ROS Framework used by Team Hector Darmstadt

TECHNISCHE UNIVERSITÄT DARMSTADT

ROS Workshop Koblenz 2011

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Team Hector TU Darmstadt

ROS.org

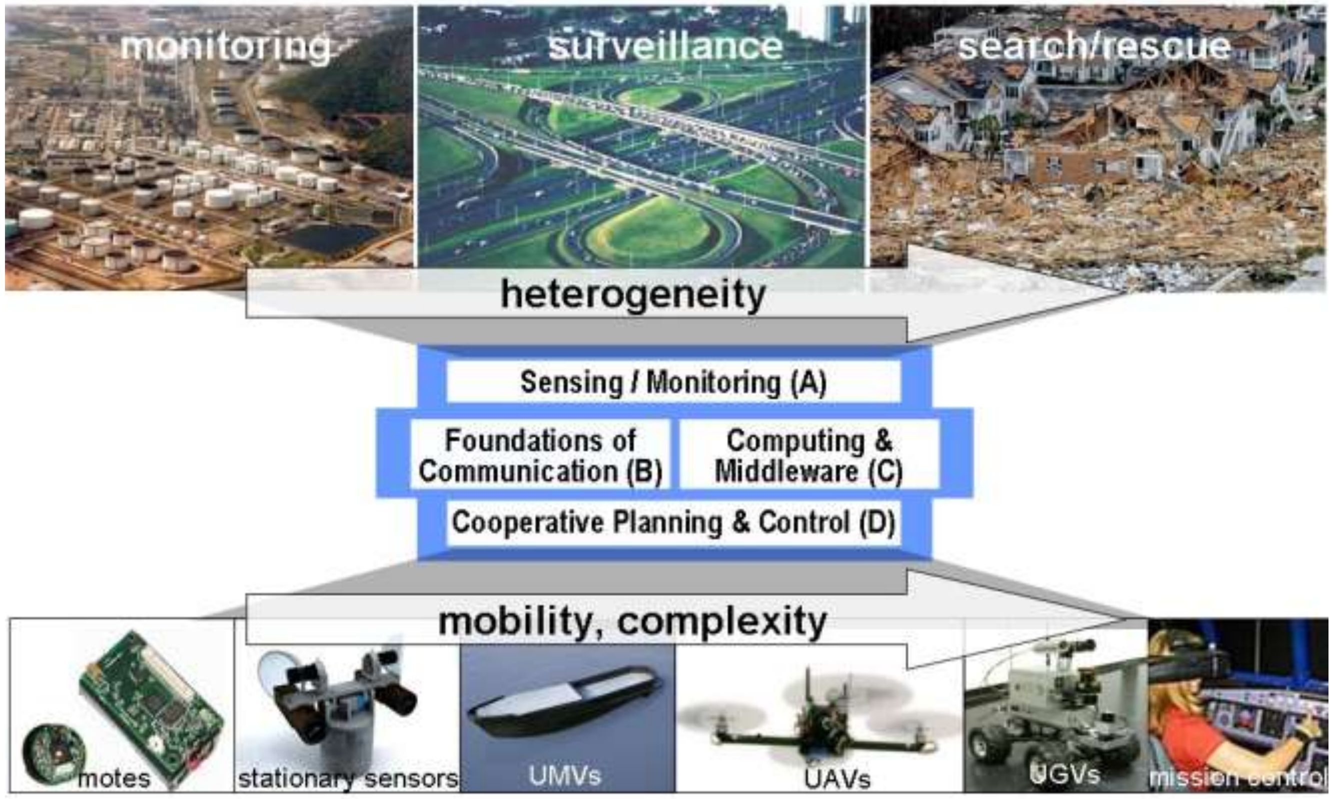
RoboCup Rescue

Outline

- **Introduction**
- **Hardware Platforms**
- **Building Blocks for a (Semi-)Autonomous Rescue Robot**
  - System Overview
  - Drivers and Controllers
  - Localization and Mapping
  - Navigation and Path Planning
  - Victim/Object Detection
  - High-Level Control
  - Human-Robot Interaction
  - Simulation
- **Current state of ROS packages**

