Hector SLAM for robust mapping in USAR environments

ROS RoboCup Rescue Summer School Graz 2012

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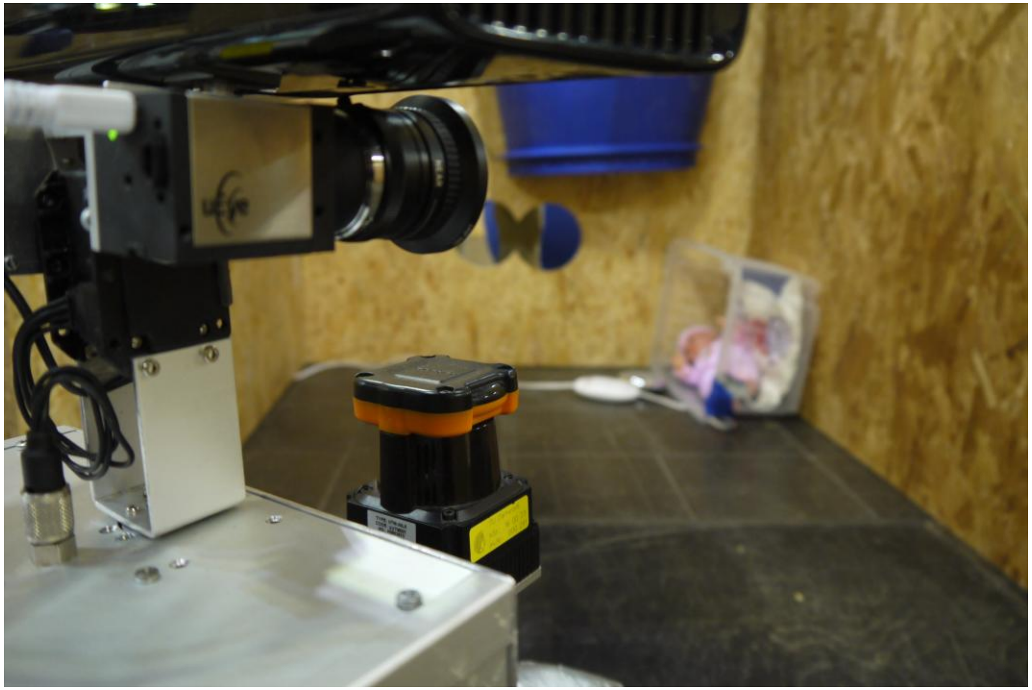
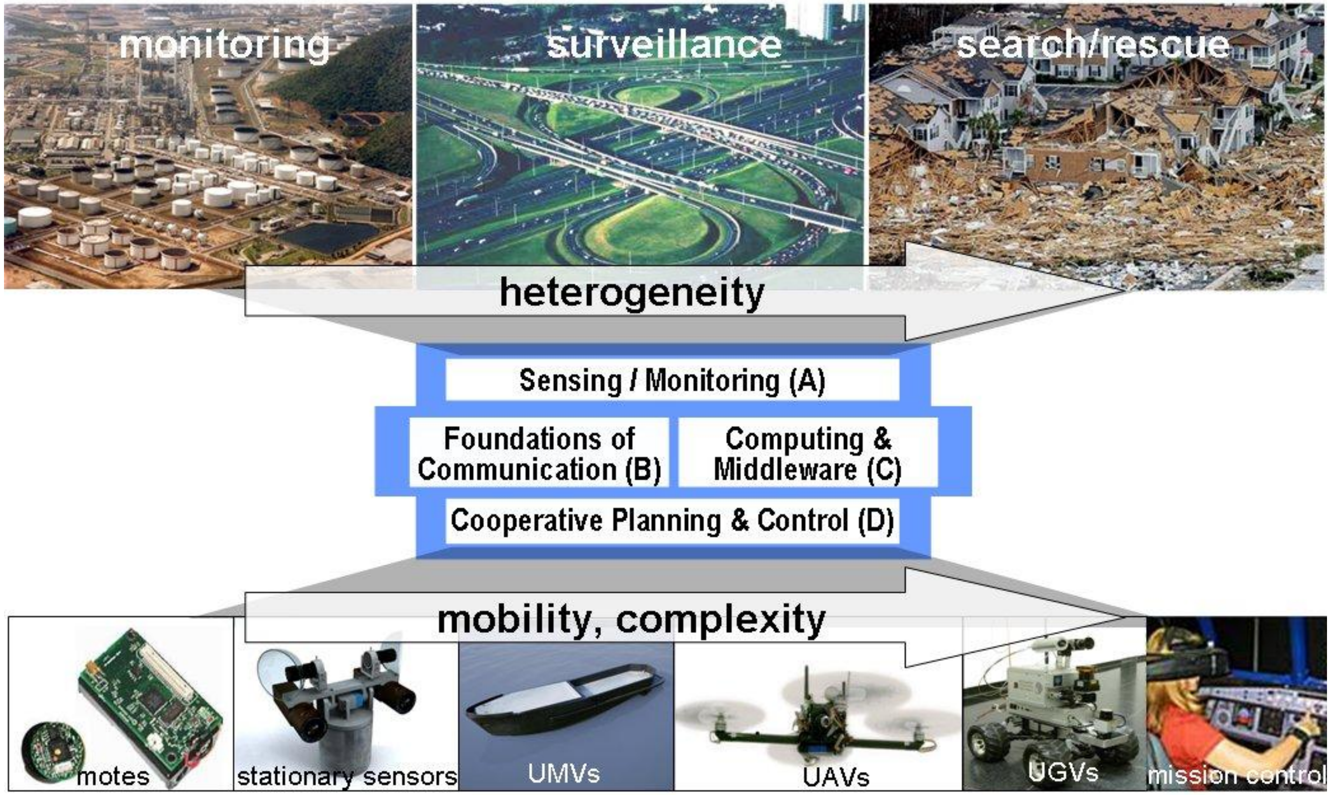
- **Hector Elevation Mapping**
- **Examples**
- **Conclusion**

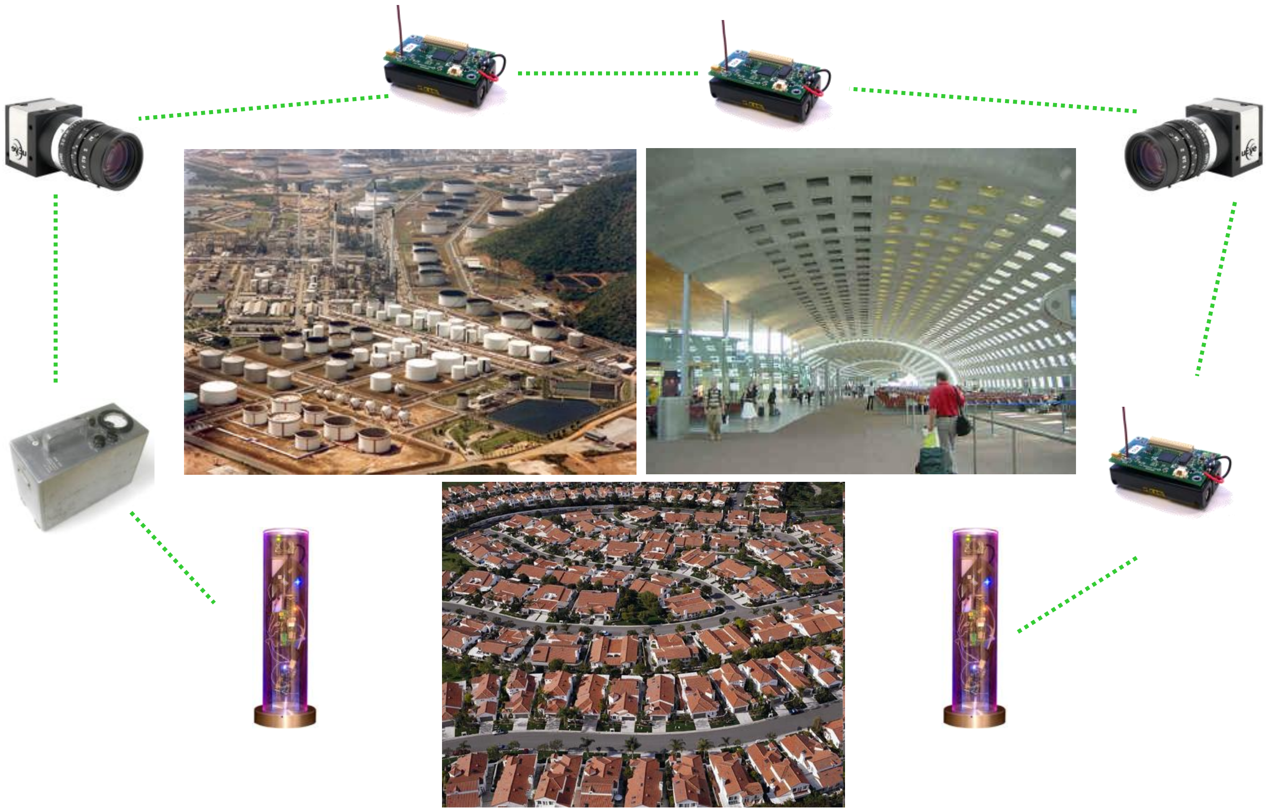


Background

- Team Hector is part of the RTG1362: *“Cooperative, Adaptive and Responsive Monitoring in Mixed Mode Environments”*



