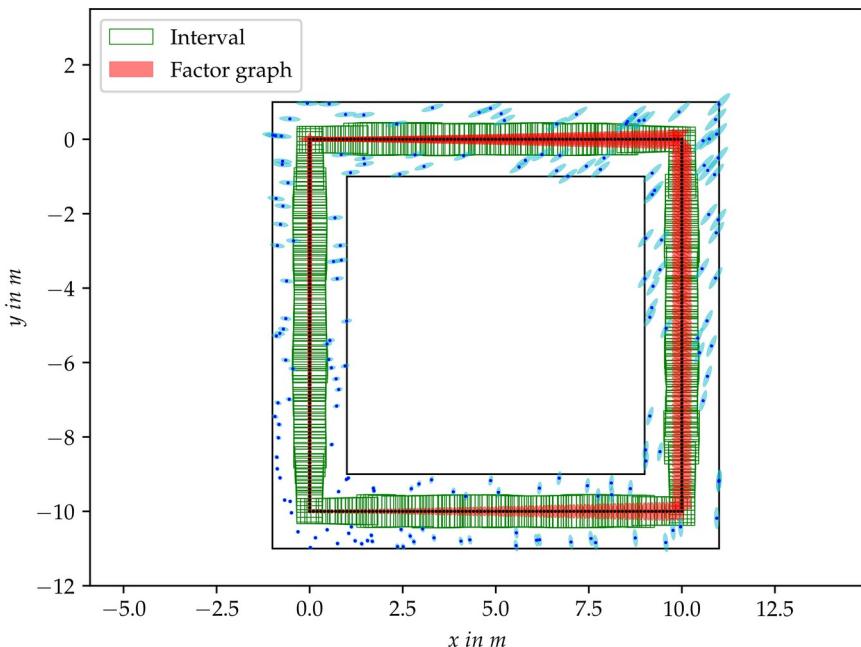
-- only measurement factors with systematic error(range + 1sigma), no map factors

example22.pdf:(x13.txt lm13.txt cov_x13.txt cov_lm13.txt x14.txt lm14.txt cov_x14.txt

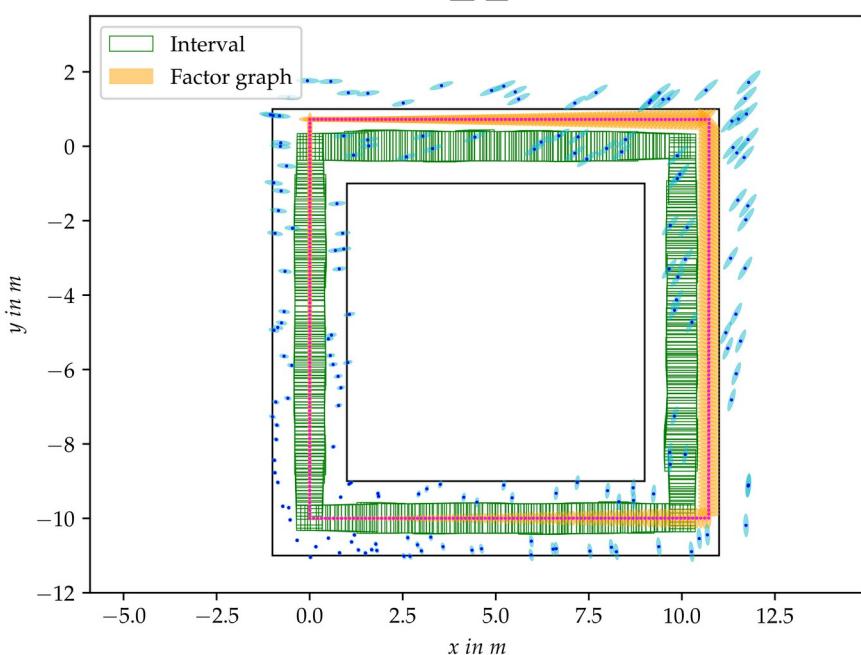
cov_lm14.txt box14.txt)