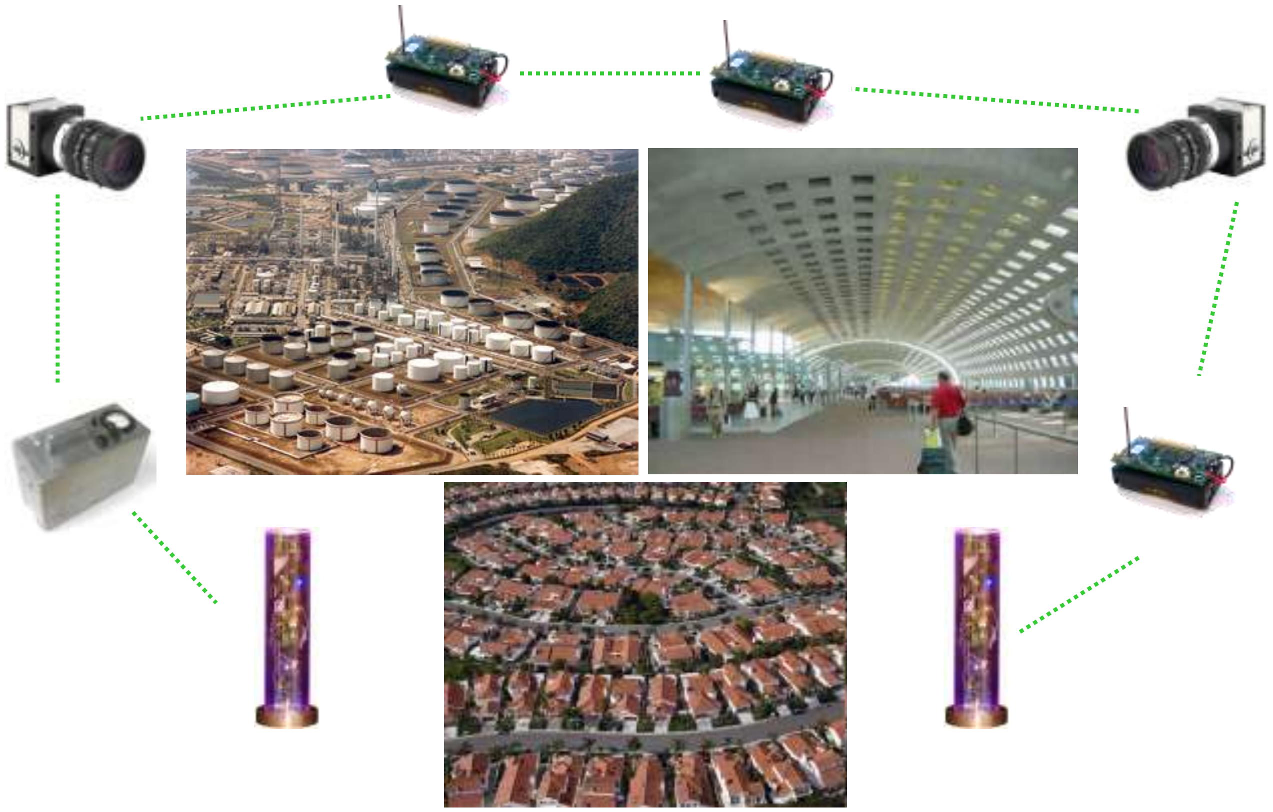
Background

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



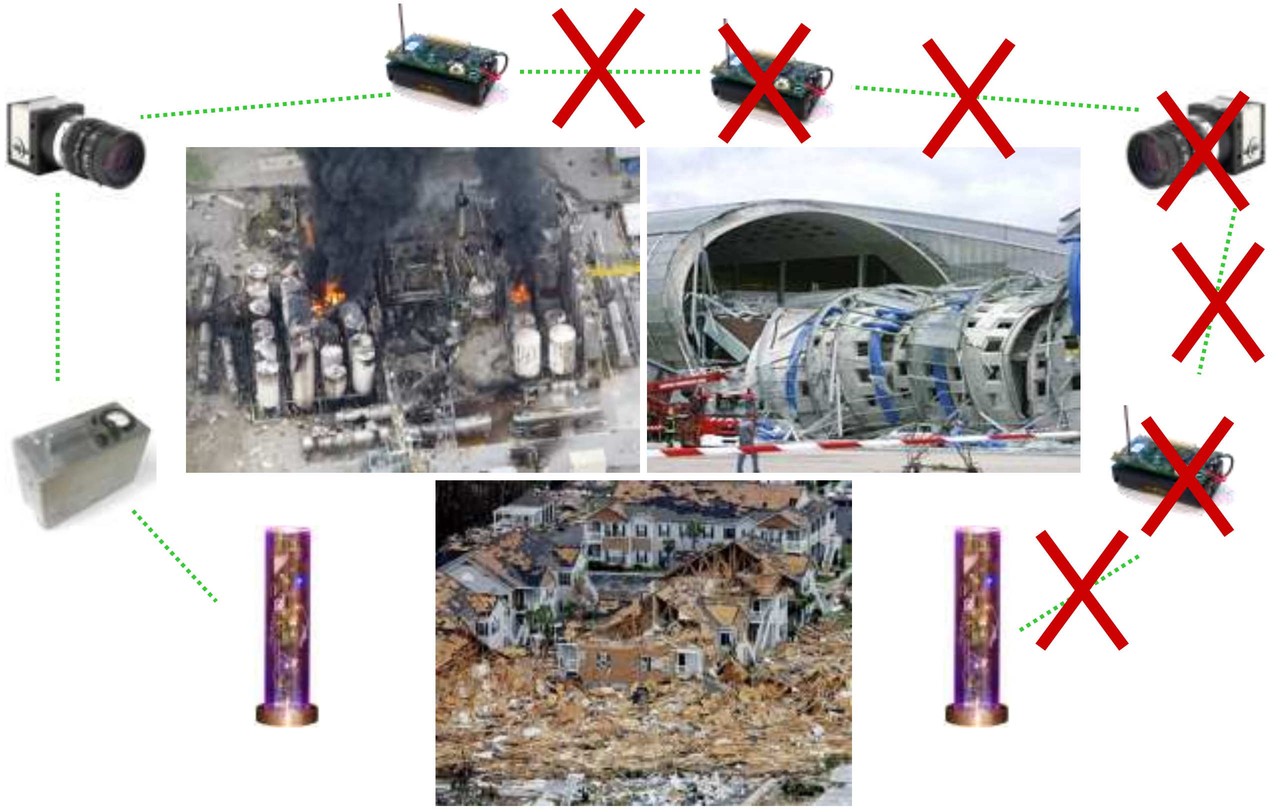
Example

Monitoring in Normal Operation



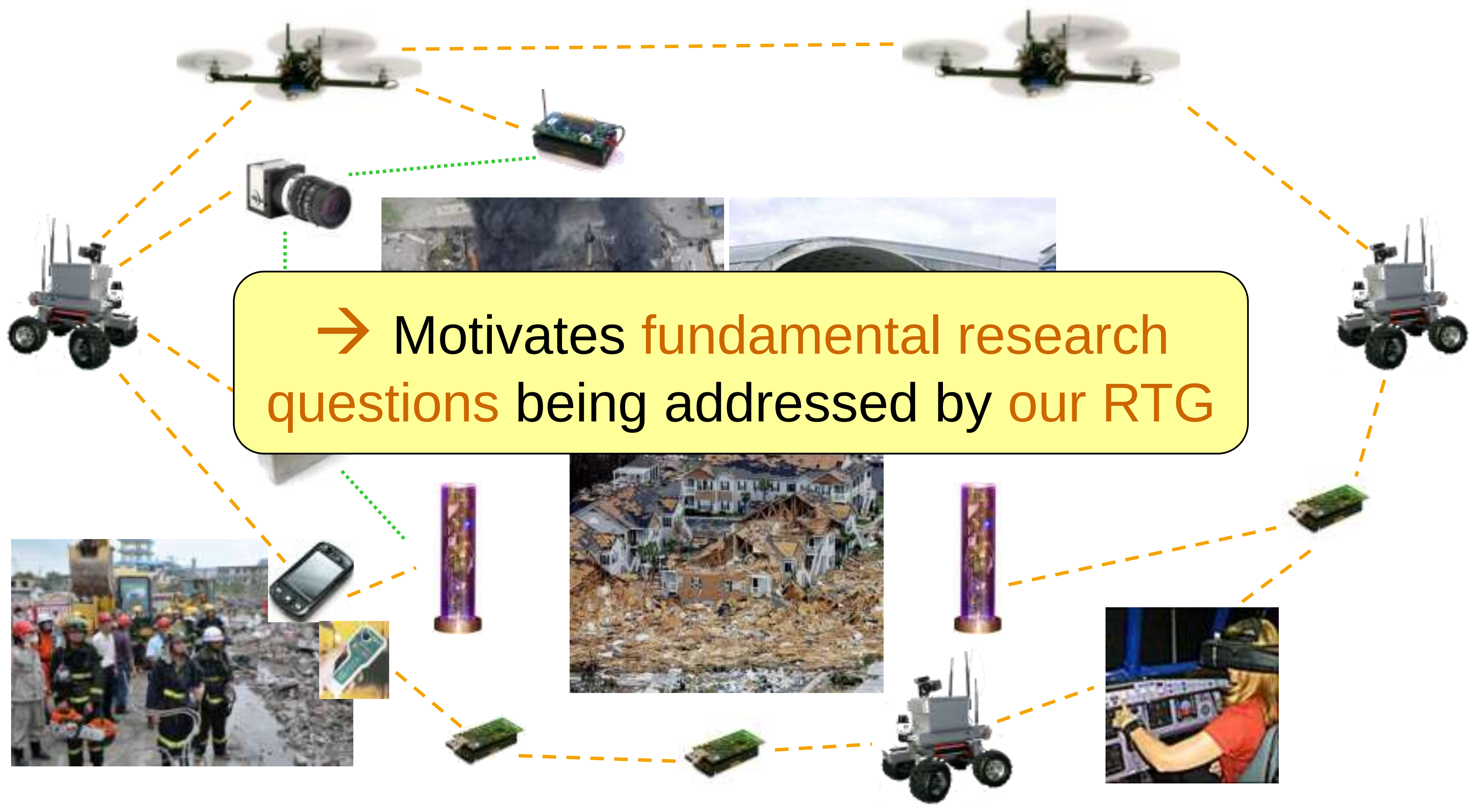
Example

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 2009
- 9 PhD Students involved in the past:
  - Mykhaylo Andriluka, Martin Friedmann, Johannes Meyer, Stefan Kohlbrecher (team captain), Karen Petersen, Christian Reinl, Paul Schnitzspan, Armin Strobel, Thorsten Graber
- Transition from RoboFrame to ROS as the central middleware since late 2010

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 (out of 27) “Best in Class Autonomy” at RoboCup 2011, Istanbul

Hardware Platforms

Hector UGV

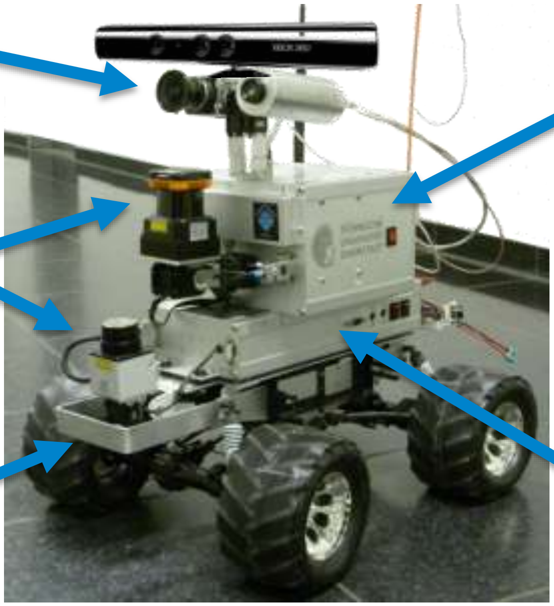
Pan/Tilt Camera Head

- Daylight Camera
- Thermal Camera
- RGB-D Camera

2 actuated LIDAR sensors

R/C Car Chassis

- 4-Wheel-Steering
- 1:5 Gear
- Wheel Encoders



Vision Computer

- Core 2 Duo CPU
- Nvidia GPU

Motion and Navigation

- µC Board / Geode LX
- IMU / GPS / Compass

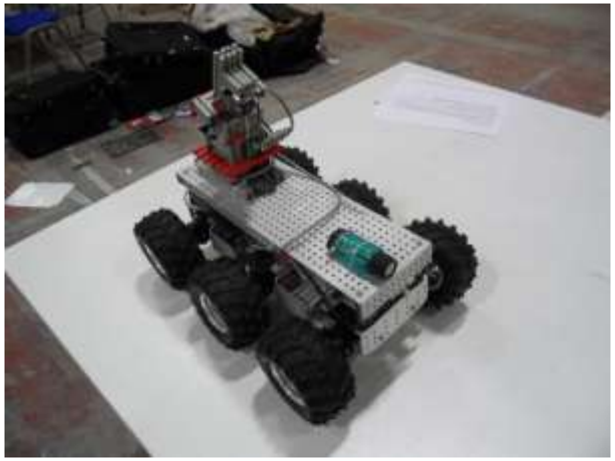
Total HW Cost: approx. 14.000 Euro (including payload)

Endurance: 30 - 40 minutes

State-of-the-art computing power of a mobile PC onboard

Hardware Platforms
Hector Lightweight UGV

- Based on commercial platform **"Wild Thumper"**
  - Low cost (~300 EUR)
  - Good mobility
  - First tested at RoboCup 2011
- **ROS Integration**
  - Arduino based motorcontroller
  - fitPC2 (Atom Z530 1.6 GHz)
- Investigate low cost, low weight platform
- **Ongoing work**
  - Sensor arm integration using ROS arm_navigation



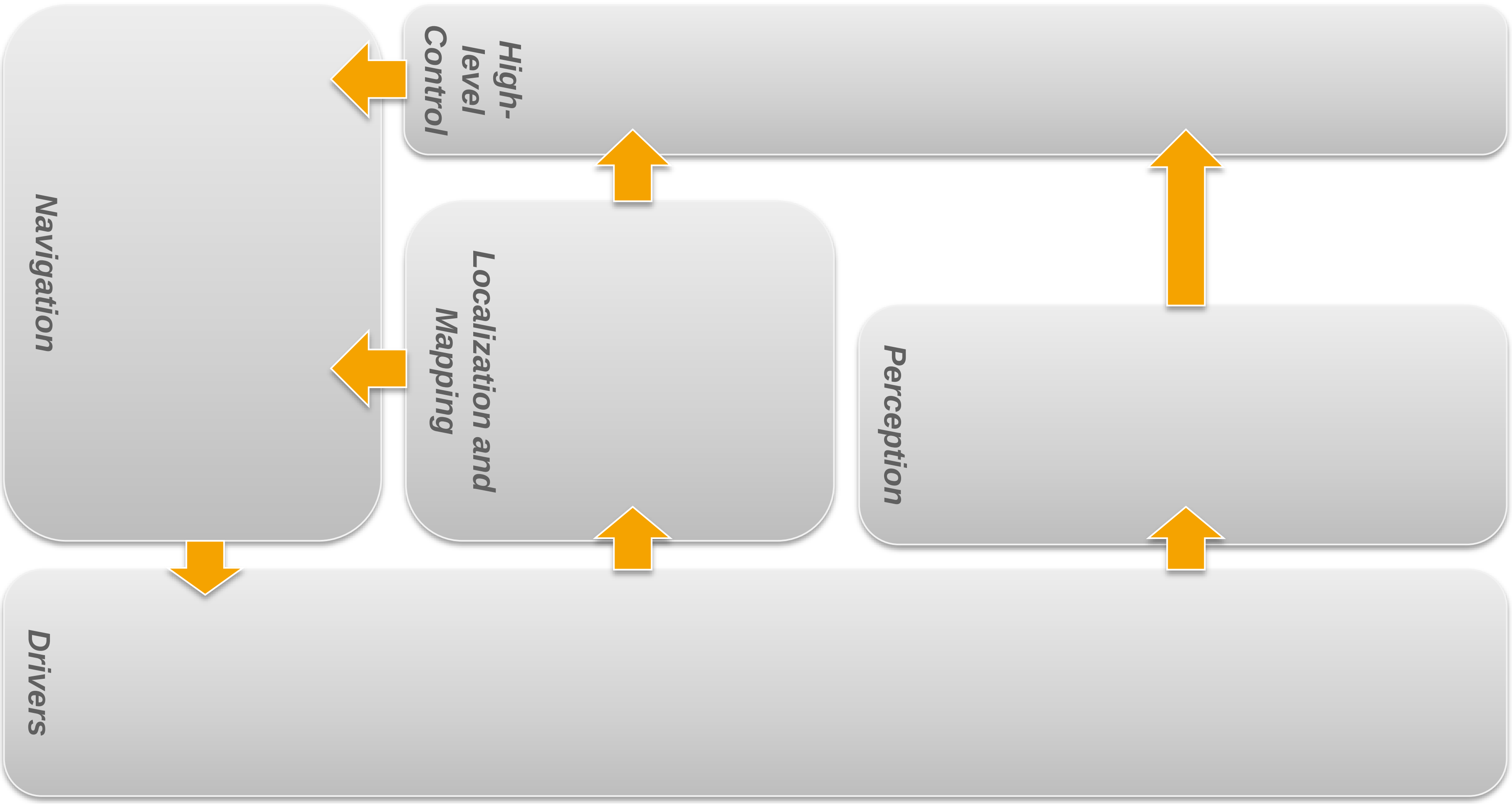
Hector Lightweight UGV
Teleoperation Demonstration
RoboCup 2011 Rescue Arena
9th July 2011 Istanbul

