Whole-body sensor fusion for localization, mapping and balance estimation of legged robots

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Journées Nationales de la Robotique Humanoïde

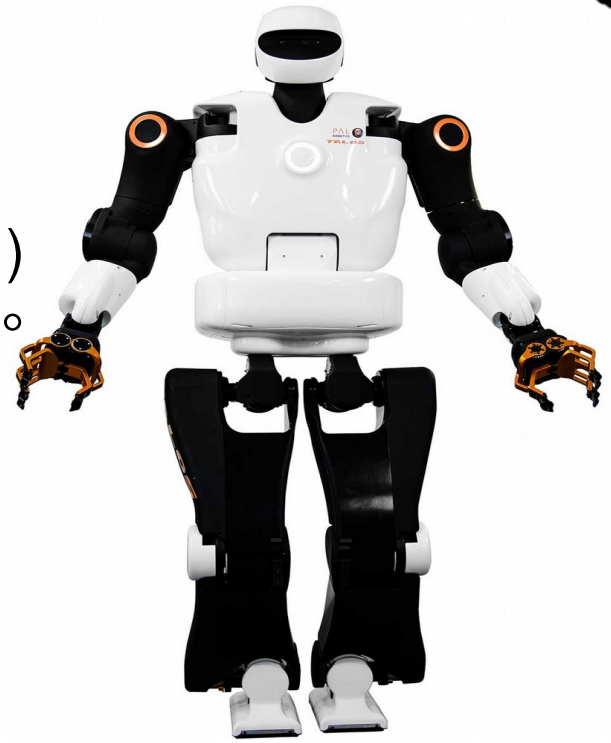
Outline

- Problem statement
- Estimation as trajectory optimisation
- Visual Inertial SLAM
- Whole body estimation

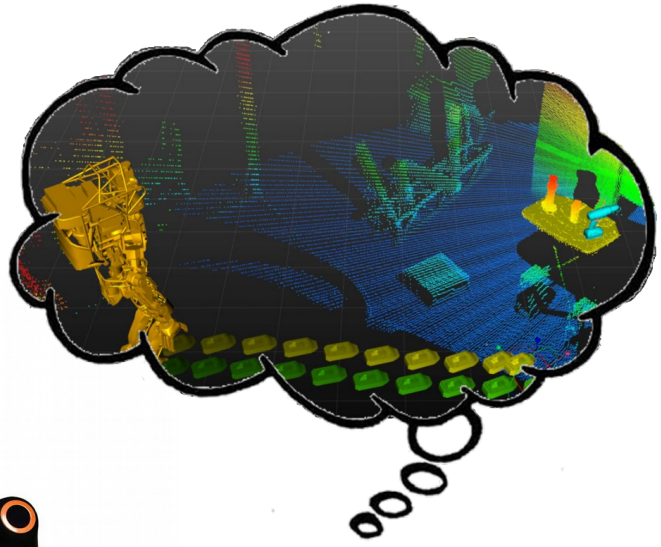
Estimation problem(s)

Balance

- Rich state (P,V,O,CoM…)
- Direction of gravity ~ 0.5°
- Highly dynamic motions
  - Feedback at (1kHz)
  - Low latency



Planning



- Solid surfaces mapped at 1cm accuracy
- Exteroceptive sensors far from contacts
- Plane extraction

Questions

- Which sensor modalities?

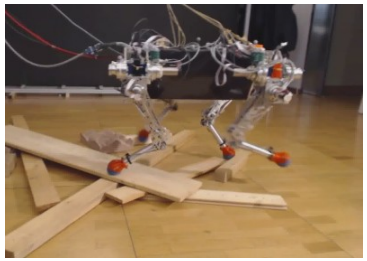


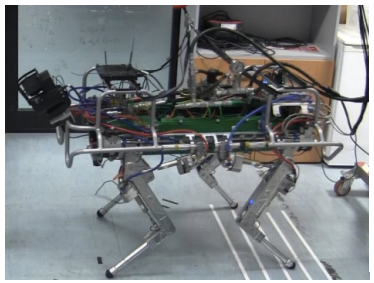

- Tightly vs loosely coupled approach?

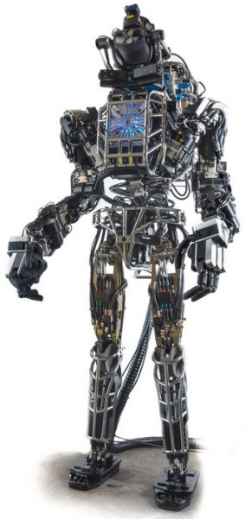
- How to exploit sensor redundancy?

State of the art in legged robot estimation

Filtering







Bloesch et al. 12,13
Rotella et al. 14
Fallon et al. 14
Nobili et al.17
Flayols et al. 17

2010's paradigm:

Process: IMU driven

Update: kinematics

+ sometimes loosely coupled exteroceptive sensors

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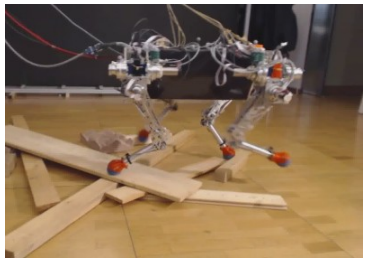