Example
Monitoring in Normal Operation



Example
Some Monitoring Elements and Channels Knocked-Out

Motivation

Deployment of Additional Equipment (Robots, Sensors)

→ Motivates fundamental research questions being addressed by our RTG

Team Hector

- Hector: **He**terogeneous **C**ooperating **T**eam **o**f **R**obots
- Established in Fall 2008
- Transition from RoboFrame to ROS as the central middleware since late 2010
- You can also like/follow us on facebook: http://www.facebook.com/TeamHectorDarmstadt ;)

Team Hector

1st place in the European Micro Air Vehicle Conference (EMAV) in category “Outdoor Autonomy”, Sep. 2009, Delft

3rd place (out of 12 & 16 teams) at the SICK Company’s Robot Day, October 2009 & 2010, Waldkirch

2nd place (out of 27) “Best in Class Autonomy” at RoboCup 2010, Singapore

Winner and “Best in Class Autonomy” at Robocup 2011 GermanOpen

2nd place “Best in Class Autonomy” at RoboCup 2011, Istanbul

Requirements – SLAM in USAR environments



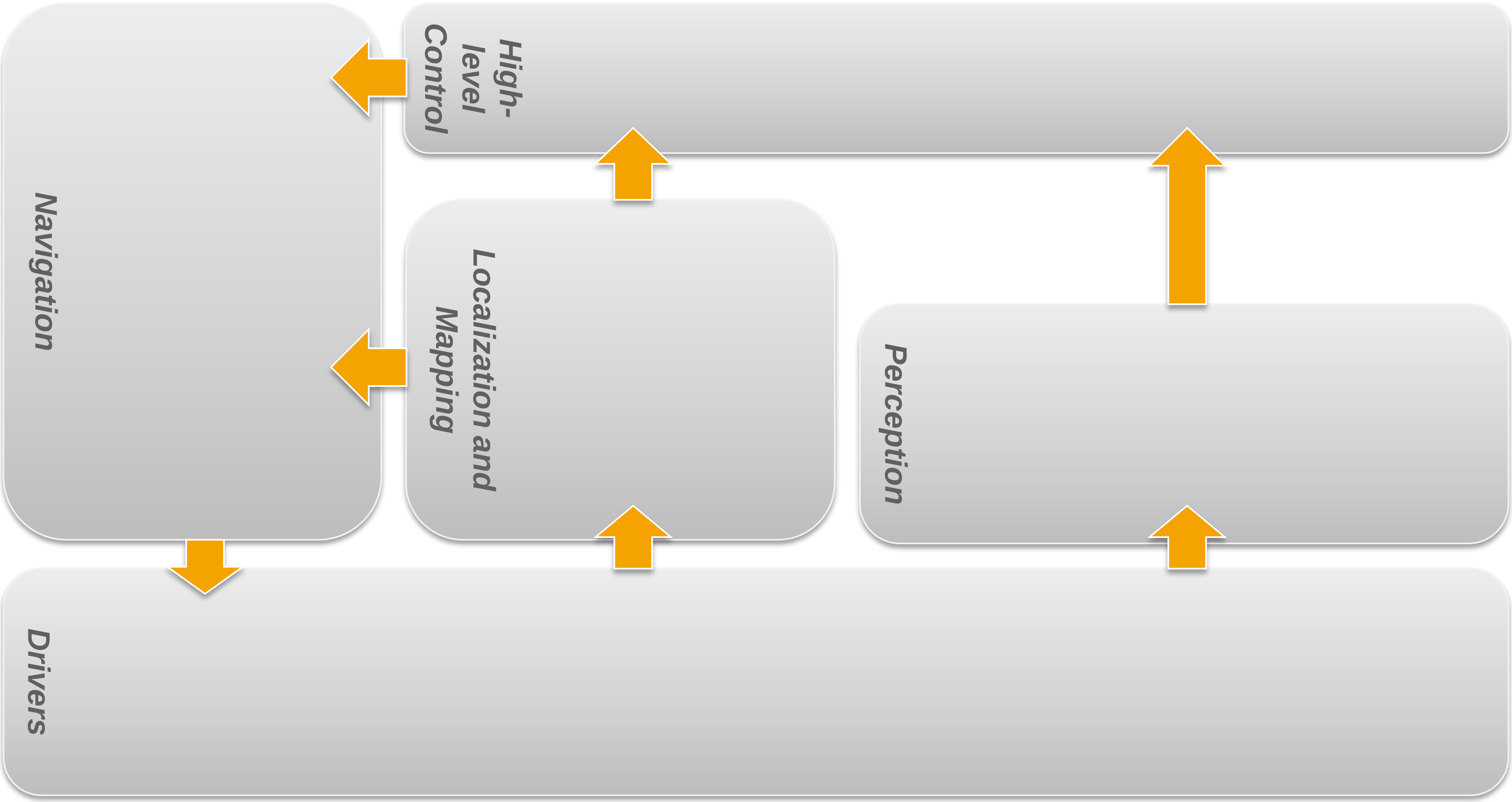
- SLAM
  - ➢Map the environment
  - ➢Localize Robot
  - ➢Realtime capable
- Harsh Terrain
  - ➢Full 6DOF pose estimation
  - ➢Cannot rely on (wheel/drivetrain) odometry
  - ➢Robustness
- Primary Mission is search for victims/exploration
  - ➢Mapping/Localization should not interfere
- Georeferenced Map with robot trajectory and objects of interest
  - ➢Saving GeoTiff maps

Requirements - Related Work

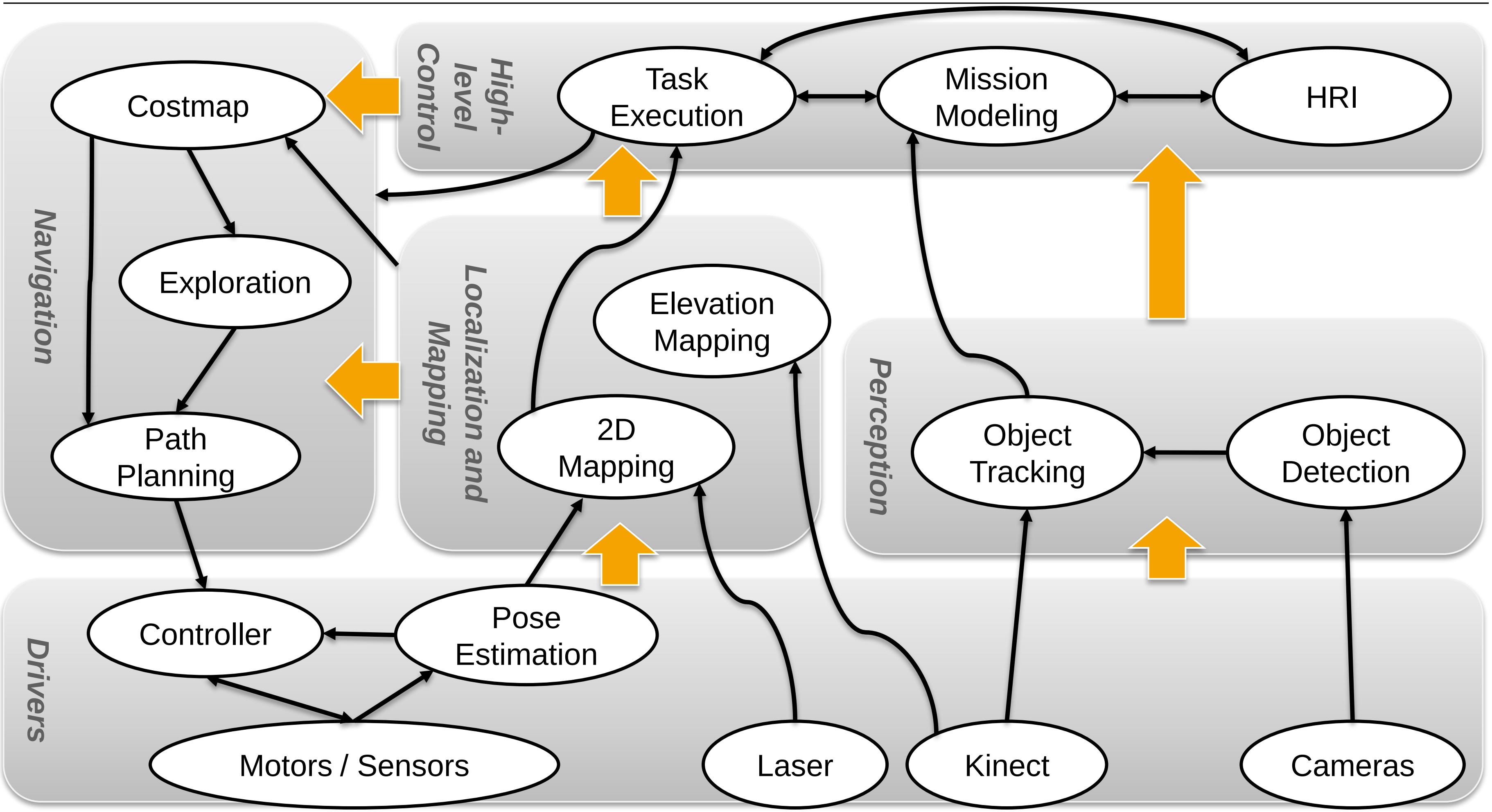
- Gmapping (2D SLAM, Rao-Blackwellized particle filter)
  - Odometry needed (can be simulated through separate scanmatcher)
  - Robot pose and map data “jump” relative to map frame
  - Does not leverage high scan rates of modern LIDARs