Building Blocks for a (Semi-)Autonomous Rescue Robot

- **Requirements**
  - Robust and flexible hardware platform
  - Autonomous exploration of unknown, complex environments
  - Detection of victims and other objects of interest
  - Interaction with other robots/with human rescue forces/with a human supervisor

➢ **Some problems to be solved…**
  - Self localization including full 3D pose estimation
  - Environment perception and mapping (2D or 3D)
  - Path planning and control
  - Detection, identification and tracking of objects using multiple cues
  - Reliable communication infrastructure
  - High-level decision making based on all inputs and external communication

System Overview



System Overview

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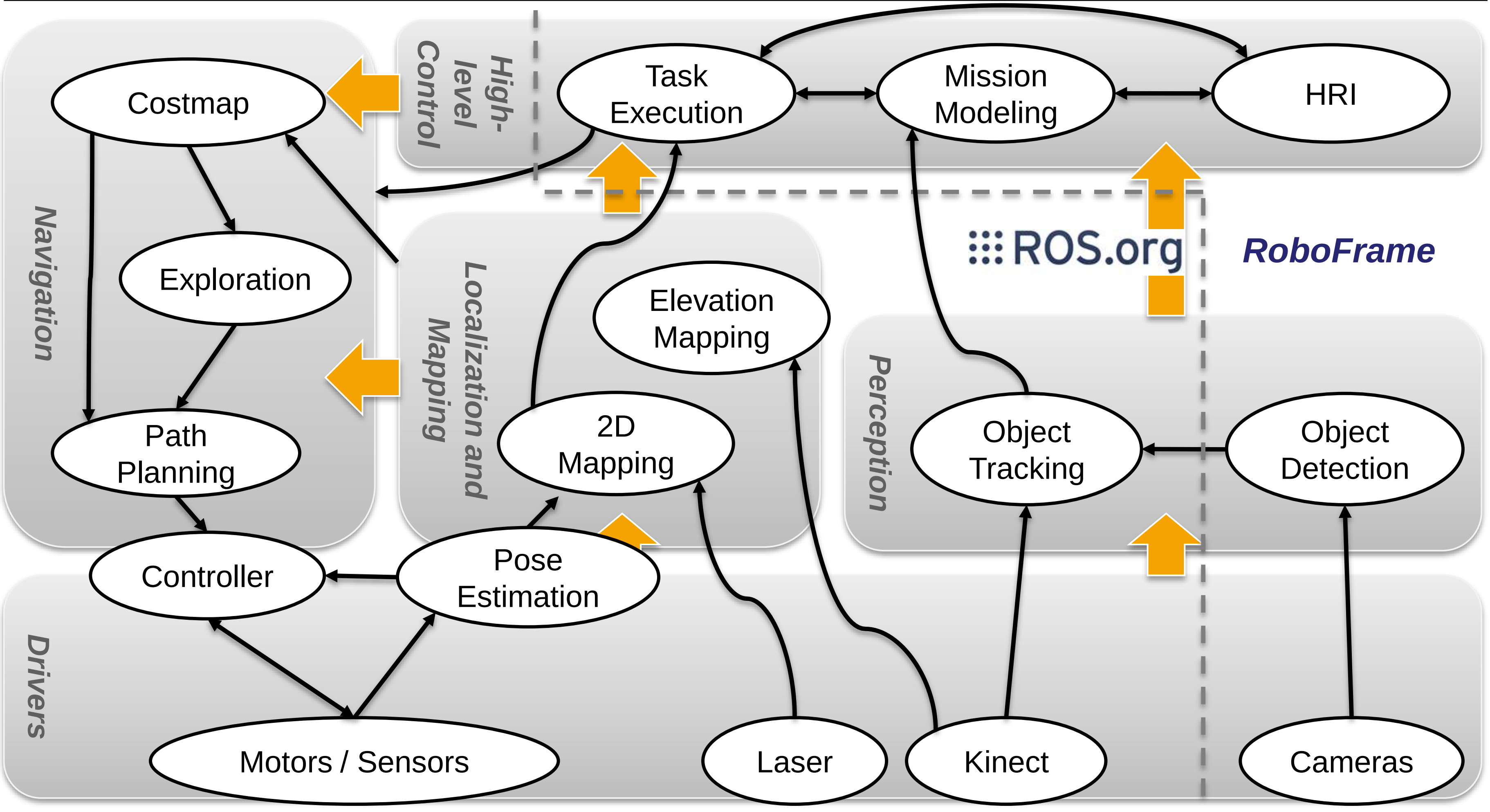
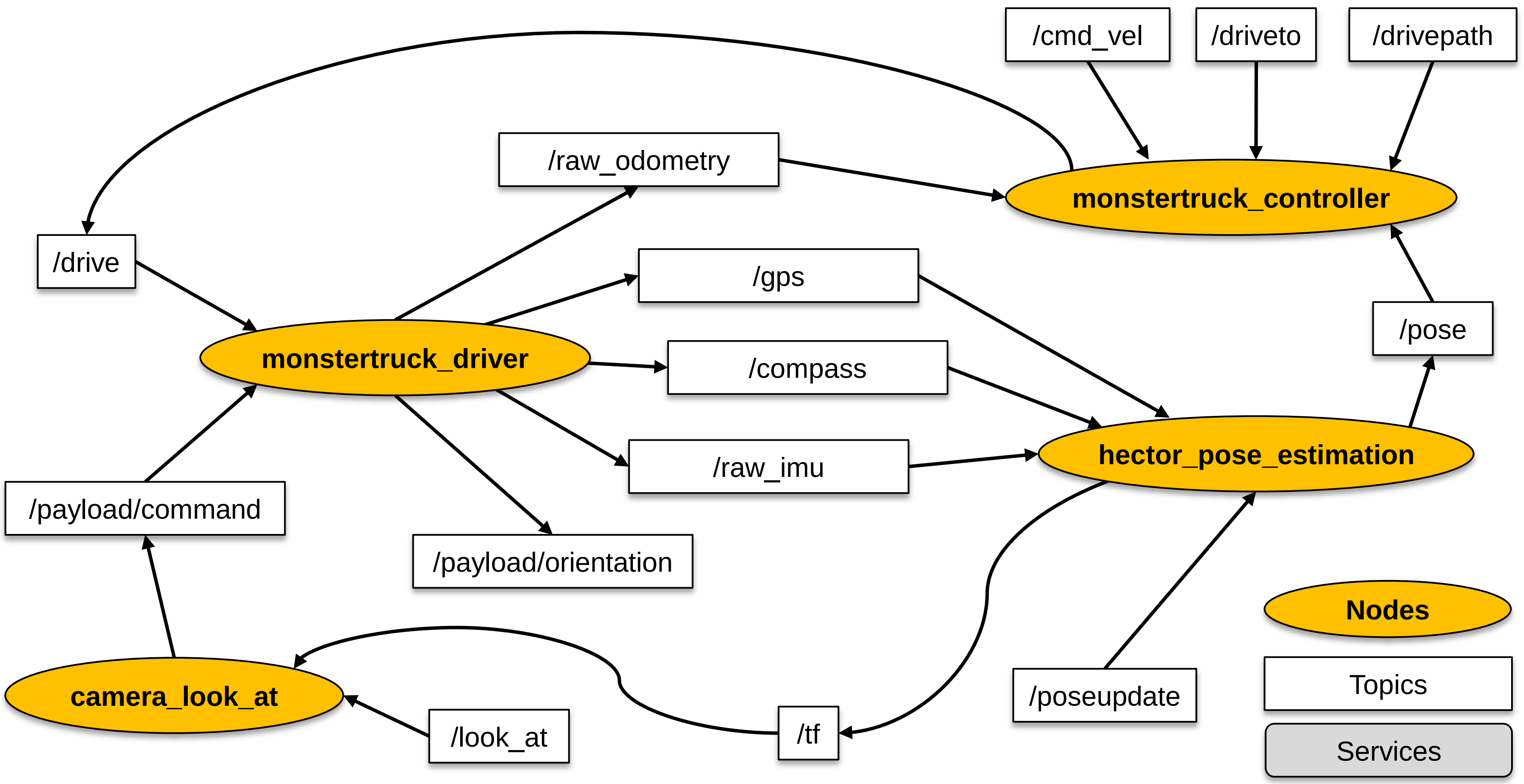