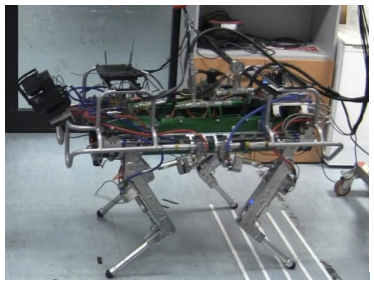

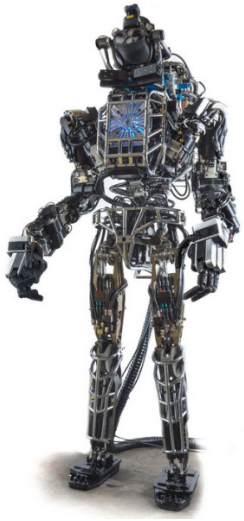

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<u>2010's paradigm:</u>

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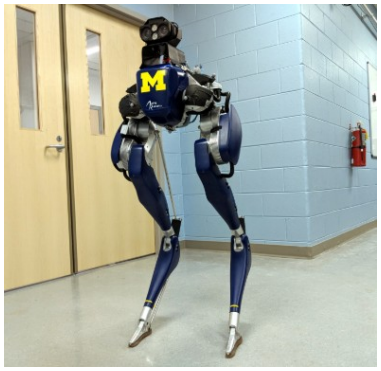
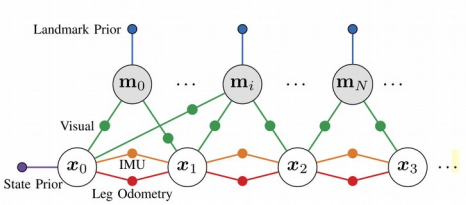
Trajectory optimization



Hartely et al. 18



Wisth et al. 19

<u>Inspired by SLAM community:</u>

Visual Inertial Navigation (VIN) state of the art since ~ 10 years

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SLAM Problem

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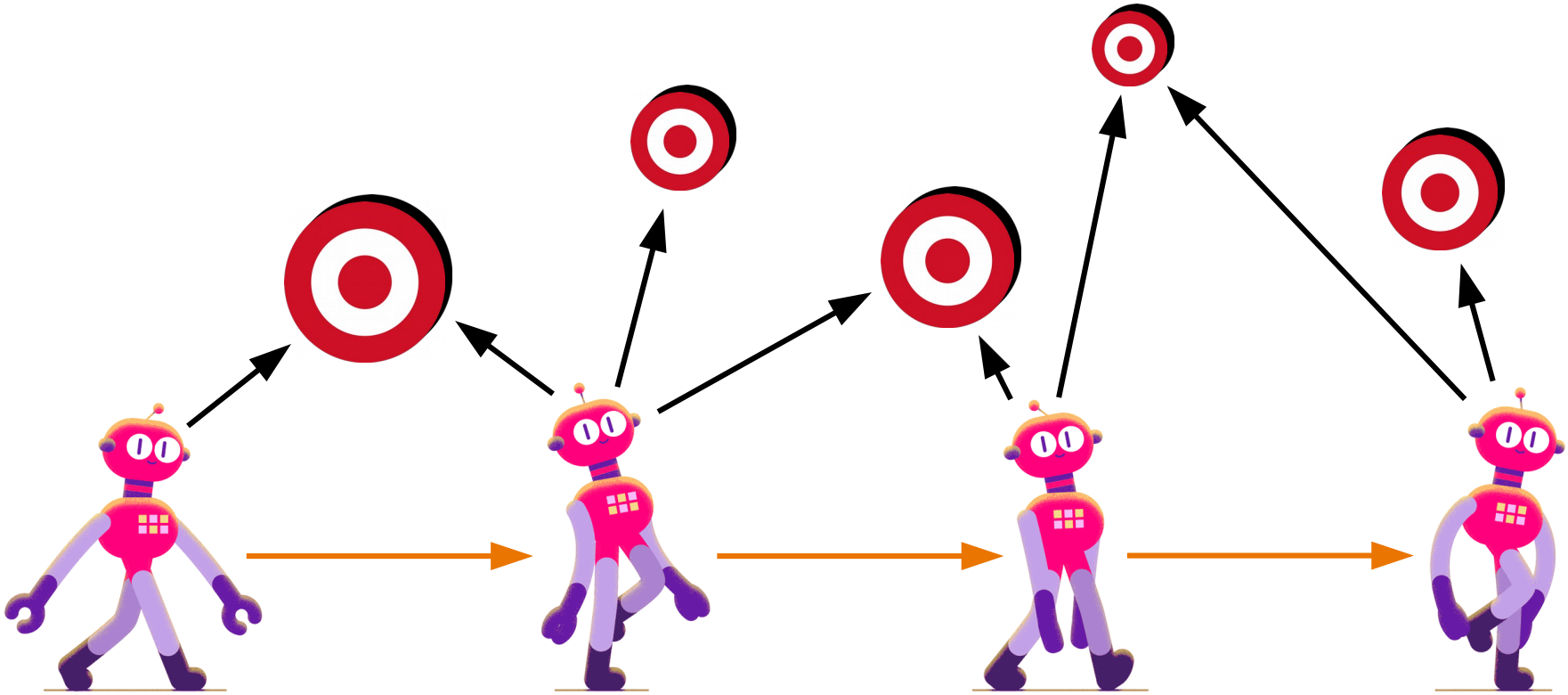
Odometry between **Key Frames** (IMU, kinematics...)