-- comparison of example 21 and 22

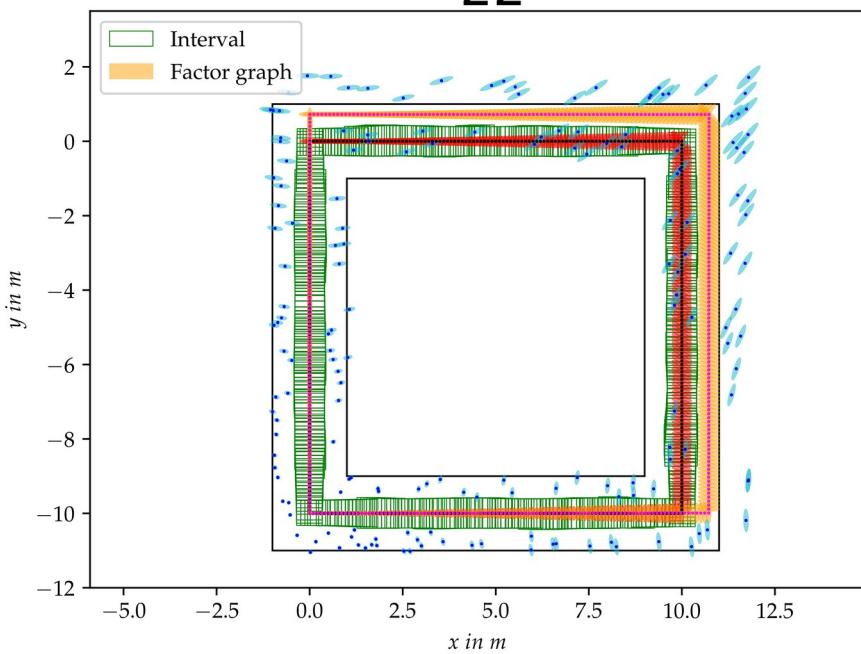
20



21



22



Basic Parameters 8: (rotate the whole scene by 45 degrees)

robot trajectory: **a_clock45** starting from upper left corner(0, 0) and goes clockwise

map landmarks: **c_map** (map has to be generated again randomly)

range of observation: double r_obs = 3;

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(0.0, 0.0, 0.0) priorNoise = Sigmas(0.02, 0.02, 0.01) // 20cm x, y, 0.01 rad bearing
- measurement measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range

example23.pdf: (x.txt lm.txt cov_x.txt cov_lm.txt box1.txt)

-- only measurement factors, no map factors

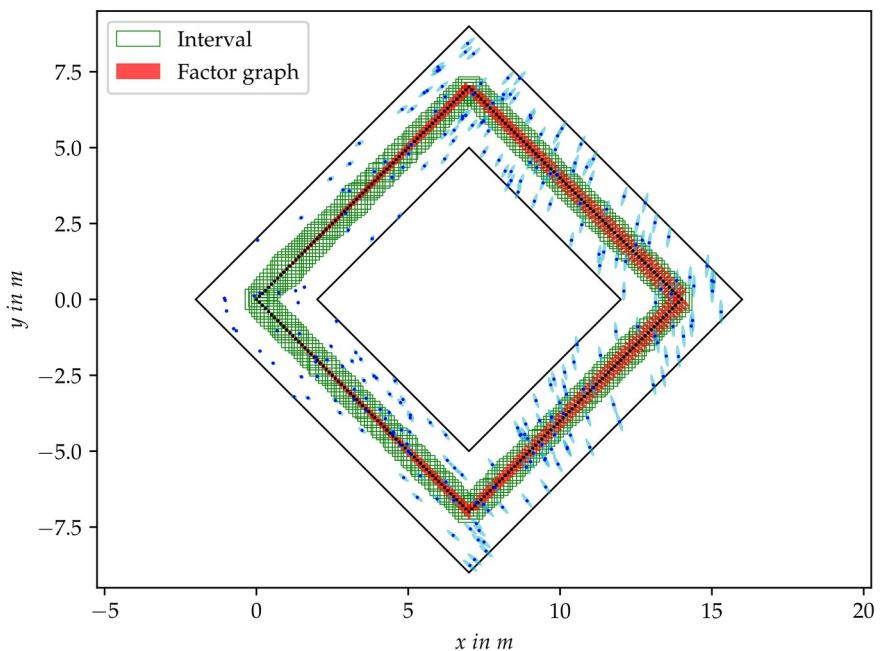
example24.pdf: (x1.txt lm1.txt cov_x1.txt cov_lm1.txt box2.txt)