Hardware Drivers and Controllers

- **Real-time driver** running in Xenomai-enabled Linux
  - Speed control based on wheel odometry
  - Servo control
  - Interface to the integrated sensors
- **Controller** nodes provides platform independent motion interface
  - Drive to point, follow path
  - Look at point (using tf)
- **Pose Estimation** node
  - Extended Kalman Filter estimating the fused 9-DOF state vector (orientation, position, velocity)

Hardware Drivers and Controllers

ROS Graph



Localization and Mapping
The SLAM problem

- Build a map representation of the environment and simultaneously localize the robot within that map:
  - Range sensors / Laser scanner (LIDAR)
  - (3D-/Stereo-) Camera

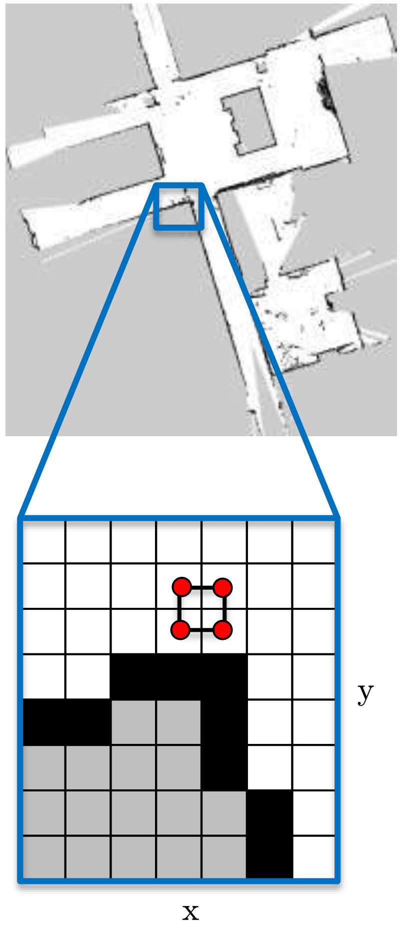
State of the Art:

- 2D SLAM: Gmapping, …
  $\rightarrow$ planar environments, odometry
- 3D SLAM: SLAM6D, …
  $\rightarrow$ currently not applicable for online use
- Visual SLAM: SBA, RGB-D-SLAM…
  $\rightarrow$ computationally expensive and error prone

Localization and Mapping

Occupancy Grid Mapping

- Map is represented by a 2D grid holding the probability P_{xy} of cell occupancy



1. Scan Transformation

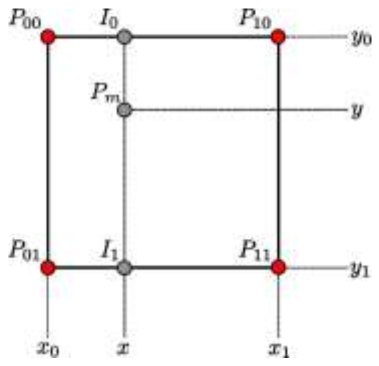
- Transformation of laser rays into the map frame

2. Scan Matching

- Alignment of incoming laser scans to the **map**

3. Map Update

- Increase P for each ray endpoint
- Decrease P for free cells



➢ **Efficient map query!**

Localization and Mapping

Inertial Navigation System

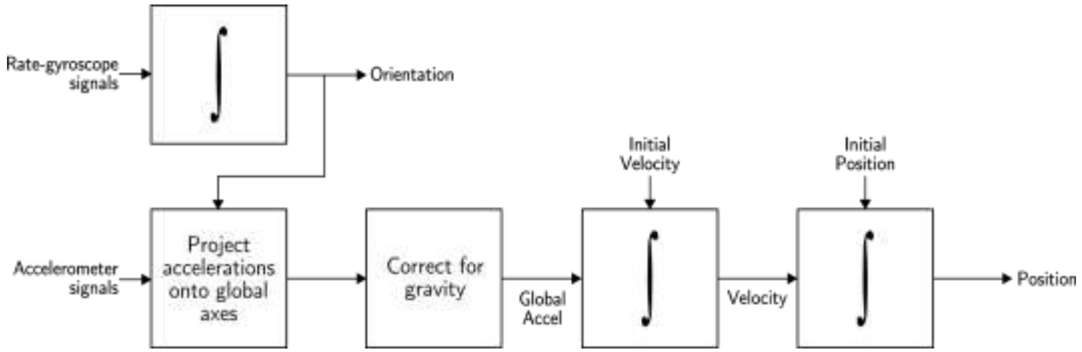
- Estimation of the **full 3D state** (position, orientation, velocity) of the robot from different sensor sources:
  - Inertial Measurement Unit (IMU)
  - Compass (Magnetic Field)
  - Global Satellite Navigation
  - Altimeter, Range Sensors etc.

$\}$ 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

Localization and Mapping

Navigation Filter

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

$$\bar{\mathbf{x}}_k = \left(\boldsymbol{\Omega}_k^{\mathrm{T}} \quad \mathbf{p}_k^{\mathrm{T}} \quad \mathbf{v}_k^{\mathrm{T}} \quad \delta\boldsymbol{\omega}_k^{\mathrm{T}} \quad \delta\mathbf{a}_k^{\mathrm{T}}\right)^{\mathrm{T}}$$

Orientation

Position

Velocity

Angular rate error

Acceleration error

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

$$\mathbf{u}_k = \left(\boldsymbol{\omega}_k^{\mathrm{T}} \quad \mathbf{a}_k^{\mathrm{T}}\right)^{\mathrm{T}}$$

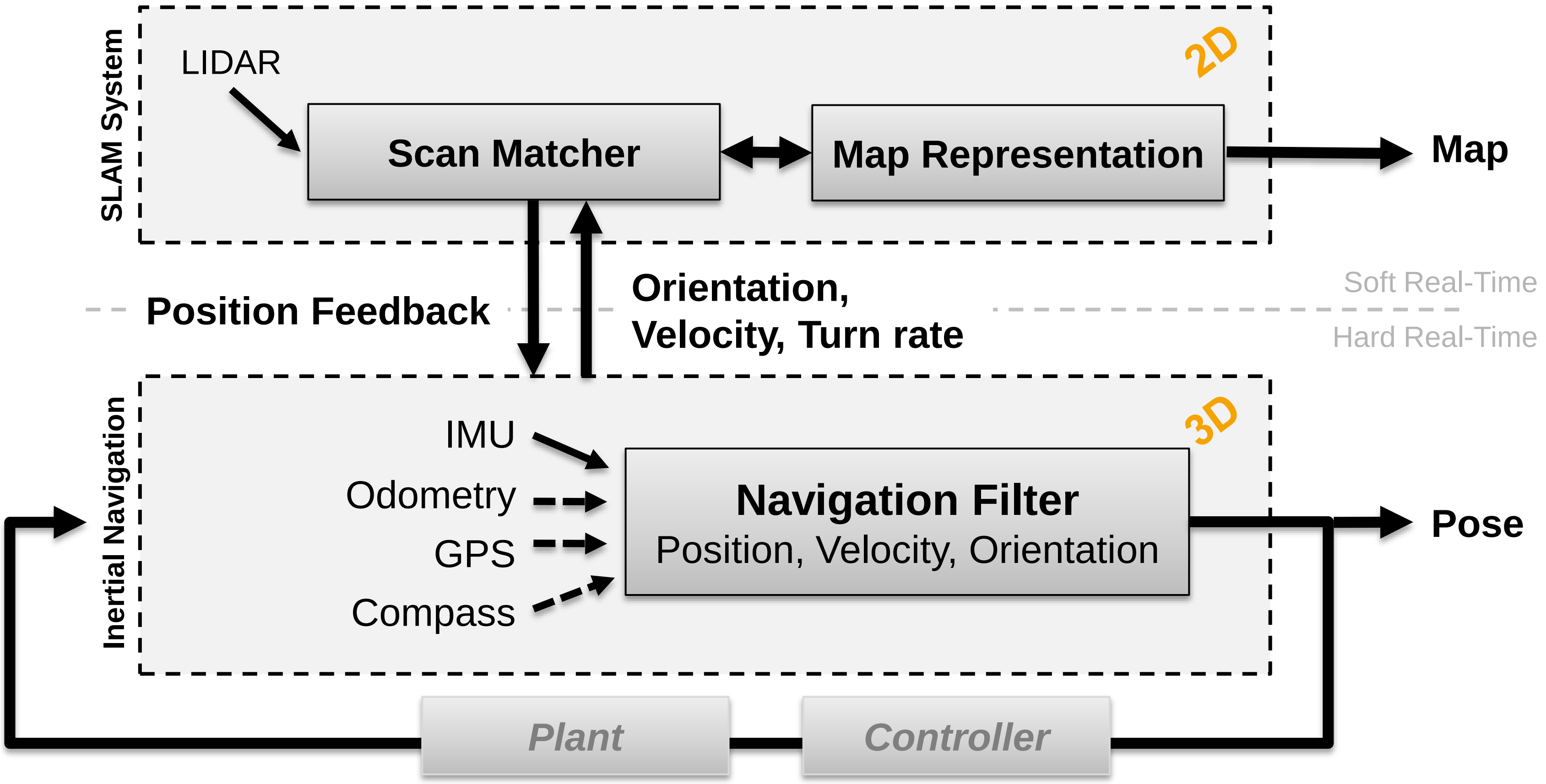
Angular rates

Accelerations

Localization and Mapping

Combine SLAM and EKF

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



Localization and Mapping
Integration

Pose Update from SLAM:

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

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

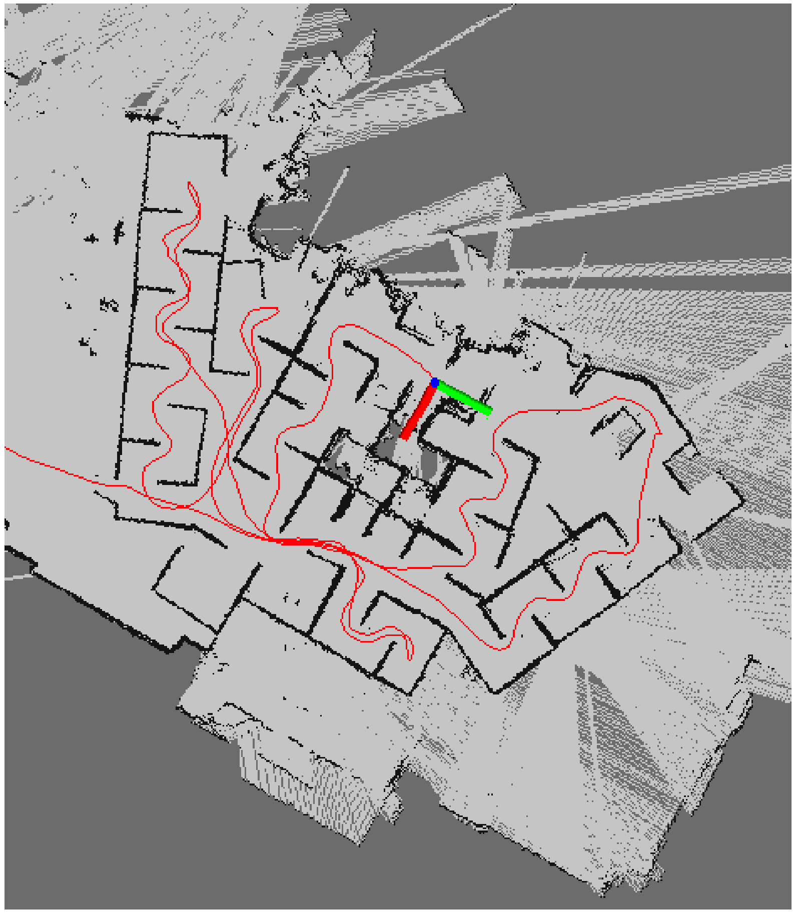
$$\boldsymbol{\mu}^{+} = \mathbf{P}^{+}\left((1-\omega)\cdot\mathbf{P}^{-1}\boldsymbol{\mu} + \omega\cdot\mathbf{C}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{z}\right)^{-1}$$

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	$\omega \in [0,1]$

Localization and Mapping
Trajectory Server

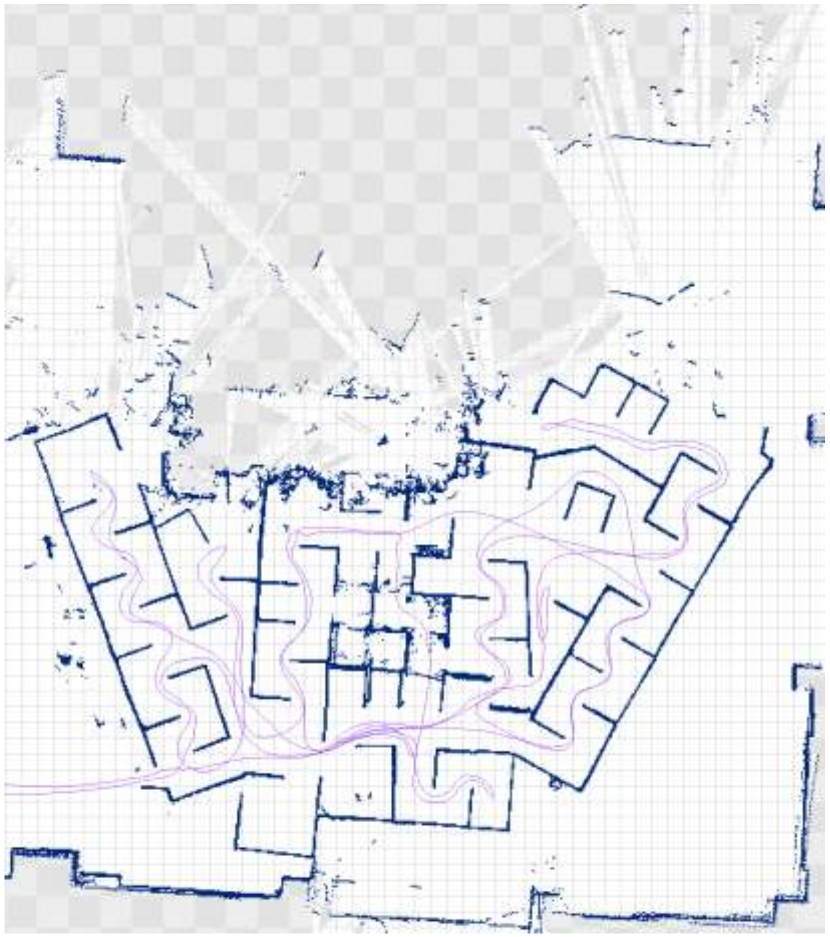
- Logs Trajectory based on tf data
- Make Data available as nav_msgs::path via
  - Regularly published topic
  - Service
- Currently used for
  - Visualization
  - GeoTiff node
- Can log any tf based trajectories



Localization and Mapping

GeoTiff node

- 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
  - Victim Locations



Localization and Mapping
Handheld Mapping

- 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

Localization and Mapping
Handheld Mapping

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

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

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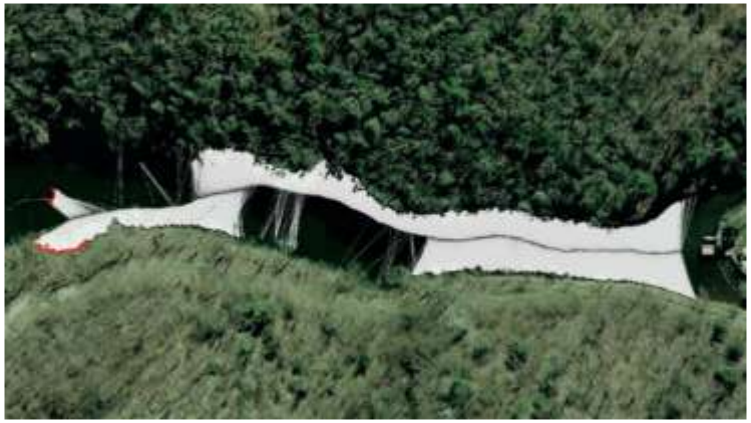
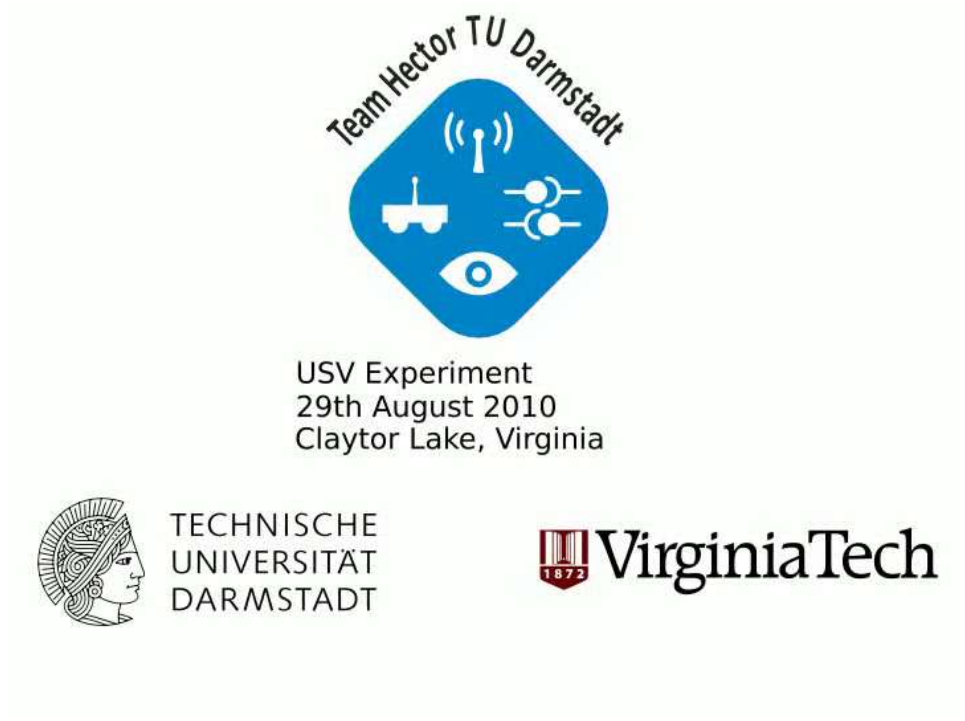
Localization and Mapping
USV mapping