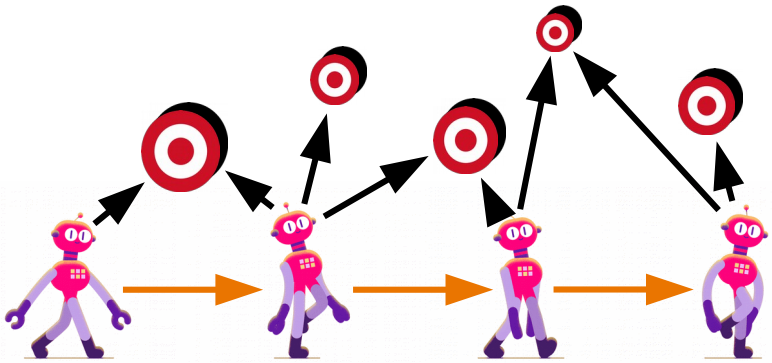
SLAM Problem



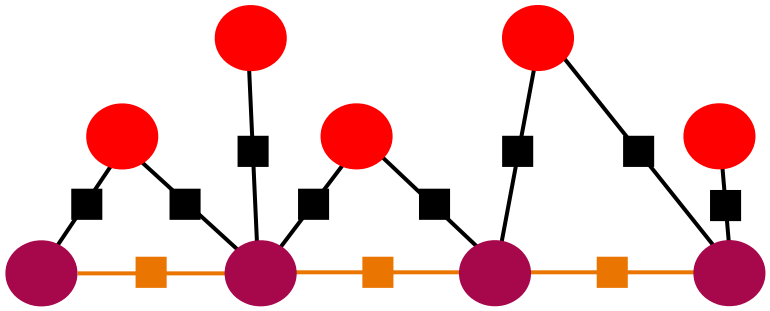
Odometry between **Key Frames** (IMU, kinematics...)

Landmark relative measurements (Camera, LIDAR...)

SLAM Problem



1. Real problem



2. Factor Graph representation

$$x^* = \underset{x}{argmin} \sum_{k}^{n \ factors} e_k(x_i, x_j)^T \Omega_k e_k(x_i, x_j)$$

3. NLLS optimization problem

Incremental, Iterative Non-linear optimization via sparse Cholesky or QR factorizations. (Ceres, GTSAM...)