-- only measurement factors with systematic error(range + 1sigma), no map factors

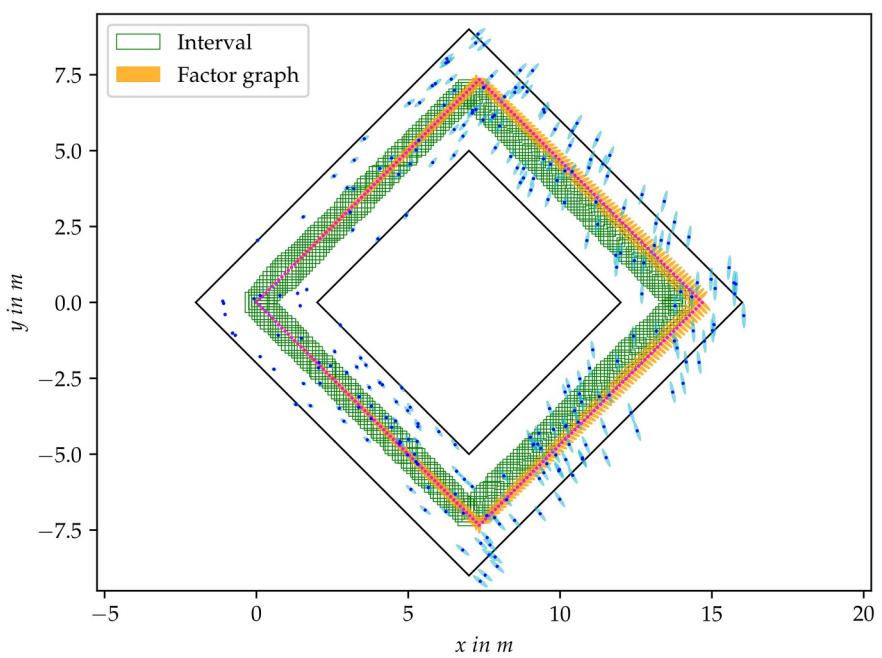
example25.pdf:(x1.txt lm1.txt cov_x1.txt cov_lm1.txt x2.txt lm2.txt cov_x2.txt cov_lm2.txt box2.txt)

-- comparison of example 23 and 24

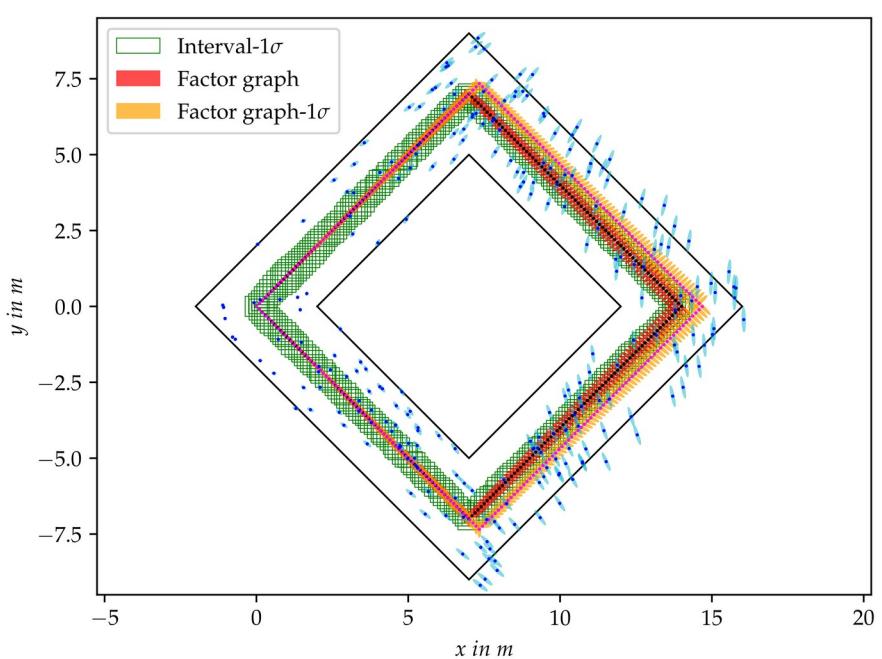
23



24



25



Basic Parameters 9: (add map factors)

robot trajectory: **a_clock** (starting from upper left corner(0, 0) and goes clockwise)

map landmarks: **b_map**

range of observation: double **r_obs** = 2;