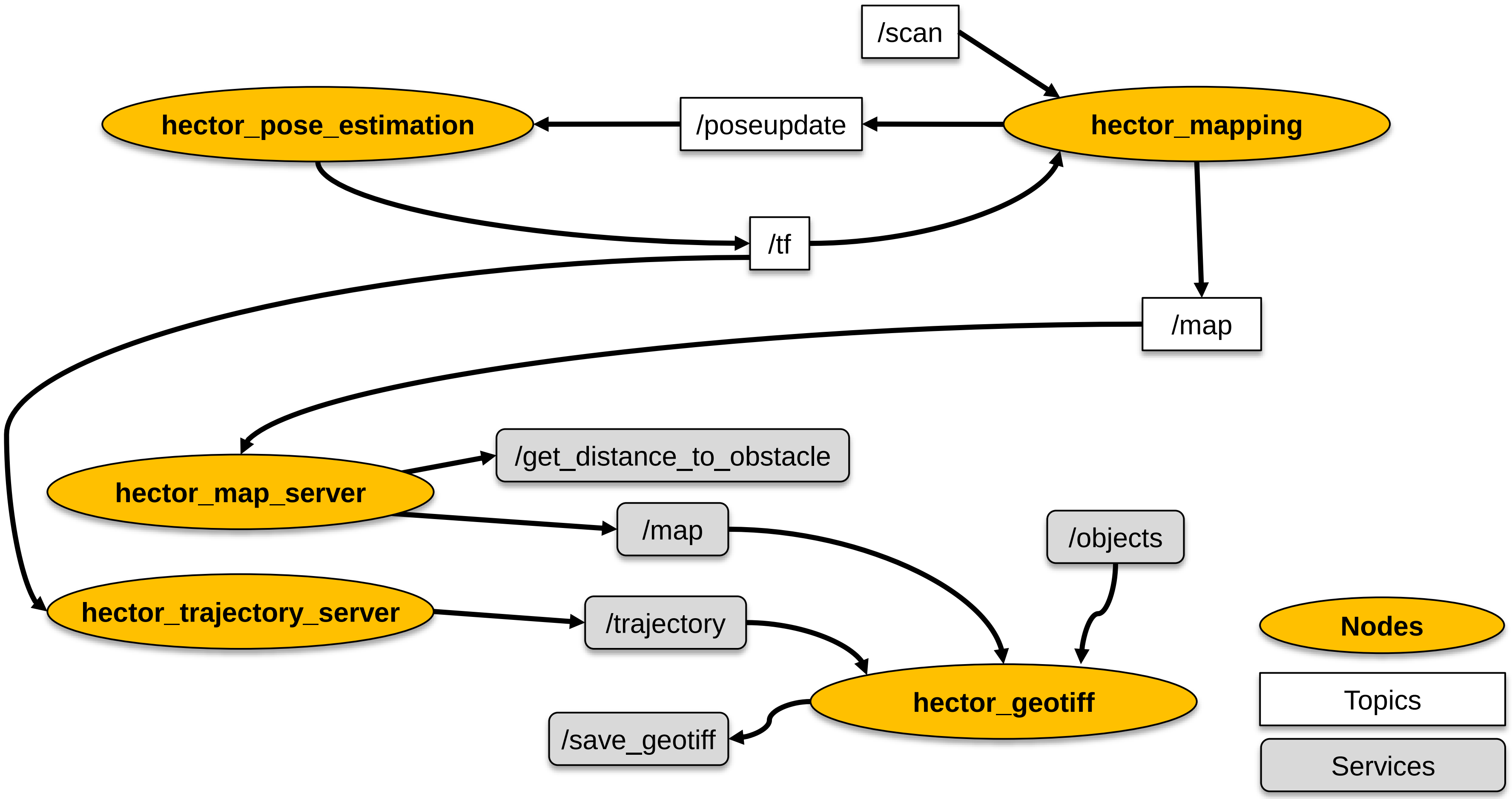
- SLAM System mounted on USV (Unmanned Surface Vehicle)
- Self-Contained, no interconnection with USV (apart from power supply)





Localization and Mapping

ROS Graph (1)



Localization and Mapping

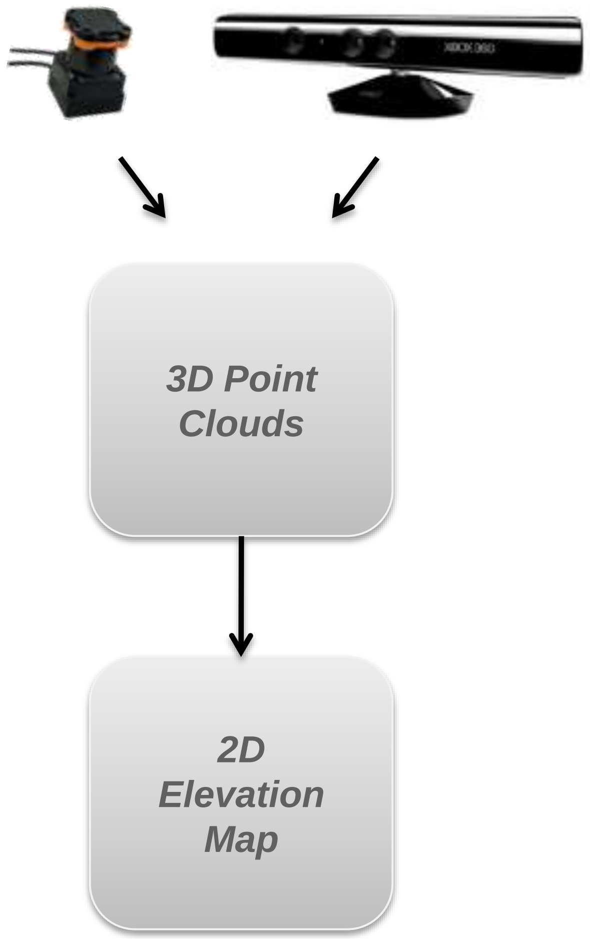
Elevation Mapping

Motivation:

- Elevation map is mandatory for ground robots
- For detection of
  - stairs
  - ramps
  - step fields
  - …
- No generic ROS package!

Proposed Map Representation:

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



Localization and Mapping

Elevation Mapping

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Kalman Filter based Approach:

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

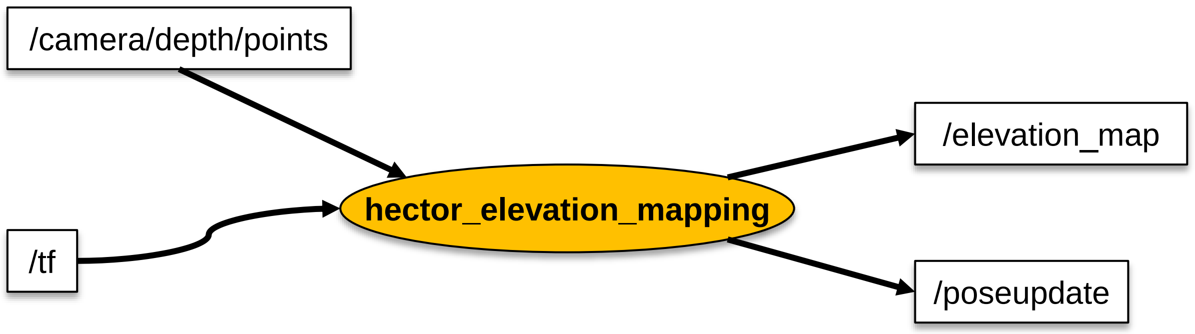
More precisely:

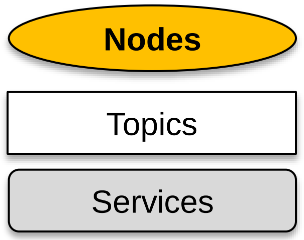
$$h(t) = \begin{cases} z(t) \\ h(t-1) \\ \frac{1}{\sigma^2_m + \sigma^2_{h(t-1)}} \left(\sigma^2_m h(t-1) + \sigma^2_{h(t-1)} m(t) \right) \end{cases} \qquad \sigma^2_{h(t)} = \begin{cases} \sigma^2_{z(t)} & \text{if } z(t) > h(t-1) \wedge dm < c \\ \sigma^2_{h(t-1)} & \text{if } z(t) < h(t-1) \wedge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

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

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

Localization and Mapping
ROS Graph (2)





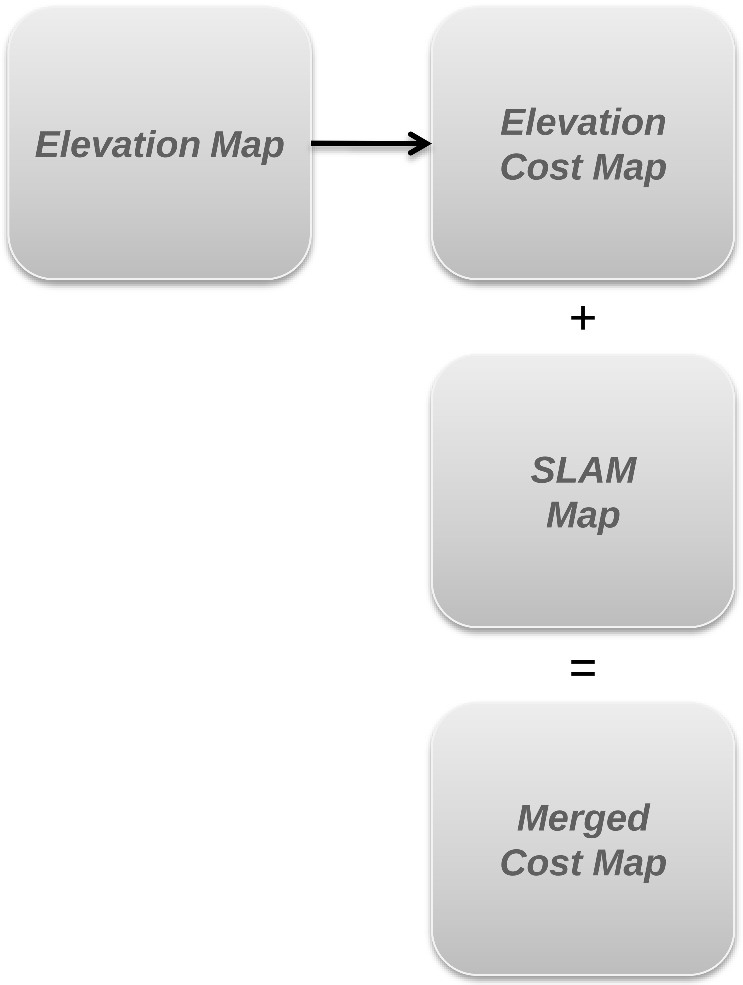
Navigation and Path Planning
Cost Mapping

Motivation:

- Avoid planning a path over untraversable regions
- Integration of depth and LIDAR information

Proposed Map Representation:

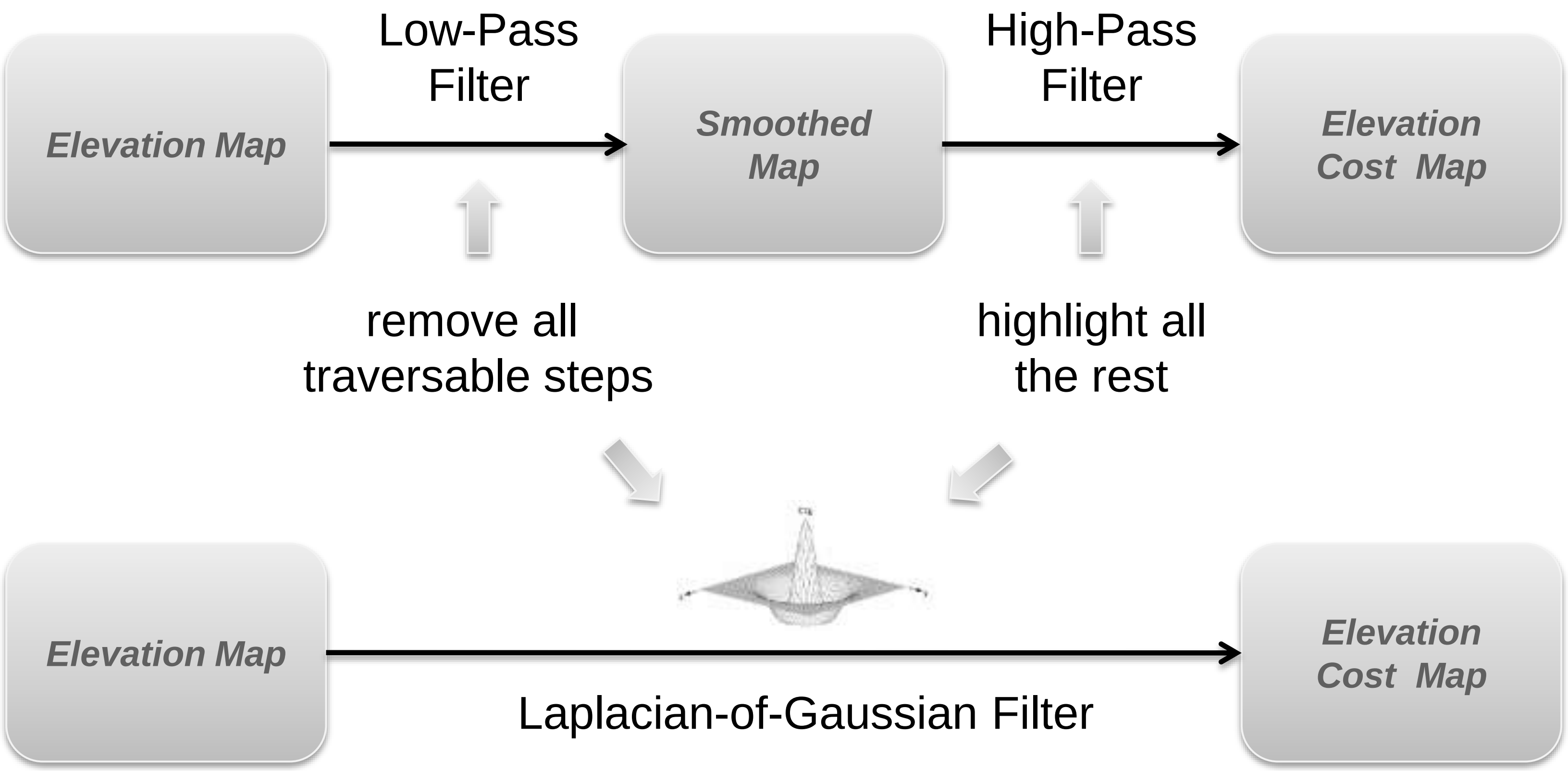
- Two-dimensional array (x,y)
- Occupancy grid map
  - Unknown
  - Free
  - Occupied



Navigation and Path Planning

Cost Mapping

Laplacian-of-Gaussian Filterkernel based Approach:

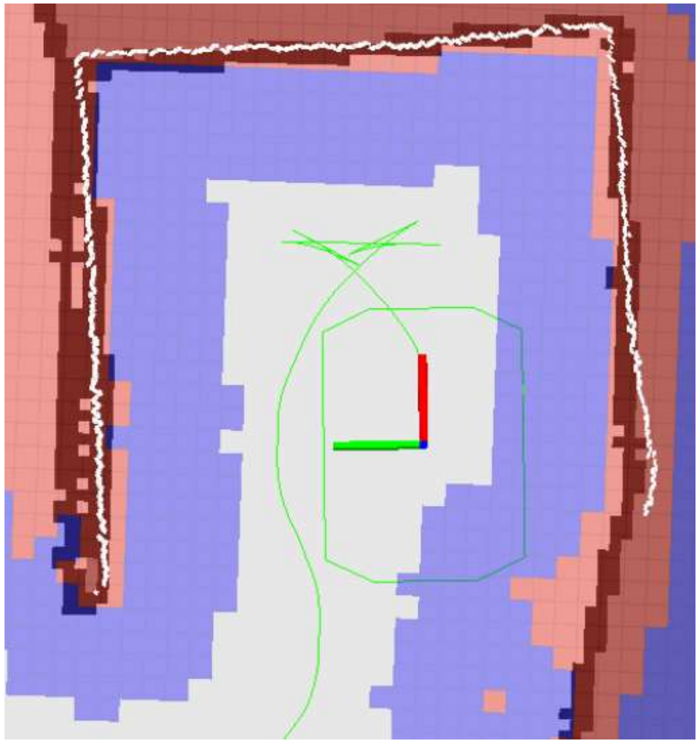


Navigation and Path Planning
Exploration

- Exploration Transform / Frontier based
- Uses CostMap2D based cost map
- Plugin for move_base
- **Capabilities**
  - Generate target pose and path simultaneously (exploration)
  - Plan path to given target pose
  - Create frontier based target pose

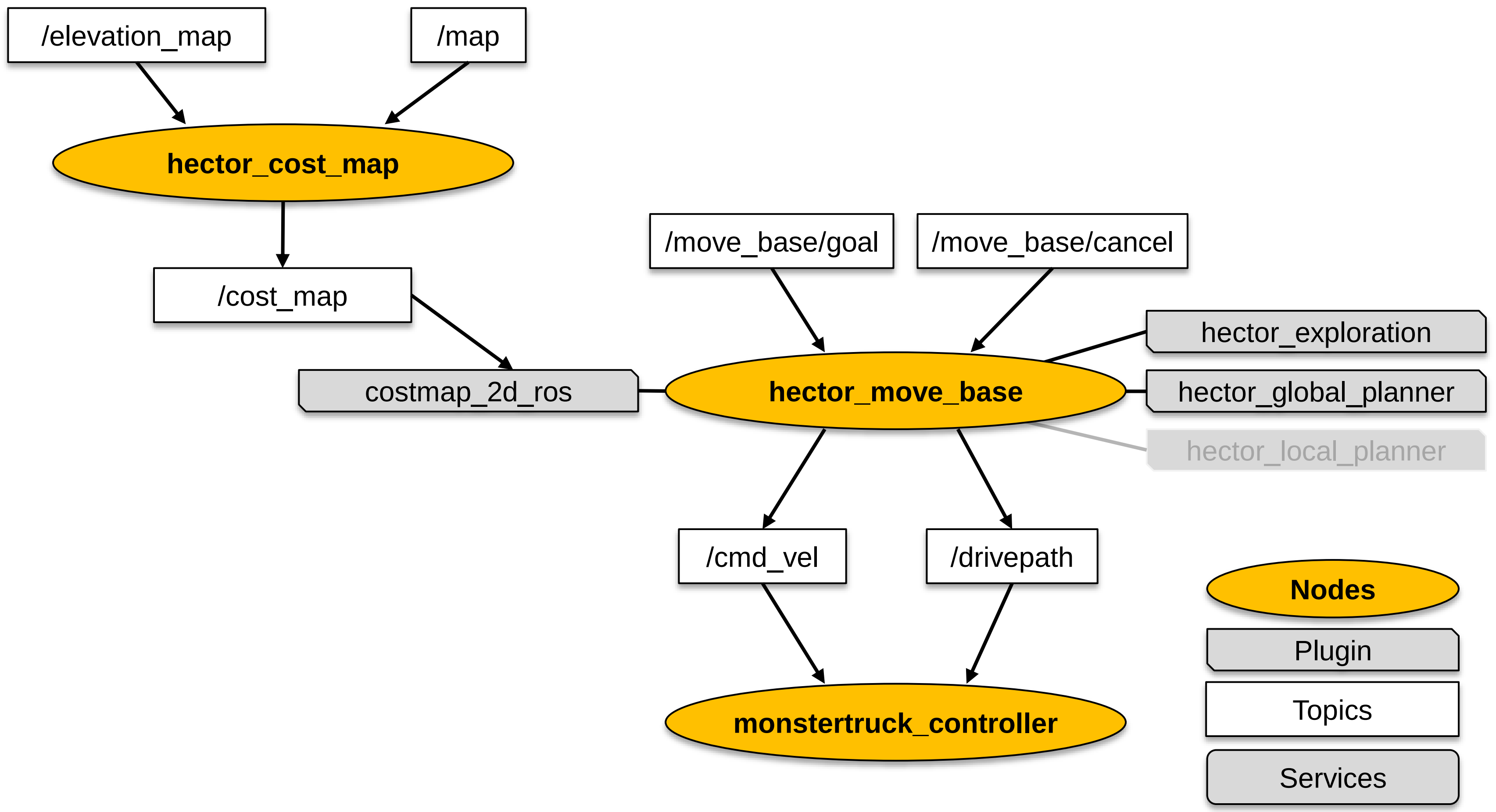
Navigation and Path Planning
Path Planning

- Problem: Hector UGV is a non-holonomic vehicle
  - Navigation stack supports only
    - Holonomic
    - Differential drive
- Solution:
  - Use OMPL/SBPL Lattice Planner
  - Modify move_base
    - Fixed Cost Map
    - Low Level Trajectory Follower for SBPL paths
    - Repeated Execution of SBPL (dynamic replanning)