4. Online solving

IMU factor preintegration

Forster et al. 17

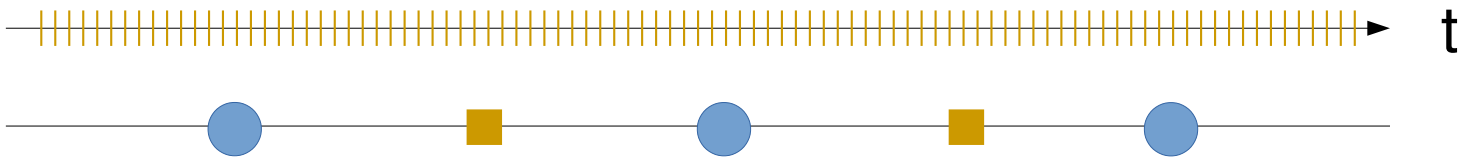
IMU factor preintegration

IMU, 1kHz

Forster et al. 17

IMU factor preintegration

IMU, 1kHz



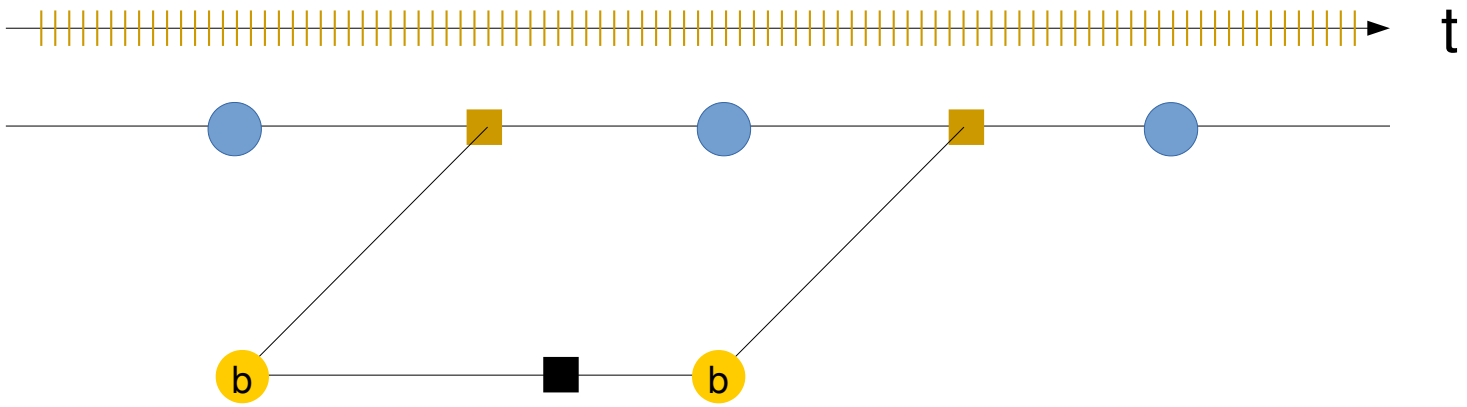
Key frame

IMU factor

Forster et al. 17

IMU factor preintegration

IMU, 1kHz



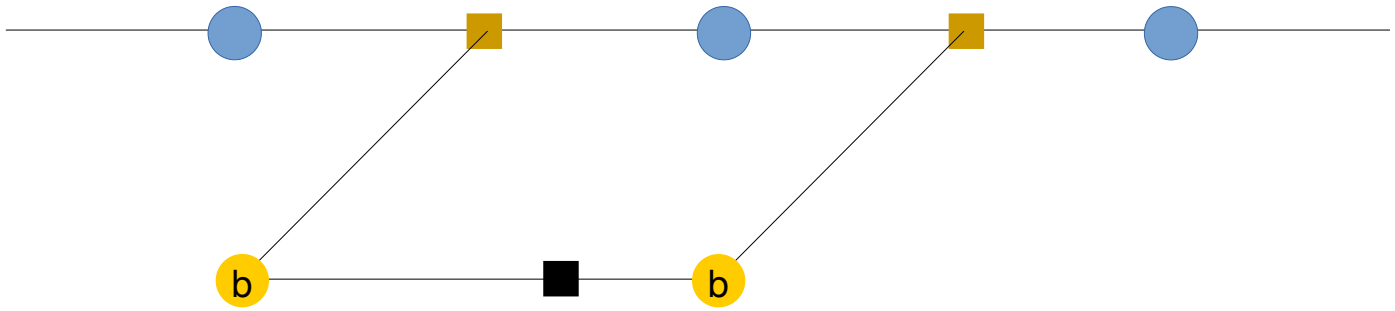
Key frame

IMU factor

b Sensor bias

Forster et al. 17

IMU factor preintegration



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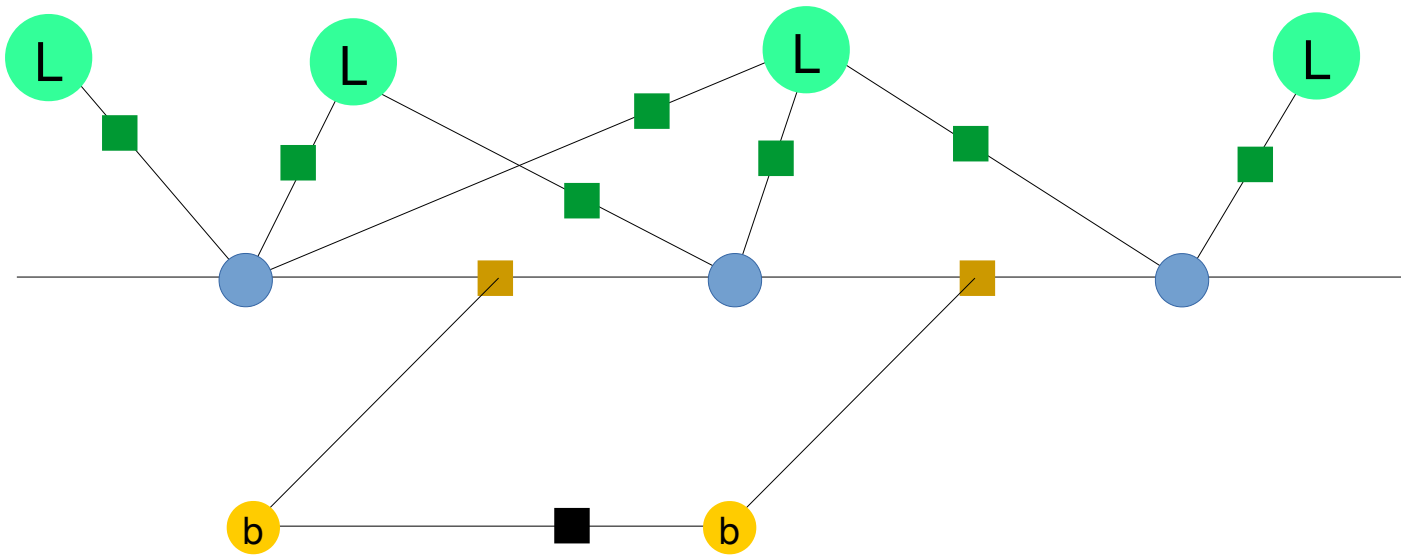