Interval:

- landmark radius = 0.3m (3*sigma)
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- landmark: **m_prior(a_map[k][0], a_map[k][1]) mapNoise = Sigmas(0.1, 0.1) // 10cm x, y**
- pose(**x0**) **prior(0.0, -10.0, M_PI_2)** **priorNoise = Sigmas(0.02, 0.02, 0.01) // 2cm x, y, 0.01 rad bearing**
- measurement **measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range**

example26:

-- measurement factors, map factors
– comparison with systematic error(range + 1sigma)

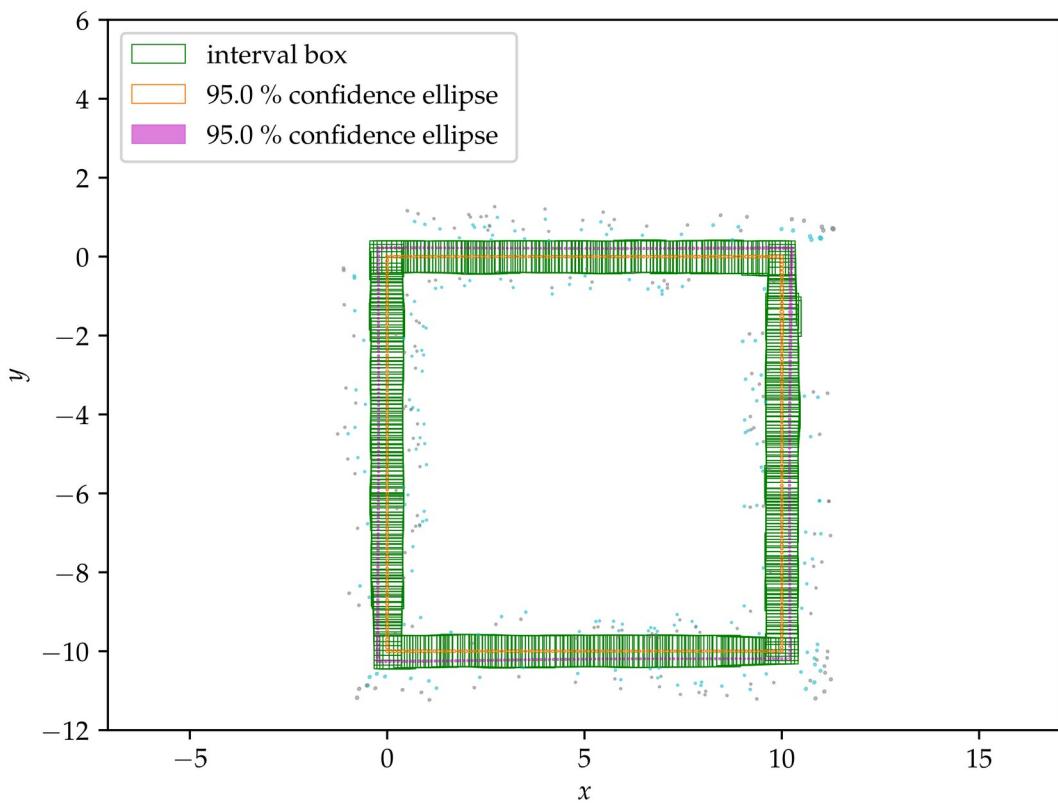
Blue ellipses are estimated landmark uncertainty without 1sigma error

Grey ellipses are estimated landmark uncertainty with 1sigma error

example27.pdf:

-- measurement factors, map factors
– comparison with systematic error(range + 2sigma)
Blue ellipses are estimated landmark uncertainty without 1sigma error
Grey ellipses are estimated landmark uncertainty with 1sigma error