- 6D SLAM
  - Requires acquisition of 3D Laser Scans of the environment
    - Impairs mobility of platform
  - Sensitive to correct parameter settings
- Visual SLAM
  - Not robust enough
  - High CPU load
  - Promising improvements lately

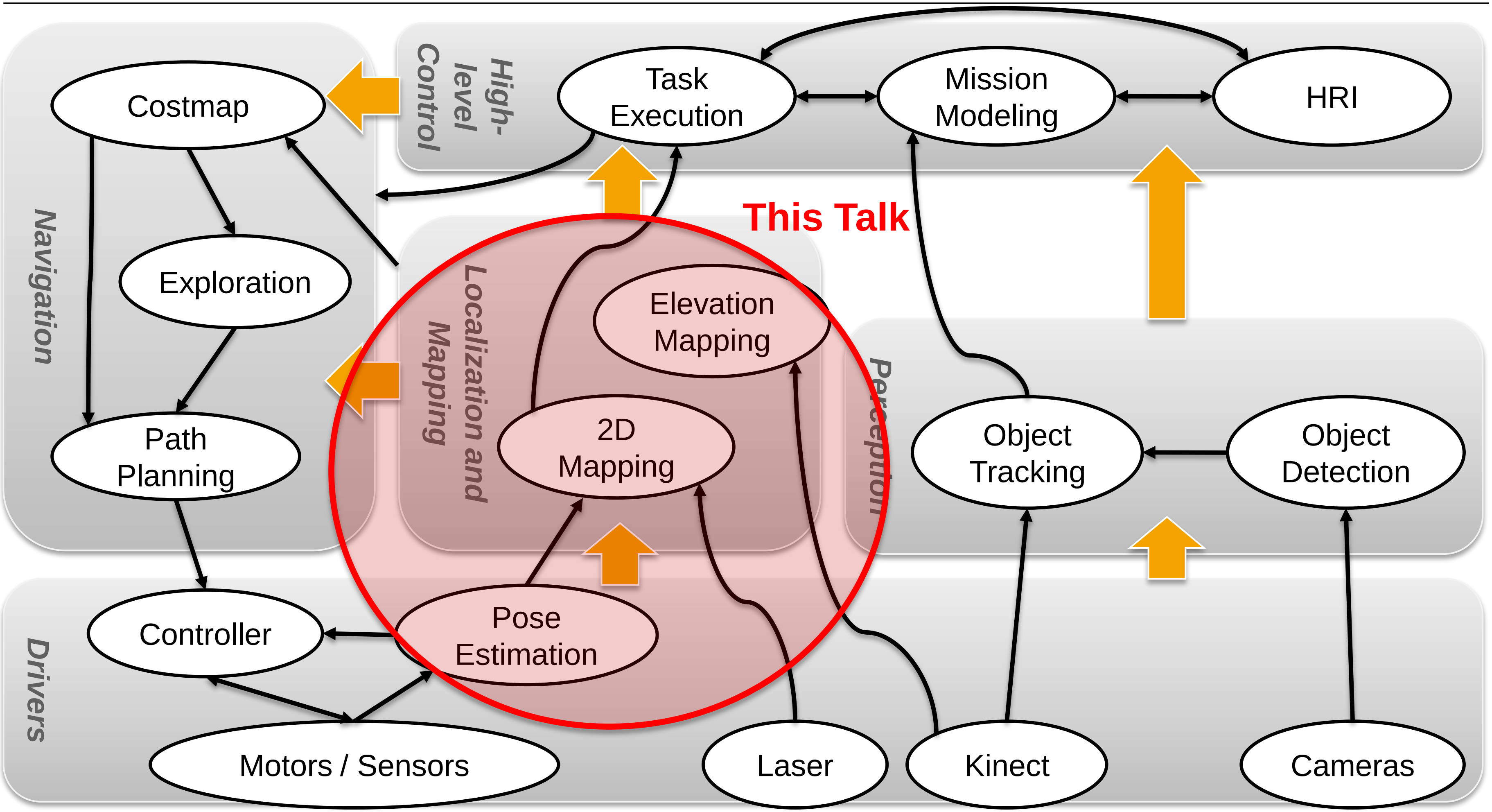
Hector Mapping - System Overview



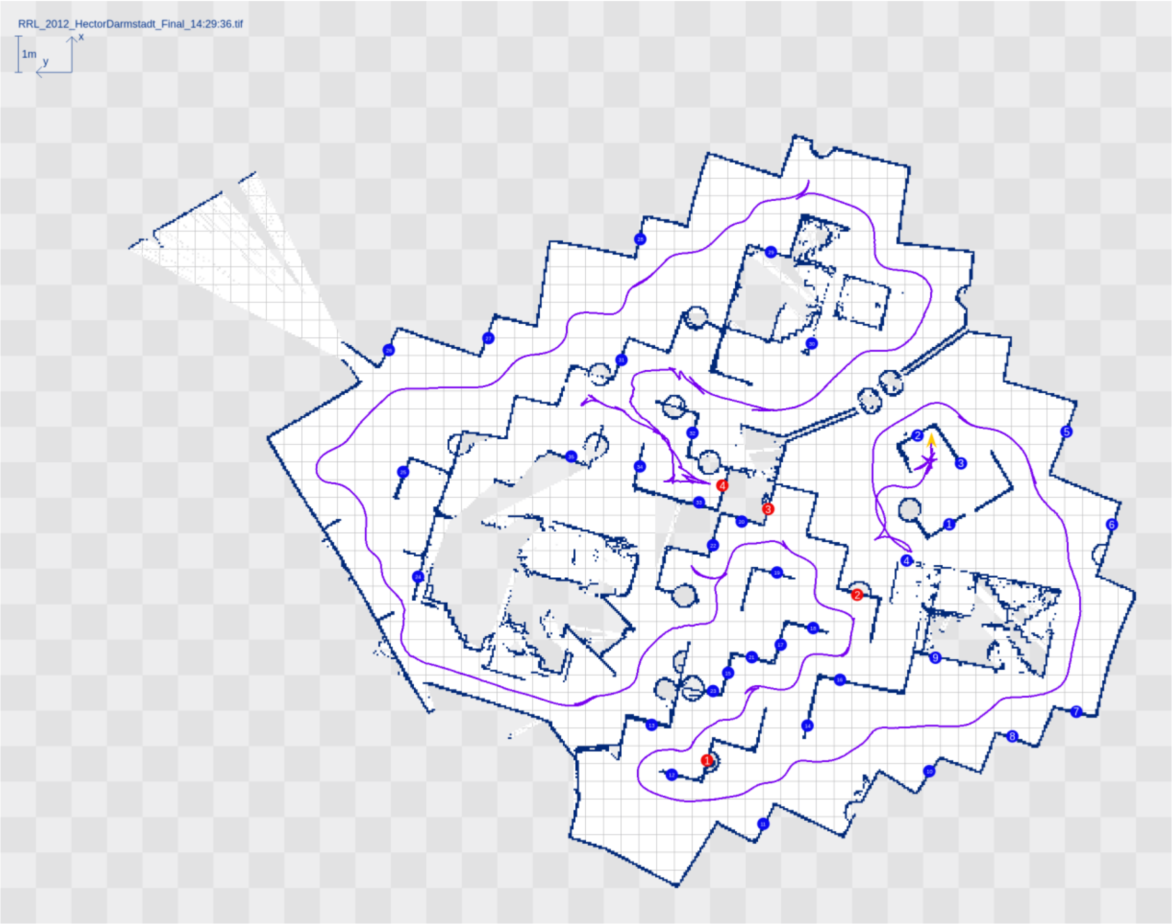
Hector Mapping - System Overview



Hector Mapping - System Overview



Hector Mapping – Recent Results



Final Mission RoboCup 2012

- 4 Victims found (3 autonomous, 1 teleop at the end)
- 35 QR codes detected and mapped
- >95% of Arena mapped
- Not a single broken map during missions at RoboCup 2012