Key frame

Sensor bias

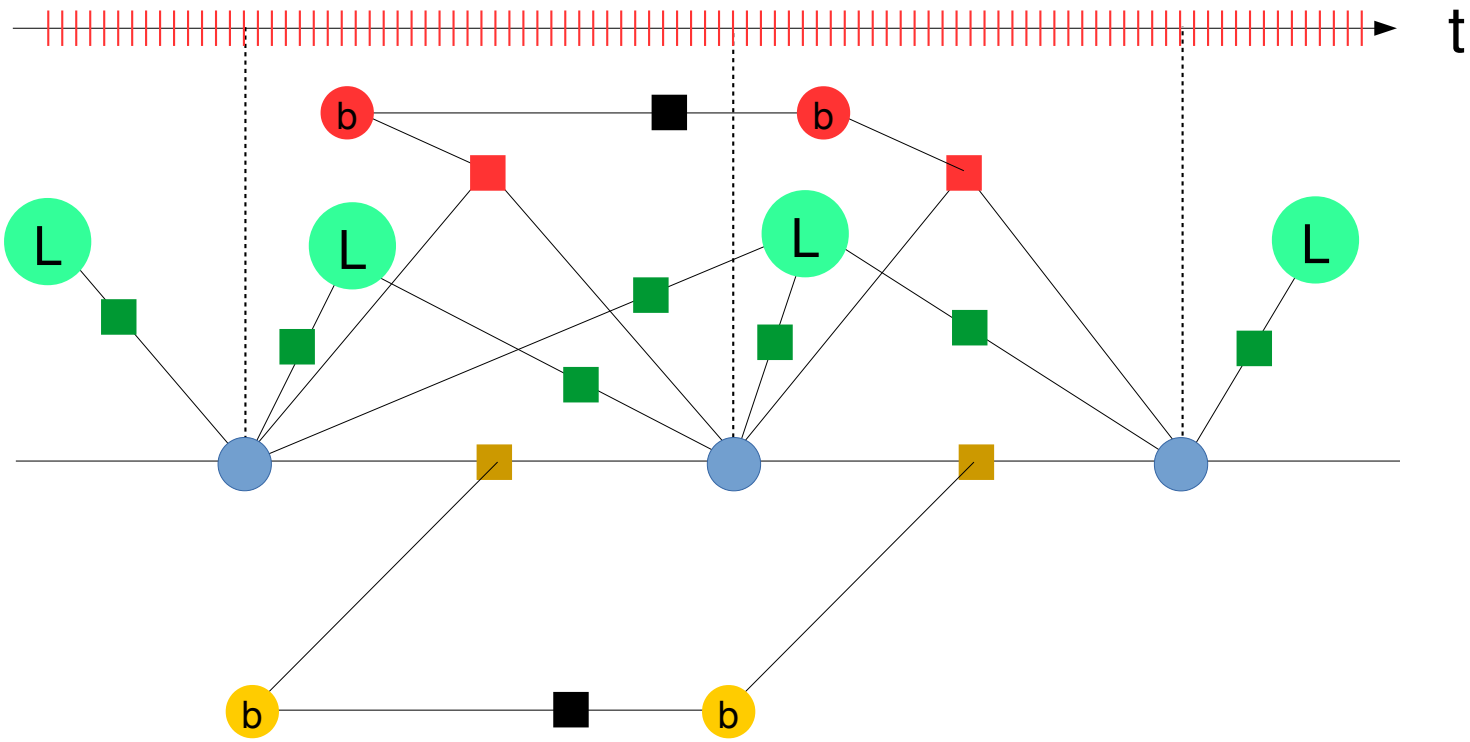
Landmark

IMU factor

Relative KF/L factor

Forster et al. 17

IMU factor preintegration



Key frame

IMU factor

b Sensor bias

Relative KF/L factor

L Landmark

Forster et al. 17

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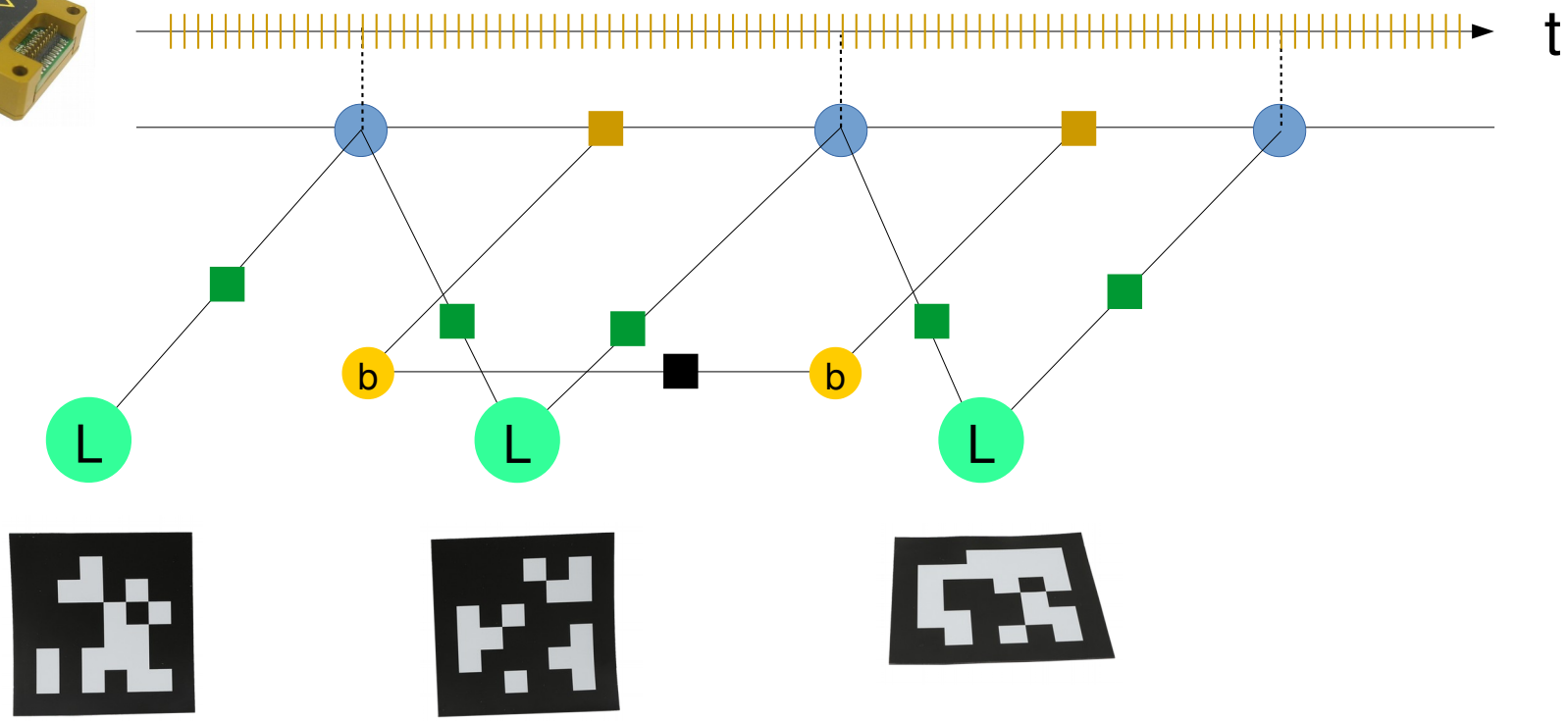
Visual Inertial System : Experimental setup

- IMU (200Hz), RGB (30Hz) hardware synchronized and rigidly linked
- Motion capure ground truth (200Hz)
- ~20 markers in the workspace
- Datasets walking, climbing/descending stairs

Apriltag IMU SLAM



Keyframe, x = [p v q]

Landmark, L = [p q]