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27

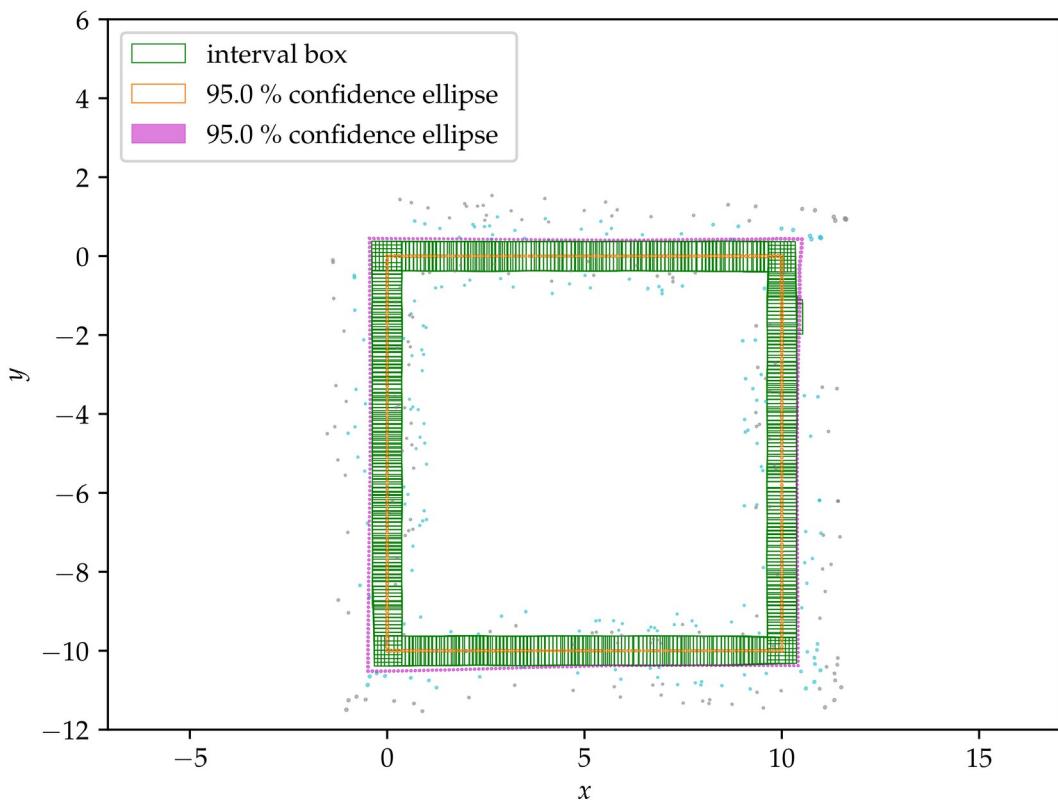


Figure 26, 27 shows that while the poses deviate in presence of systematic errors, the estimation of landmarks positions also deviate greatly.

However, give the map factor (assumes that the map should be almost fixed with small uncertainty), the estimated landmark position should not deviate so much.

Therefore the possible reason why the trajectory is pushed outward could be **that the map landmarks' uncertainty(the mapNoise, standard deviation of map factor) is set too large:**
`mapNoise = Sigmas(0.1, 0.1) // 10cm x, y`

Also the deviation of landmark estimation in experiments in **Basic Parameters 1-9** are also explainable because the measurement uncertainty in measurement factor are large:

`measurementNoise = Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range`

Basic Parameters 10: (reduce the map landmark uncertainty)

robot trajectory: a_clock (starting from upper left corner(0, 0) and goes clockwise)

map landmarks: b_map

range of observation: double r_obs = 5;

Interval:

- **landmark radius = 0.03m (3*sigma)**
- no prior on poses
- measurement range radius= 0.3m (3*sigma) , bearing radius= 0.03 rad (3*sigma)

Factor graph:

- no prior on landmarks
- pose(x0) prior(0.0, 0.0, 0.0) priorNoise = `Sigmas(0.2, 0.2, 0.01) // 20cm x, y, 0.01 rad bearing`
- measurement measurementNoise = `Sigmas(0.01, 0.1) // 0.01 rad std on bearing, 10cm on range`
map prior: m_prior(b_map[k][0], b_map[k][1]) **mapNoise = Sigmas(0.01, 0.01) // 1cm x, y**

example28.pdf:

-- measurement factors, map factors

- comparison with systematic error(range + 1sigma)

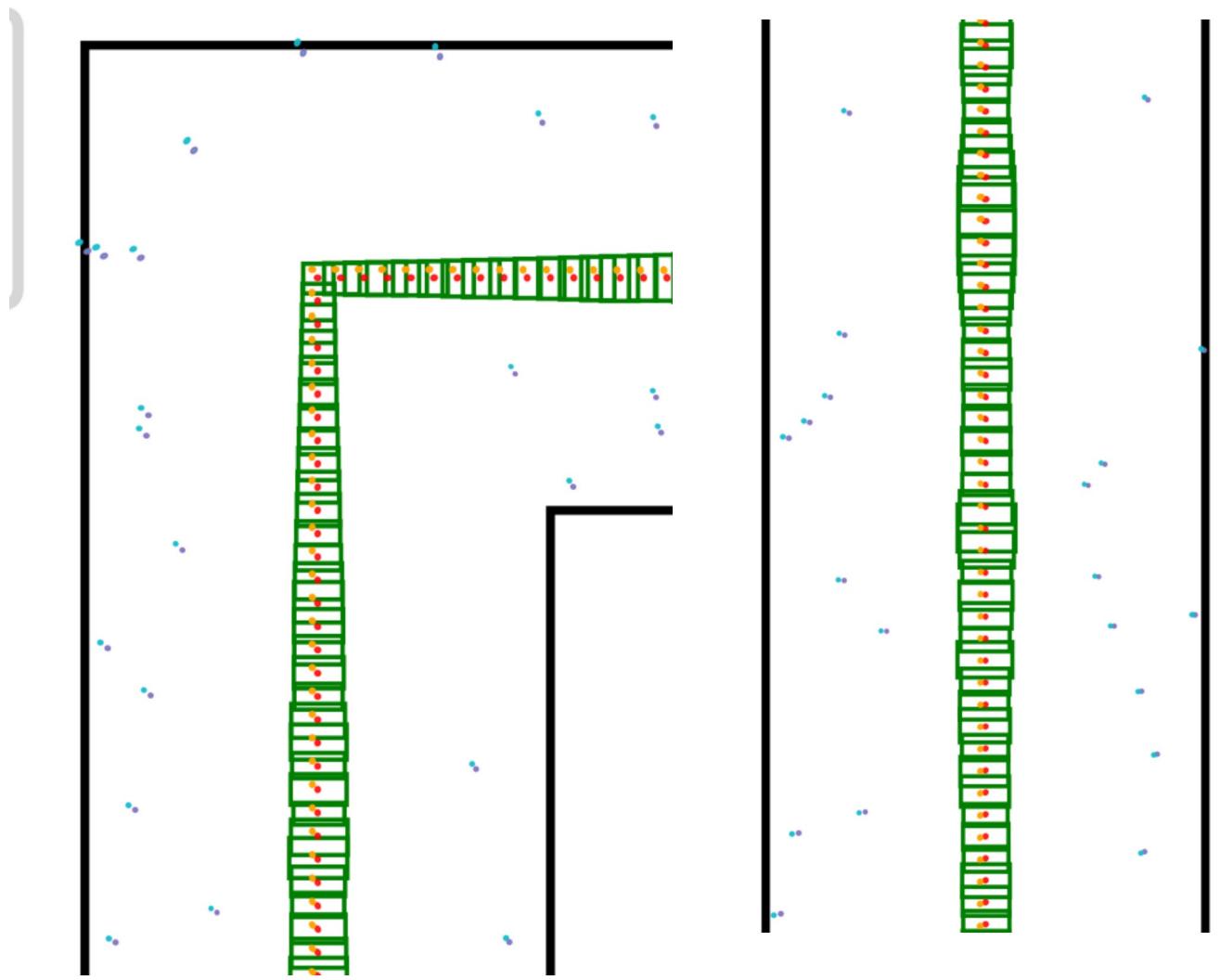