Hector Mapping – Recent Results

Hector Mapping – Recent Results

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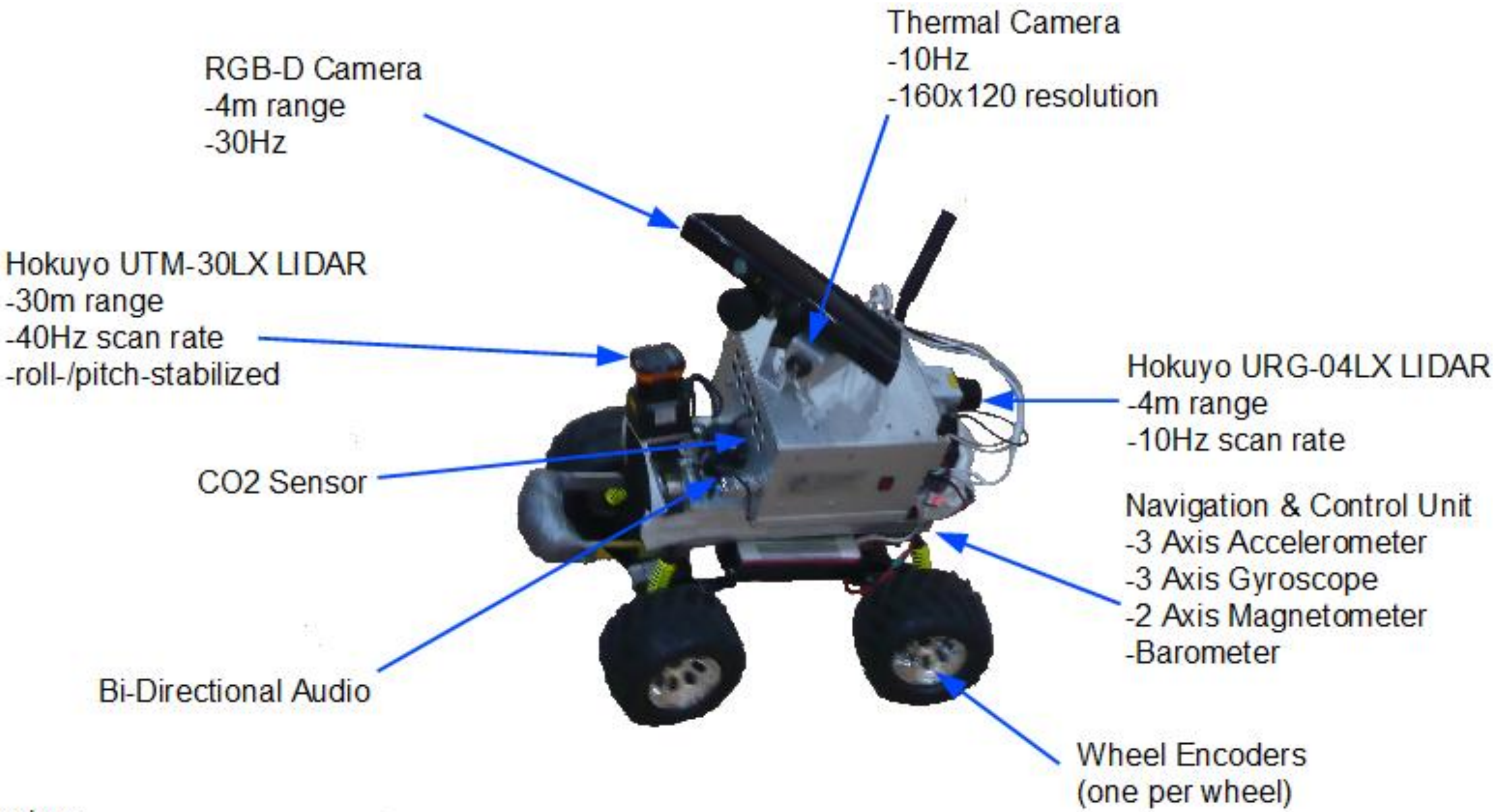


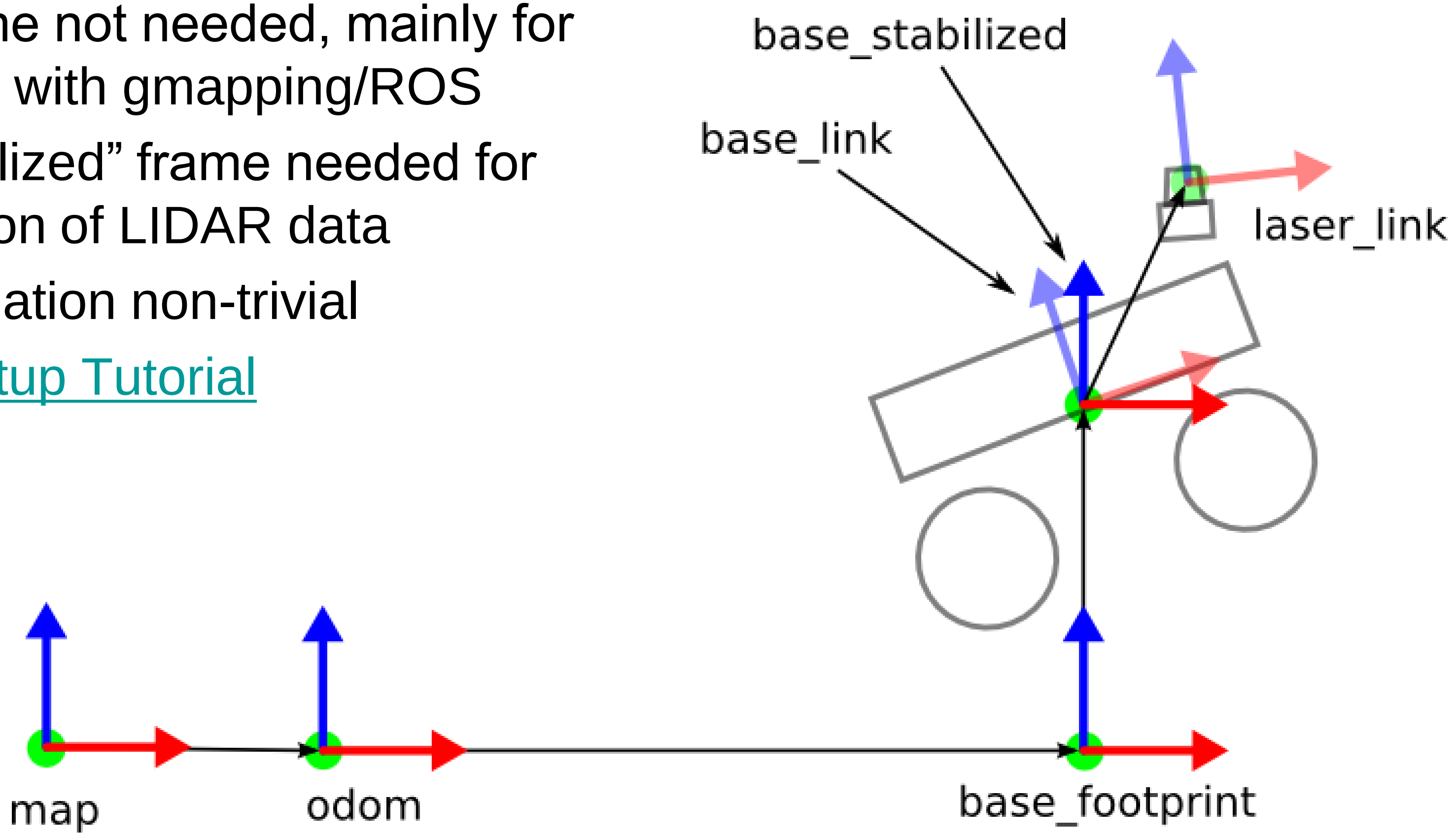
Processing:
- Geode 500 MHz (low level control)
- Core 2 Duo 2.4 GHz
- Nvidia CUDA GPU optional

Hector Mapping – ROS API

- Main SLAM node: hector_mapping
- Main Inputs:
  - Scan data on the "/scan" topic
  - Transformation data via tf (see next slides)
- Main Outputs:
  - Map on the "/map" topic
  - tf "map" -> "odom" transform (yielding pose of the robot in the map)

Hector Mapping – Coordinate frames

- "/odom" frame not needed, mainly for compatibility with gmapping/ROS
- "/base_stabilized" frame needed for transformation of LIDAR data
- Height estimation non-trivial
- See also [Setup Tutorial]