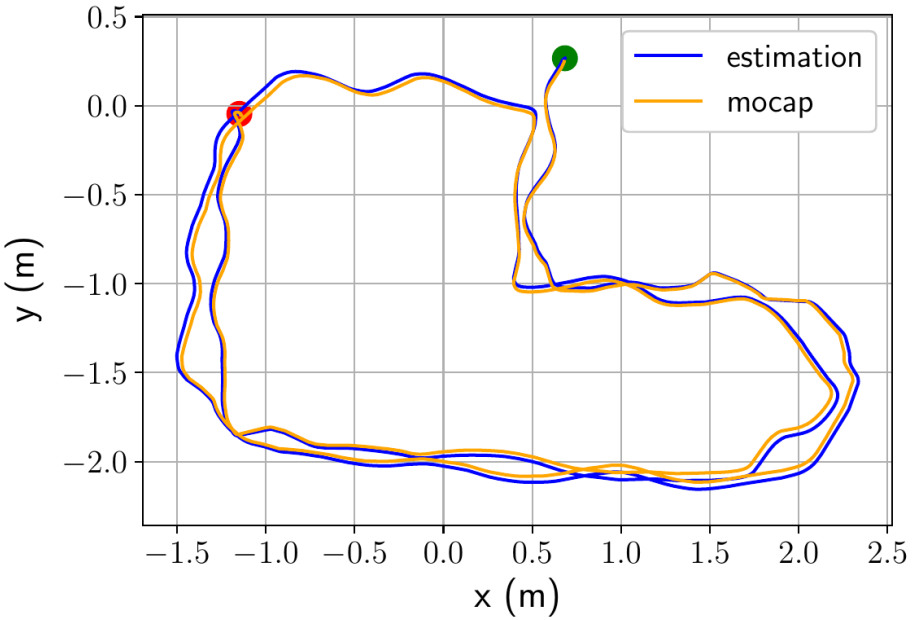
Apriltag factor: e(xi, Lj), se(3)

IMU factor: e(xi, xi+1)