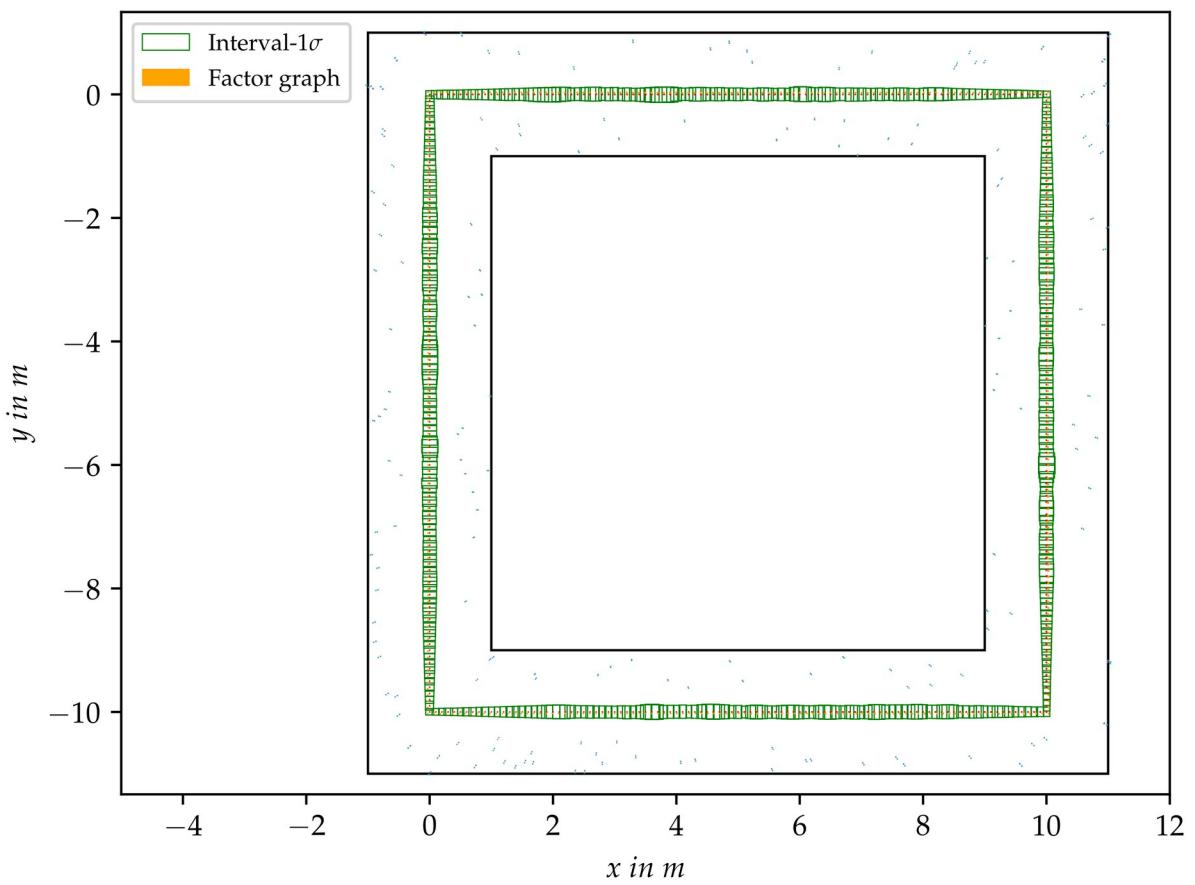
Original measurement : orange ellipse(pose), purple ellipse(estimated landmarks)