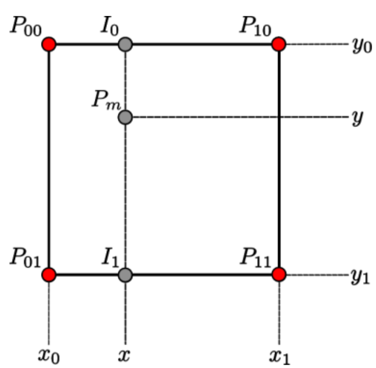


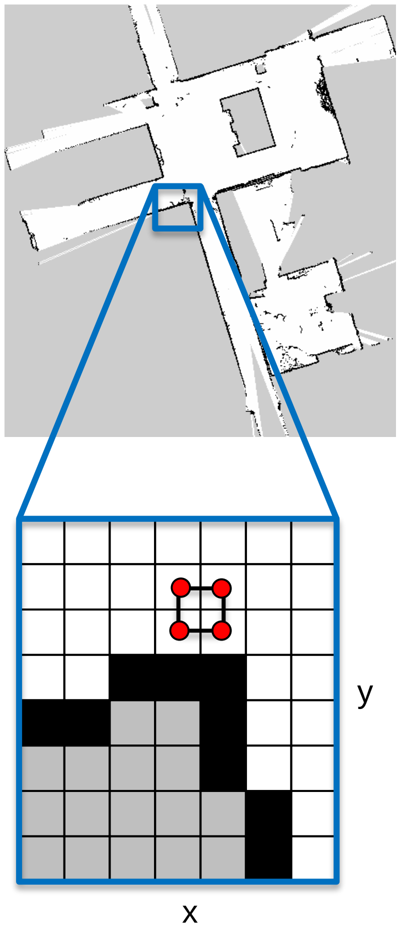
Hector Mapping – Attitude Estimation

- **Roll/Pitch Estimation** of platform/LIDAR required
  - Use IMU for attitude estimation
  - We provide the **hector_imu_attitude_to_tf** node
    - Provides base_stabilized -> base_link transform
  - LIDAR not rigidly mounted to base_stabilized frame should be transparent provided correct robot/tf setup
  - Best results if LIDAR is actuated and kept approximately level

Hector Mapping – Map Representation

- Map is represented by a 2D grid holding the (log odds representation of the) probability P_{xy} of cell occupancy
- Access map data on non-integer coordinates using bilinear filtering
  - Only approximative
  - But fast (Trilinear would be other option)
- Cache recently accessed grid points



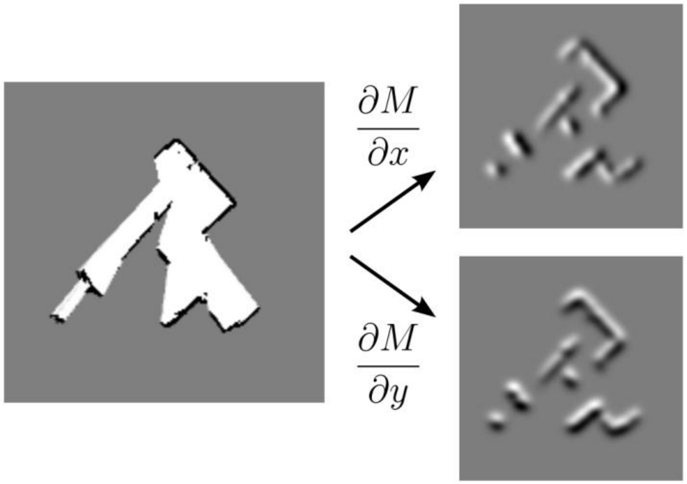


Hector Mapping – One Iteration

- Receive scan from LIDAR
- Transform scan endpoints into “/base_stabilized” frame
- Throw out endpoints outside cut-offs:
  - laser_z_min_value
  - laser_z_max_value
  - laser_min_dist
  - laser_max_dist
- Perform 2D pose estimation (next slides)
- Update map if robot is estimated to have travelled more than thresholds indicated by
  - map_update_distance_thresh
  - map_update_angle_thresh

Hector SLAM – 2D Pose Estimation (1)

- Set pose estimate, either:
  - Pose from preceding iteration
  - Pose using a tf start estimate
- Iterate:
  1. Project endpoints onto map based on current pose estimate
  2. Estimate map occupancy probability gradients at scan endpoints
  3. Perform Gauss-Newton iteration to refine pose estimate

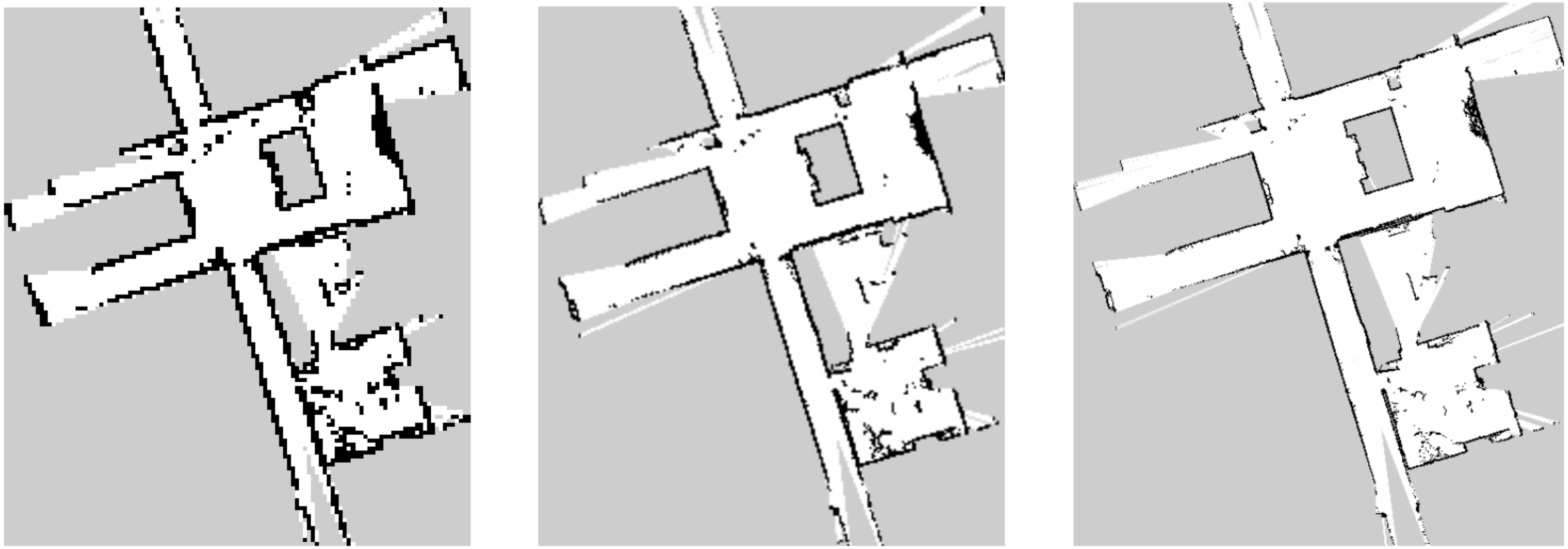


$$\mathbf{H} = \left[\nabla M(\mathbf{S}_i(\boldsymbol{\xi}))\frac{\partial \mathbf{S}_i(\boldsymbol{\xi})}{\partial \boldsymbol{\xi}}\right]^T \left[\nabla M(\mathbf{S}_i(\boldsymbol{\xi}))\frac{\partial \mathbf{S}_i(\boldsymbol{\xi})}{\partial \boldsymbol{\xi}}\right]$$

Reference:
S. Kohlbrecher and J. Meyer and O. von Stryk and U. Klingauf : *A Flexible and Scalable SLAM System with Full 3D Motion Estimation.* IEEE International Symposium on Safety, Security and Rescue Robotics 2011

Hector SLAM – 2D Pose Estimation (2)

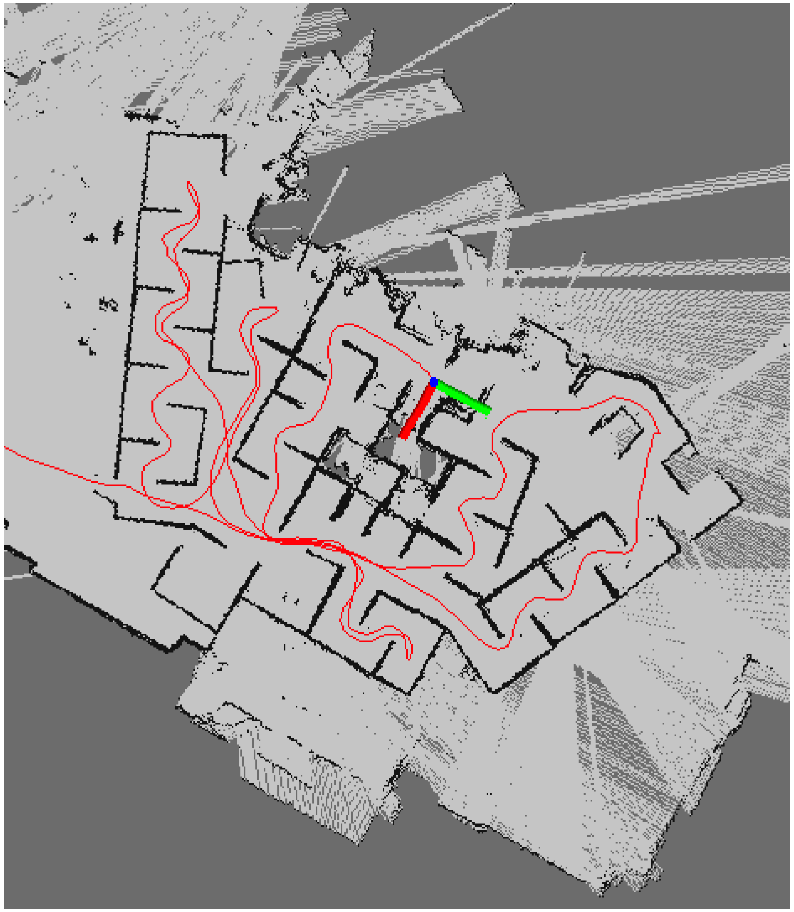
- Gradient-based Optimization can get stuck in local minima
- Solution: Use multi-level map representation
- Every level updated separately at map update step using scan data
  - No costly downsampling operations between maps anywhere