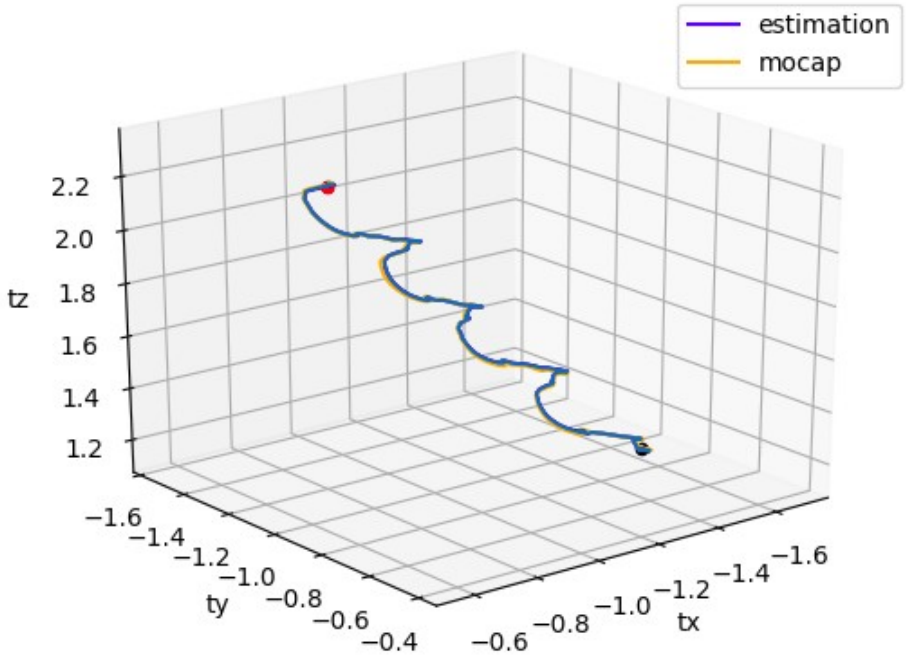
Bias drift

Fourmy et al. 19

Experimental results



Bauzil room

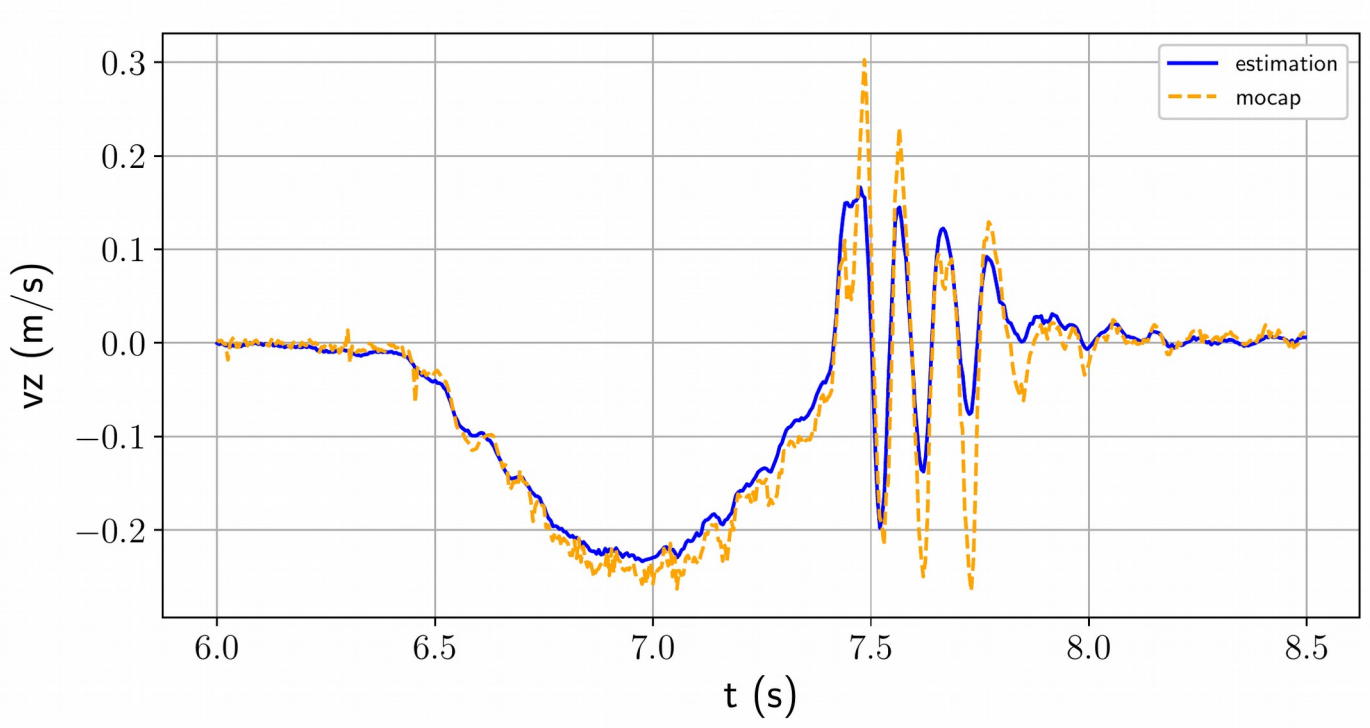


Climbing stairs

Locomotion around the room

Max 3cm position MSE for all datasets

Experimental results



Stairs descending, 1 step

Velocity estimation vs Mocap

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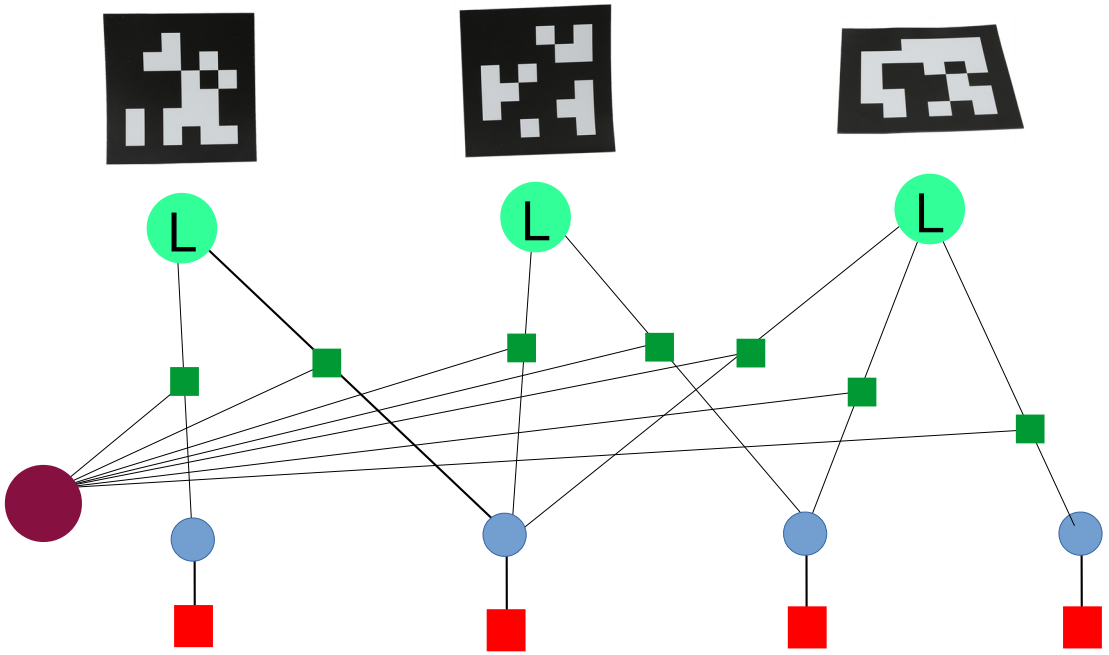
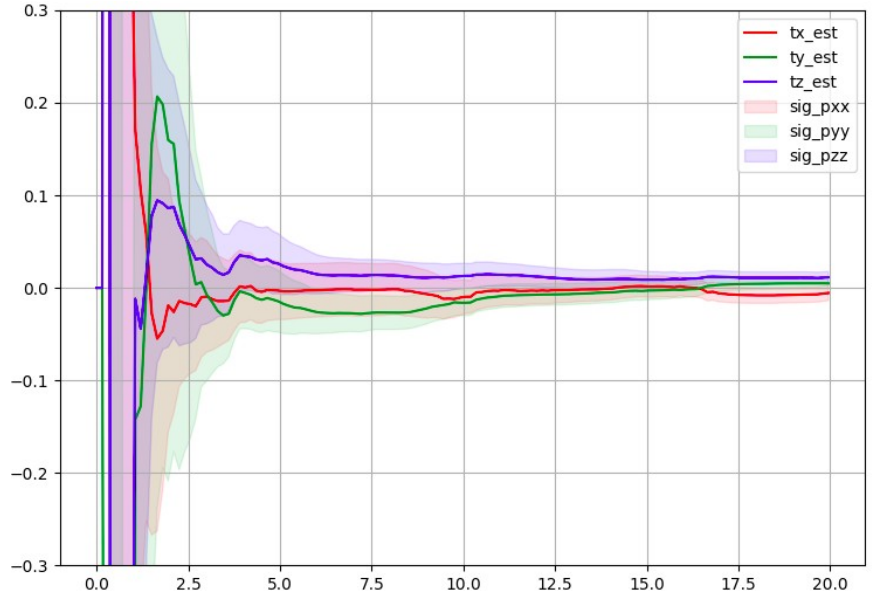
Camera extrinsics calibration





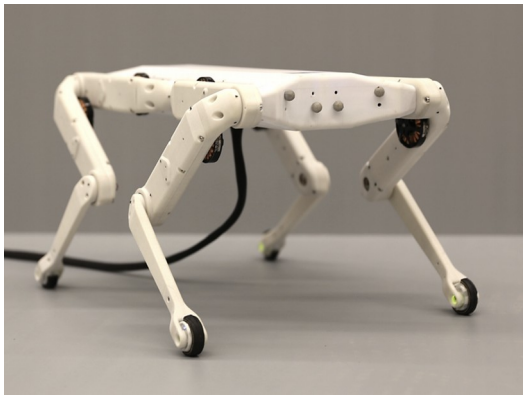
Extrinsics estimation error (3σ boundaries)