Measurement + 1sigma systematic error: red ellipse(pose), blue ellipse(estimated landmarks)

After reduction of map uncertainty, we see that both pose uncertainties for Interval and Factor graph decrease.

In zoomed-in pic we can see that pose estimation and landmark estimation are deviated less.

Also the deviation of pose estimation in the corner is more obvious than in straight hallway.



example29.pdf:

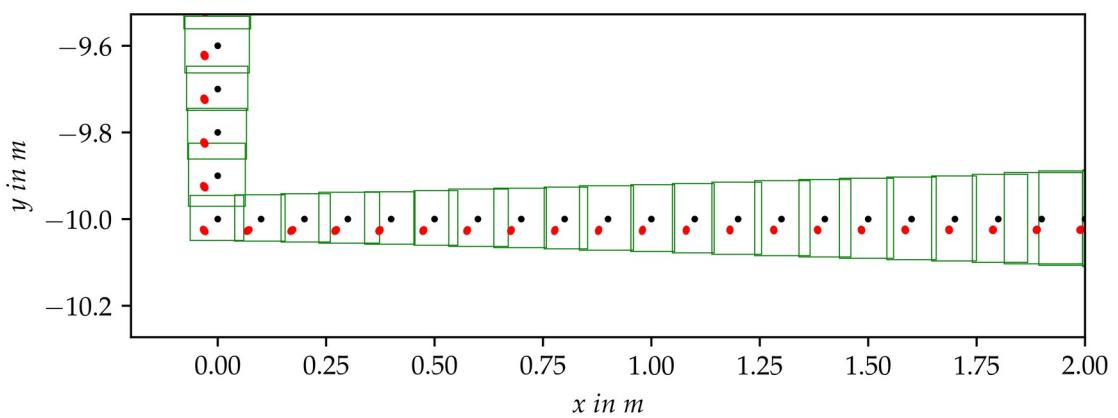
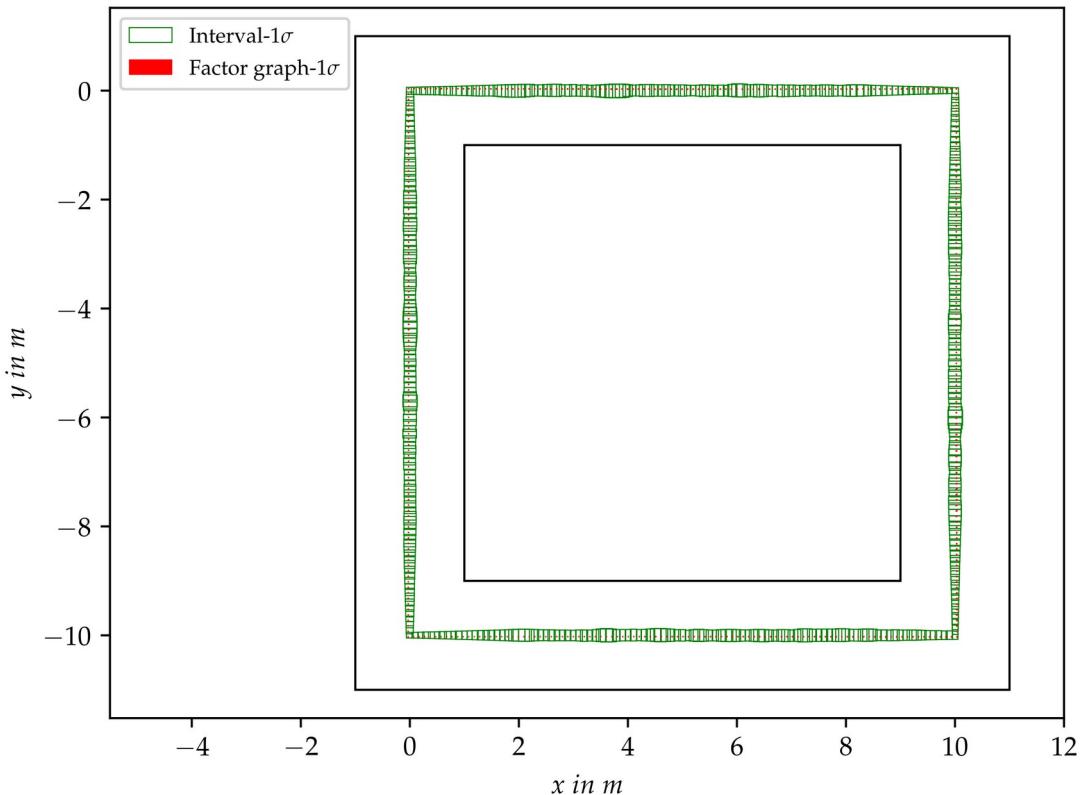
-- measurement factors, map factors

-- measurement systematic error(range + 1sigma)

--ground truth poses compared with pose estimation

Despite small map landmark uncertainty, the pose uncertainty still deviate and can not include the ground truth.

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example30.pdf:

-- measurement factors, map factors
– measurement systematic error(range + 2sigma)
--ground truth poses compared with pose estimation

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