Hector SLAM Tools – Trajectory Server

hector_trajectory_server

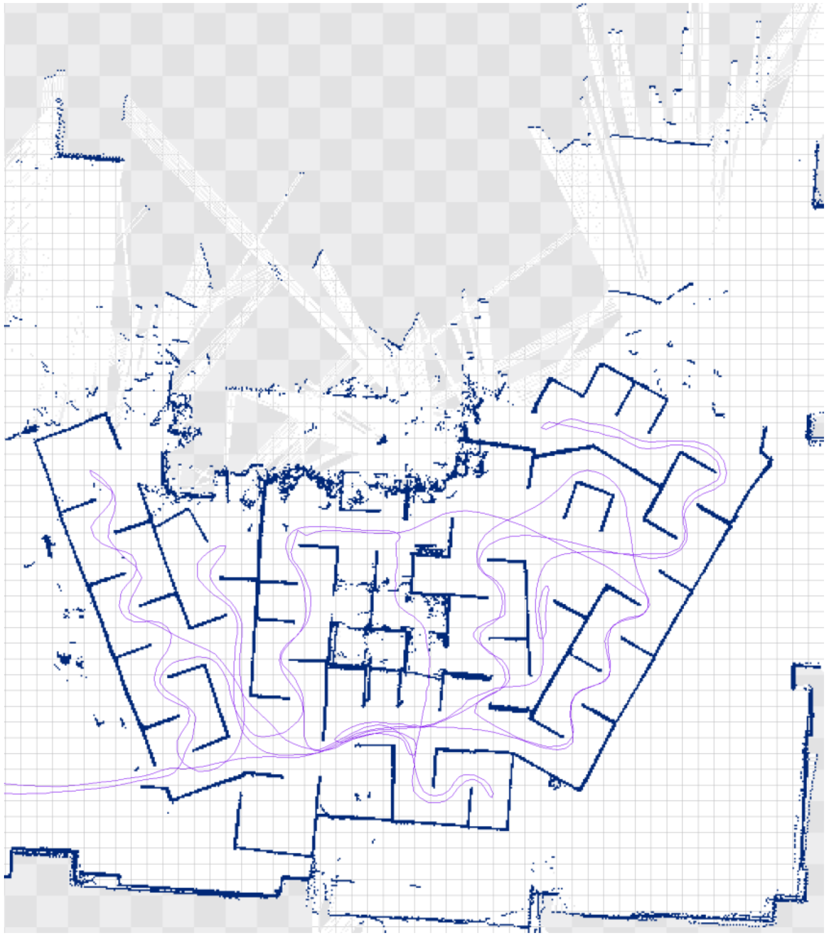
- Logs trajectory data based on tf
- Makes Data available as nav_msgs::path via
  - Regularly published topic
  - Service
- Currently used for
  - Visualization of (travelled) robot path
  - GeoTiff node
- Can be used log and visualize arbitrary tf based trajectories



Hector SLAM Tools – Geotiff Node

hector_geotiff

- Provides RC Rescue League compliant GeoTiff maps
- Trigger for saving the map
  - Regular Intervals
  - On Request (topic)
- Runs completely onboard
- Uses ROS services to retrieve
  - Map
  - Travelled path
- Objects of interest can be added using pluginlib based plugins



Hector SLAM Tools – Map Server

map_server

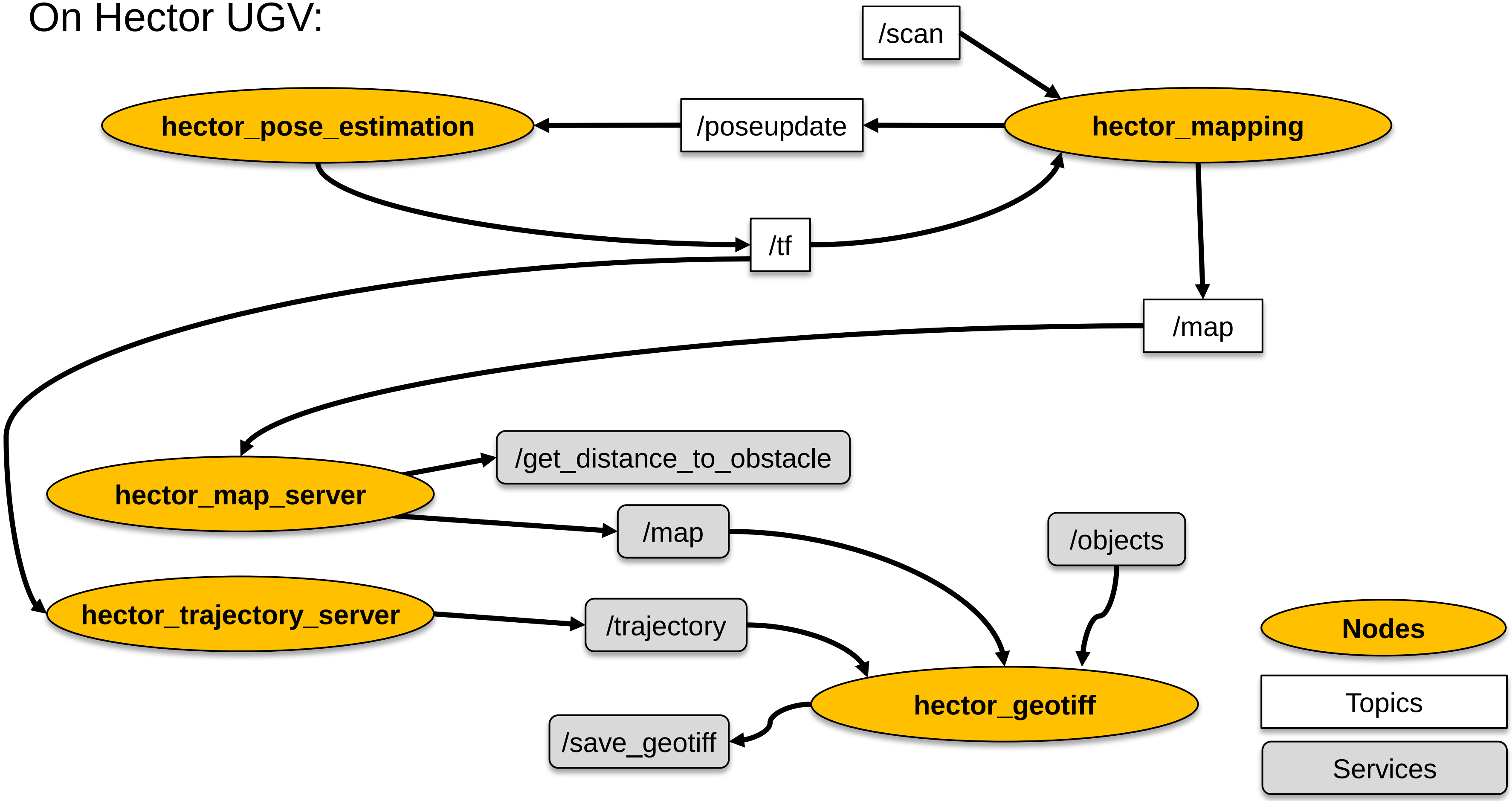
- Retrieves map data via topic
- Makes services for map queries available
- Used on our USAR robot for doing raycasting to project obstacles onto nearest walls
- Already using 3D query so switching to other server type (for example OctoMap based) is straightforward.

```
# Returns the distance to the next obstacle from the origin of frame point.header.frame_id
# in the direction of the point
#
# All units are meters.

geometry_msgs/PointStamped point
---
float32 distance
```