Camera extrinsics

Absolute SE(3) kinematic factor

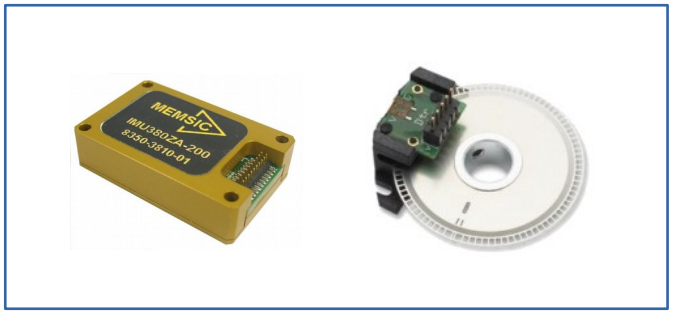
Leg Odometry

6d contact +
Kinematics
= Spatial vel

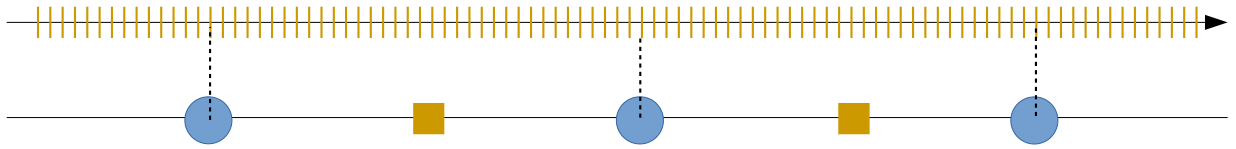


3d contact +
Kinematics +
Gyro
= Spatial vel

$$ {}_B\mathbf{v}_{WB} = -{}_B\mathbf{v}_{BK} - {}_B\boldsymbol{\omega}_{WB} \times {}_B\mathbf{p}_{BK} $$

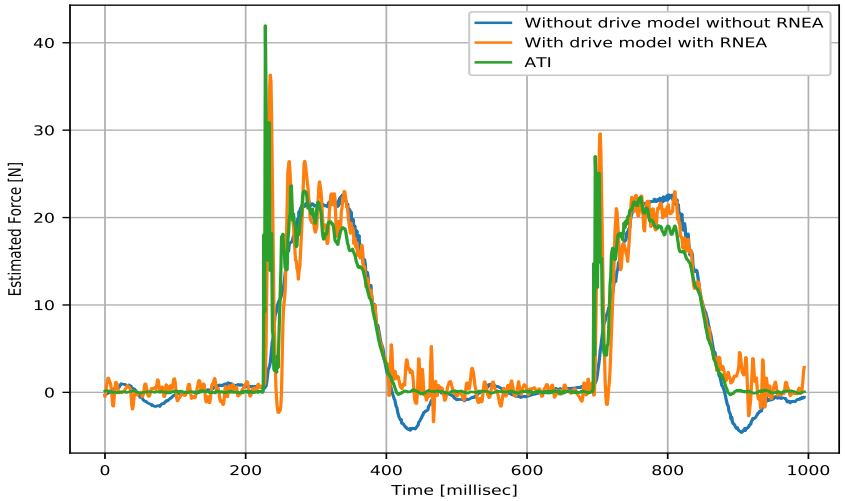


Inertial kinematics pre-integration factor



Contact detection

- Humanoids → normal force threshold
- Quadrupeds → not enough...



- State of the art: probabilistic model fusing force estimates, foot vel/acc
- Associate covariances to footholds

- Early detection or stable contact ?
- Slip detection?

Conclusion

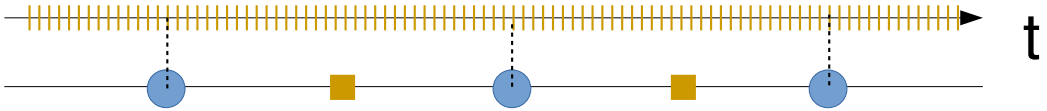
- Summary
  - Argue for the generalized use of trajectory optimization for legged robot estimation (debatable)
  - VIN algorithm implemented and tested on HRP2
  - Experimental campaign needed for contact estimation/odometry on Solo/Talos

- Perspective
  - Other sensor modalities in preparation
  - Move towards other vision system
  - Dense mapping

THANK YOU

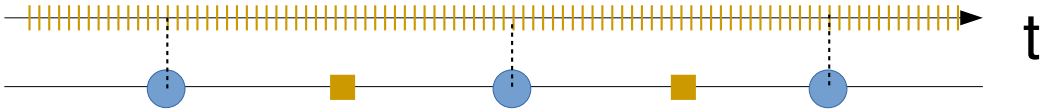
Appendices

Pre-integration theory



- IMU factor e(xi, xi+1) = dist(xi,xj) - Delta_ij

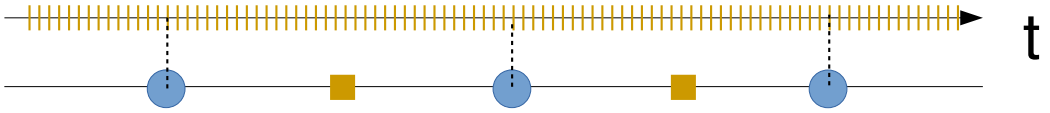
Pre-integration theory



- IMU factor e(xi, xi+1) = dist(xi,xj) - Delta_ij

Incremental computation: Delta_ij = Delta_ik + f(z_kj) Q_Delta_ij = Q_Delta_ik + F(z_kj)

Pre-integration theory



- IMU factor e(xi, xi+1) = dist(xi,xj) - Delta_ij

Incremental computation: Delta_ij = Delta_ik + f(z_kj) Q_Delta_ij = Q_Delta_ik + F(z_kj)

- If Delta_ij = f(xi, Zij, bi) → Reintegration needed each time xi changes

- If Delta_ij = f(Zij, bi) → No need to reintegrate, adapt to bi change through first order approximation

Pre-integration