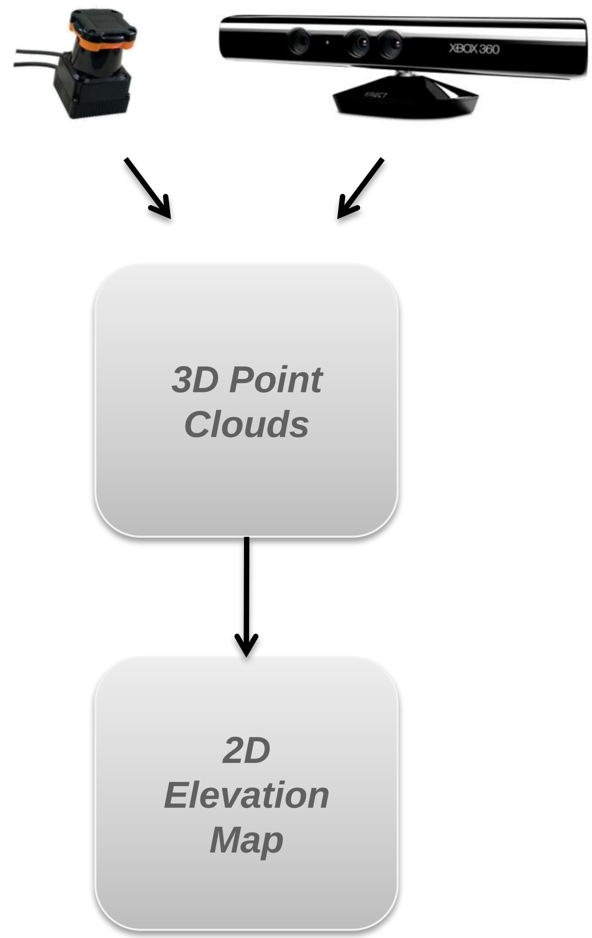
Hector SLAM – Putting it together

On Hector UGV:



Hector Elevation Mapping

hector_elevation_mapping



Motivation:

- Elevation map is mandatory for ground robots
- For detection of
  - stairs
  - ramps
  - step fields
  - …

Proposed Map Representation:

- Two-dimensional array (x,y)
- Height value (h)
- Variance (σ^2)

Hector Elevation Mapping

Kalman Filter based Approach:

$$h(t) = \frac{1}{\sigma^2_{z(t)} + \sigma^2_{h(t-1)}} \left(\sigma^2_{z(t)} h(t-1) + \sigma^2_{h(t-1)} m(t) \right)$$

$$\sigma^2_{h(t)} = \frac{\sigma^2_{z(t)} \sigma^2_{h(t-1)}}{\sigma^2_{z(t)} + \sigma^2_{h(t-1)}}$$

More precisely:

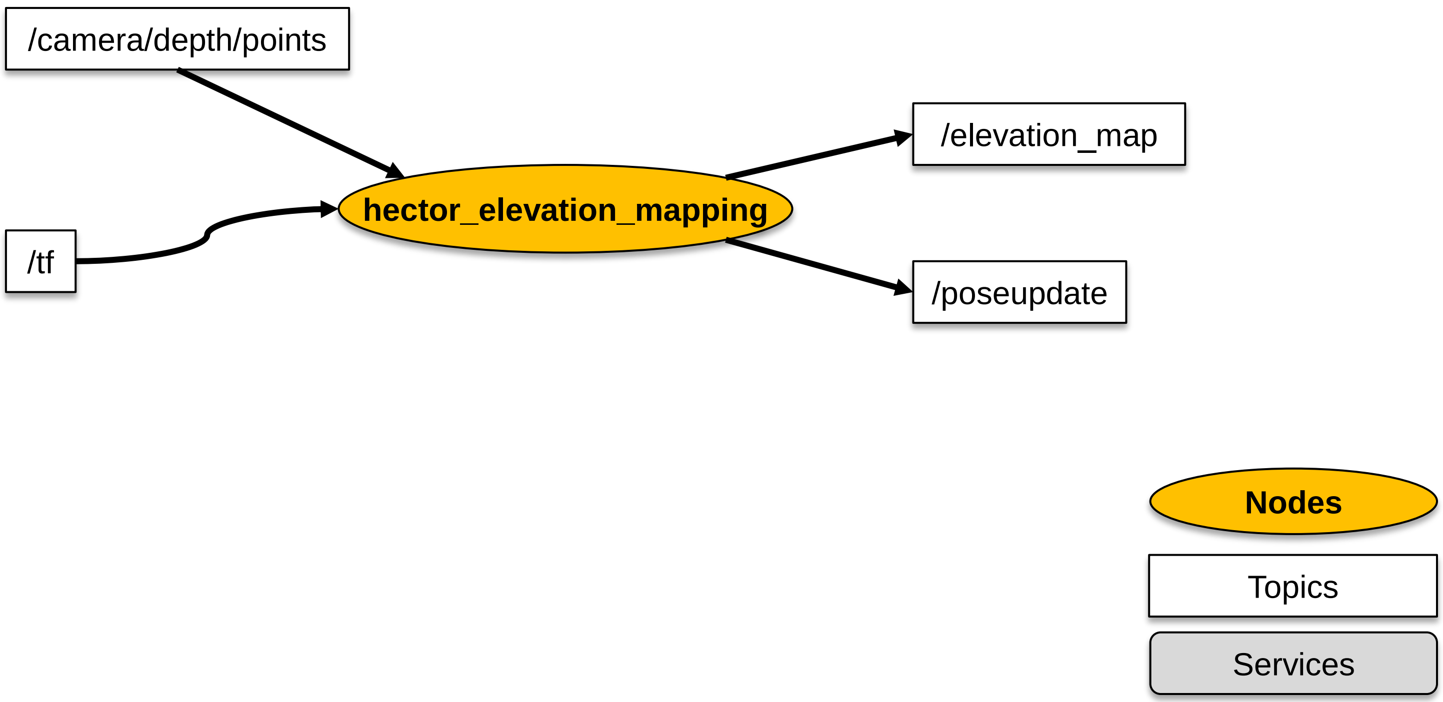
$$h(t) = \begin{cases} z(t) \\ h(t-1) \\ \frac{1}{\sigma^2_m + \sigma^2_{h(t-1)}} \left(\sigma^2_m h(t-1) + \sigma^2_{h(t-1)} m(t) \right) \end{cases}$$

$$\sigma^2_{h(t)} = \begin{cases} \sigma^2_{z(t)} & \text{if } z(t) > h(t-1) \wedge dm < c \\ \sigma^2_{h(t-1)} & \text{if } z(t) < h(t-1) \wedge dm < c \\ \frac{\sigma^2_{z(t)} \sigma^2_{h(t-1)}}{\sigma^2_{z(t)} + \sigma^2_{h(t-1)}} & \text{else} \end{cases}$$

where dm denotes the Mahalanobis distance: $dm = \sqrt{\frac{(z(t) - h(t-1))^2}{\sigma^2_{h(t)}}}$

Reference:
A. Kleiner and C. Dornhege: *Real-time Localization and Elevation Mapping within Urban Search and Rescue Scenarios.* Journal of Field Robotics, 2007.

Hector Elevation Mapping



Examples - Handheld Mapping System

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- Integration of our SLAM system in a small hand-held device
  - Intel Atom processor
  - Same hardware as on our quadrotor UAV
  - Optional connections to GPS receiver, Magnetometer, Barometer for airborne application

Examples - Handheld Mapping System

- RoboCup 2011 Handheld Mapping System dataset
- Small Box with
  - Hokuyo UTM-30LX LIDAR
  - Low Cost (<100$) IMU
  - Atom Z530 1.6 GHz board
- Dataset available at our GoogleCode repository

Embedded Mapping System
RoboCup 2011 Rescue Arena Dataset
11th July 2011 Istanbul

Examples - Handheld Mapping System

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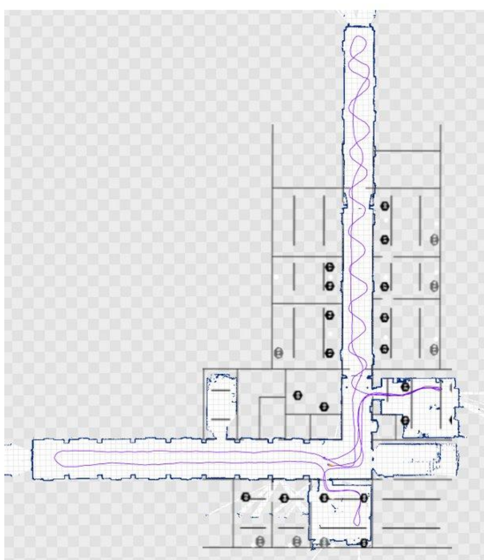
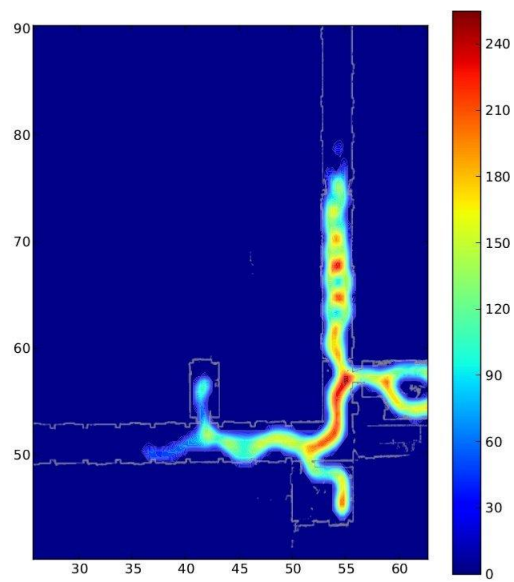
- Used to collect data about Wireless Sensor Network (WSN)
- Five minute walk gave 12787 localized WSN signal strength samples
- Much less cumbersome than manual annotation using a floor plan





Reference:
P. M. Scholl and S. Kohlbrecher and V. Sachidananda and K. van Laerhoven : *Fast Indoor Radio-Map Building for RSSI-based Localization Systems.* International Conference on Networked Sensing Systems 2012

Examples- Unmanned Surface Vehicle

- SLAM System mounted on USV (Unmanned Surface Vehicle)
- Self-Contained, no interconnection with USV (apart from power supply)

Team Hector TU Darmstadt

USV Experiment
29th August 2010
Claytor Lake, Virginia

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VirginiaTech

Conclusion

- Hector SLAM:
  - Robust SLAM in simulated USAR environments
  - Accurate enough to not need explicit loop closure in many real world environments
  - Lets you focus on your other research topics (path planning, high level planning etc.)
  - Relies on high update rate laser scanners, does not need odometry

- People at Google Munich looking into combining Hector Mapping and Octomap for real 3D support (Repo here)

Appendix: Localization and Mapping
Inertial Navigation System

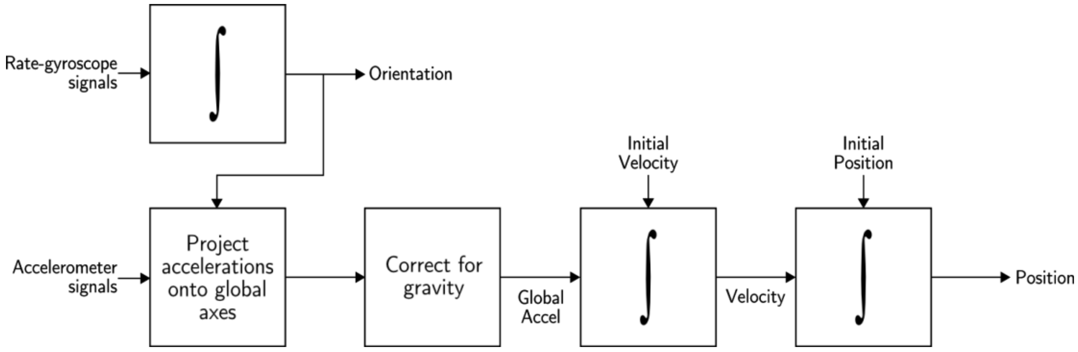
- Estimation of the **full 3D state** (position, orientation, velocity) of the robot from different sensor sources:
  - Inertial Measurement Unit (IMU)
  - Compass (Magnetic Field)
  - Global Satellite Navigation
  - Altimeter, Range Sensors etc.

} Attitude and Heading Reference System (AHRS)

Xsens MTi

Problems:

- Absolute position is not very accurate or not available at all
- Solution suffers from drift
- Acceleration can lead to significant orientation errors



Strapdown inertial navigation algorithm

Appendix: Localization and Mapping
Combine SLAM and EKF

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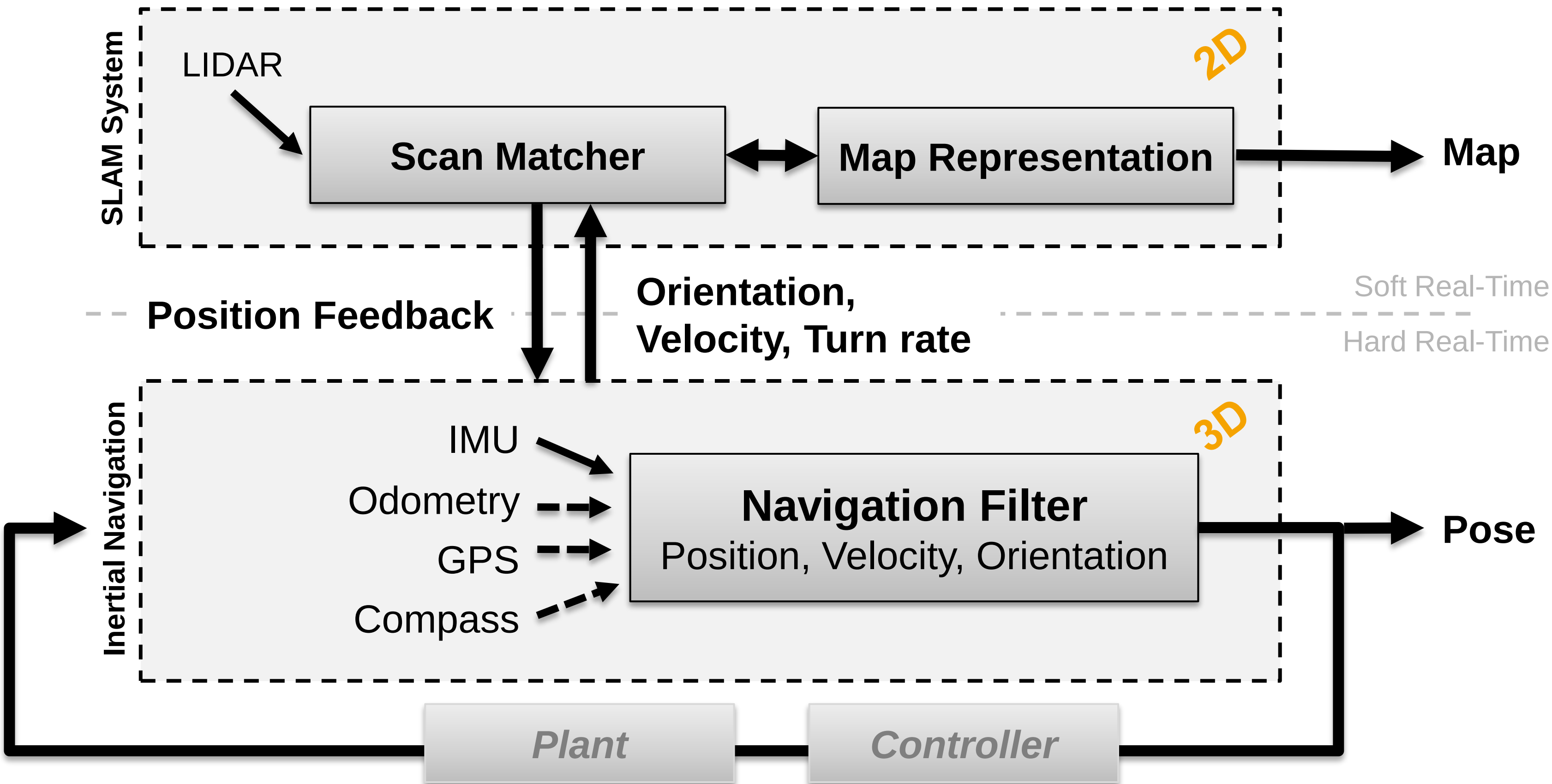
- **Our approach:** Couple both localization approaches in a loose manner



Appendix: Localization and Mapping

Navigation Filter

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- Sensor information is fused using an **Extended Kalman Filter (EKF)**
- **State Vector**

$$\bar{\mathbf{x}}_k = \left(\underbrace{\boldsymbol{\Omega}_k^{\mathrm{T}}}_{\text{Orientation}} \quad \underbrace{\mathbf{p}_k^{\mathrm{T}}}_{\text{Position}} \quad \underbrace{\mathbf{v}_k^{\mathrm{T}}}_{\text{Velocity}} \quad \underbrace{\boldsymbol{\delta\omega}_k^{\mathrm{T}}}_{\text{Angular rate error}} \quad \underbrace{\boldsymbol{\delta}\mathbf{a}_k^{\mathrm{T}}}_{\text{Acceleration error}} \right)^{\mathrm{T}}$$

- **System Input** (= Inertial Measurements)

$$\mathbf{u}_k = \left(\underbrace{\boldsymbol{\omega}_k^{\mathrm{T}}}_{\text{Angular rates}} \quad \underbrace{\mathbf{a}_k^{\mathrm{T}}}_{\text{Accelerations}} \right)^{\mathrm{T}}$$

Appendix: Localization and Mapping
Integration

Pose Update from SLAM:

- Pose estimates from EKF and SLAM have **unknown correlation**!
- Solution: **Covariance Intersection (CI)** approach [5]

$$(\mathbf{P}^{+})^{-1} = (1-\omega) \cdot \mathbf{P}^{-1} + \omega \cdot \mathbf{C}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{C}$$

$$\boldsymbol{\mu}^{+} = \mathbf{P}^{+}\left((1-\omega) \cdot \mathbf{P}^{-1}\boldsymbol{\mu} + \omega \cdot \mathbf{C}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{z}\right)^{-1}$$

with

- Estimated state and covariance (a-priori): $(\boldsymbol{\mu}, \mathbf{P})$
- Scan Matcher pose and covariance: $(\mathbf{z}, \mathbf{R})$
- Observation matrix $\mathbf{C}$
- Tuning parameter $\omega \in [0, 1]$