Navigation and Path Planning

ROS graph

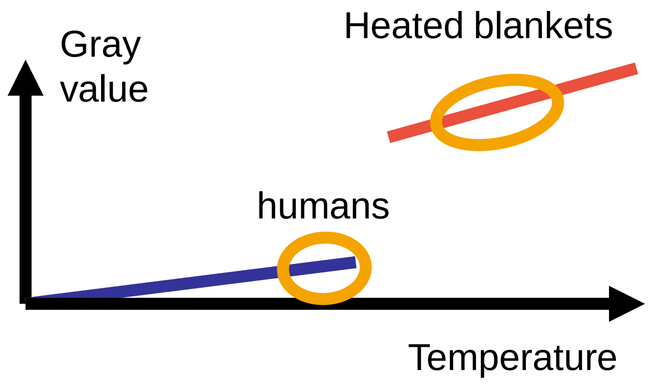


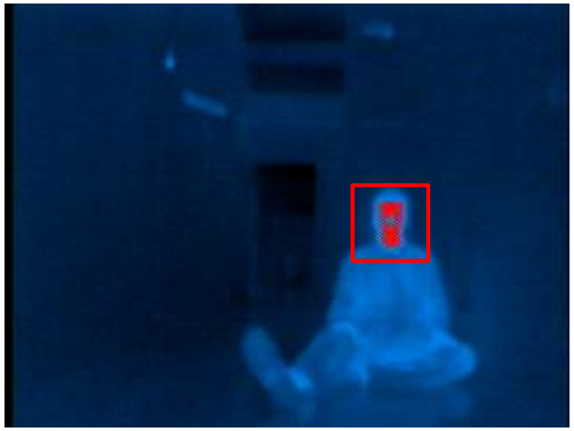
Victim and Object Detection

Thermal Victim Detection

- Search for groups of connected pixels with temperature of human body
- Significantly less reliable than visual people detection (in real-world scenarios)

- Define confidence $s^{\text{therm}} \in [0,1]$ proportional to the number of pixels within human body temperature range



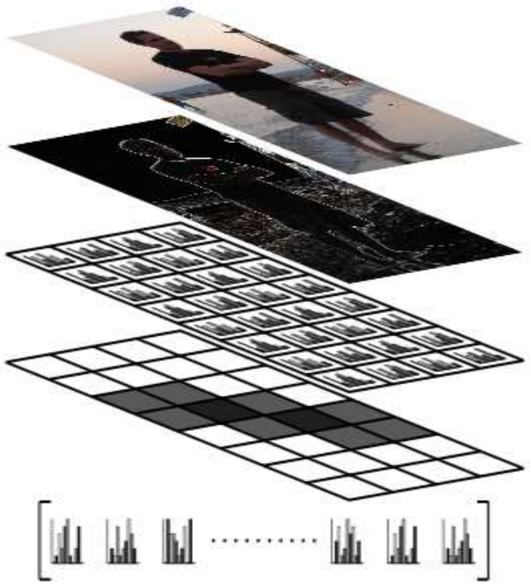


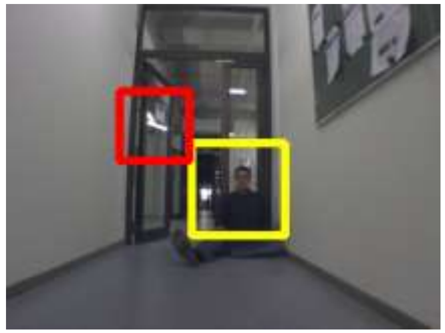
ThermalEye 3600AS

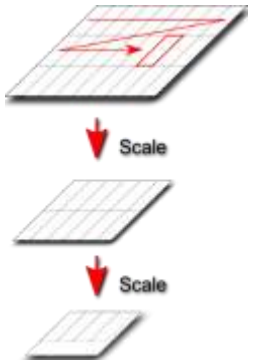
Victim and Object Detection

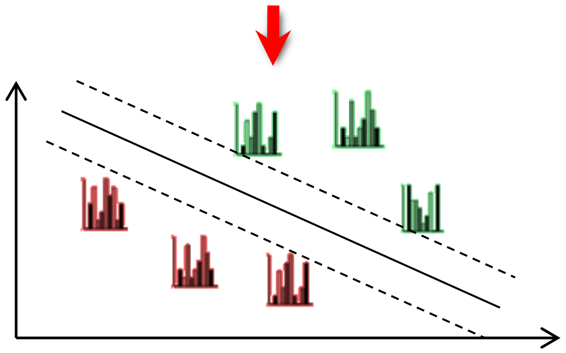
Visual Victim Detection

- Detection of upper bodies in camera images based on
  - Histograms of Oriented Gradients (HOG)
  - Discriminative SVM classifier
- Parallel computation on GPU
- Define hypothesis confidence $s^{\text{vis}} \in [0,1]$ derived from SVM score
- Generalization to other kind of objects









Victim and Object Detection

Object Association and Tracking

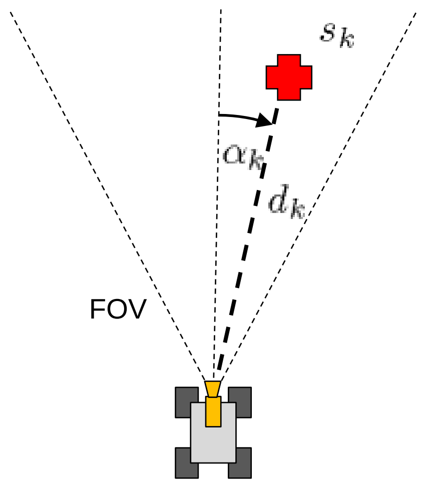
- Tracking of uncertain victim/object estimates $\{\mathbf{x}_k^j, P_k^j, \pi_k^j\}$ over time
  - $\mathbf{x}_k^j, P_k^j$ 3D position vector and covariance
  - π_k^j Confidence (1 – error probability)
- Robot position and camera transformation are assumed to be known

Algorithm:

- **For each new hypothesis $\{\mathbf{z}_k, s_k\}$ with $\mathbf{z}_k = [d_k, \alpha_k, \beta_k]^T$:**
  - **Data association:** Find best matching victim estimate j^* that minimizes a distance measure in measurement space (or instantiate a new one)
  - **Position update:** Update position using an EKF that additionally considers the hypothesis confidence s_k
  - **Confidence update:** Increase victim confidence according to

$$\pi_k^j = \pi_{k-1}^j + s_k \cdot (1 - \pi_{k-1}^j)$$

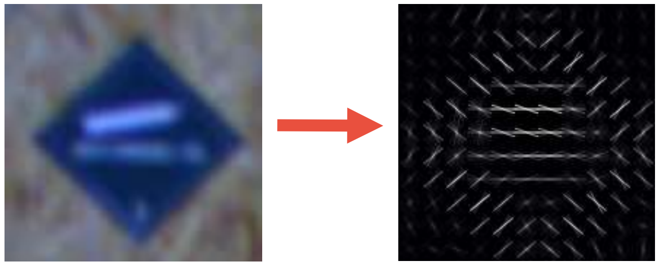
- **Negative update:** Decrease confidence of all estimates not being observed despite estimated position is within FOV (optional)



Victim and Object Detection
Hazmat Signs

- Detection of signs of hazardous materials
- HOG cannot distinguish between different objects with similar shape
- Augmentation through color histograms in LAB-space for classification
- Two step approach:
  - Search for candidates with HOG / SVM
  - K-nearest-neighbor classification

TOXIC
6
INFECTIOUS SUBSTANCE
6
INHALATION HAZARD
2
FLAMMABLE GAS
2
DANGEROUS
4
OXIDIZER
5.1
NON-FLAMMABLE GAS
2



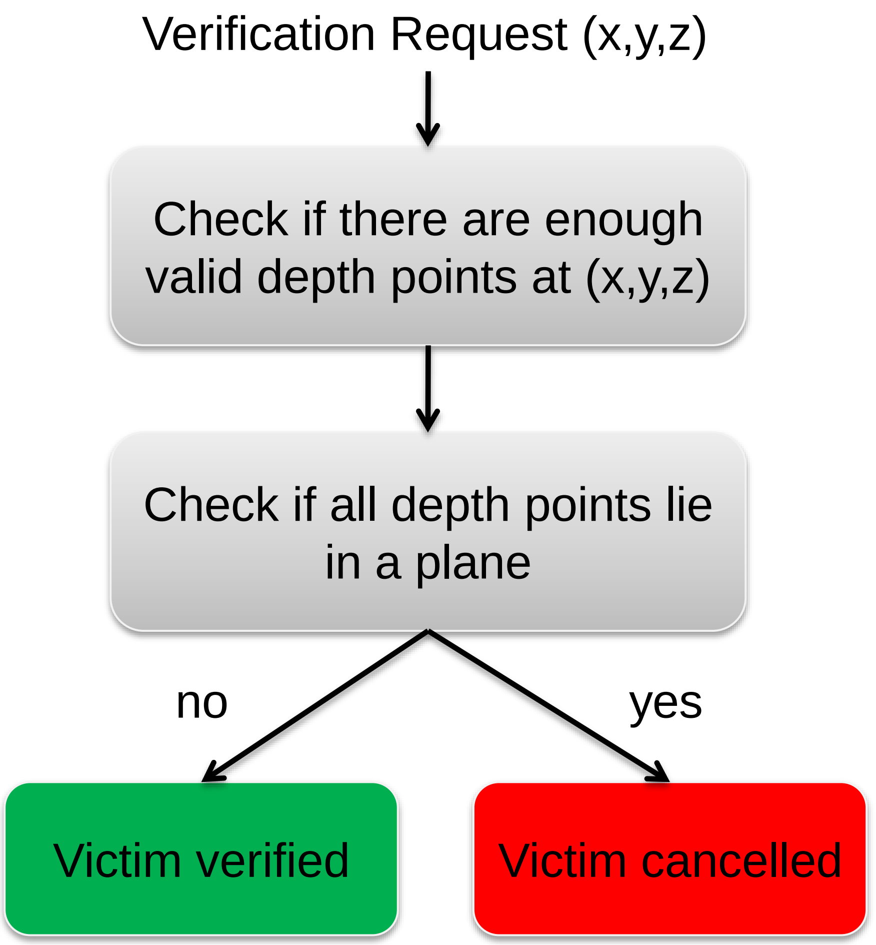
Victim and Object Detection
Victim Depth Verification

Motivation:

- Verify thermal and visual victim hypotheses
  - ➢ Eliminate false-positives
- Uses MS Kinect
- First experiments at Robocup 2011, Istanbul

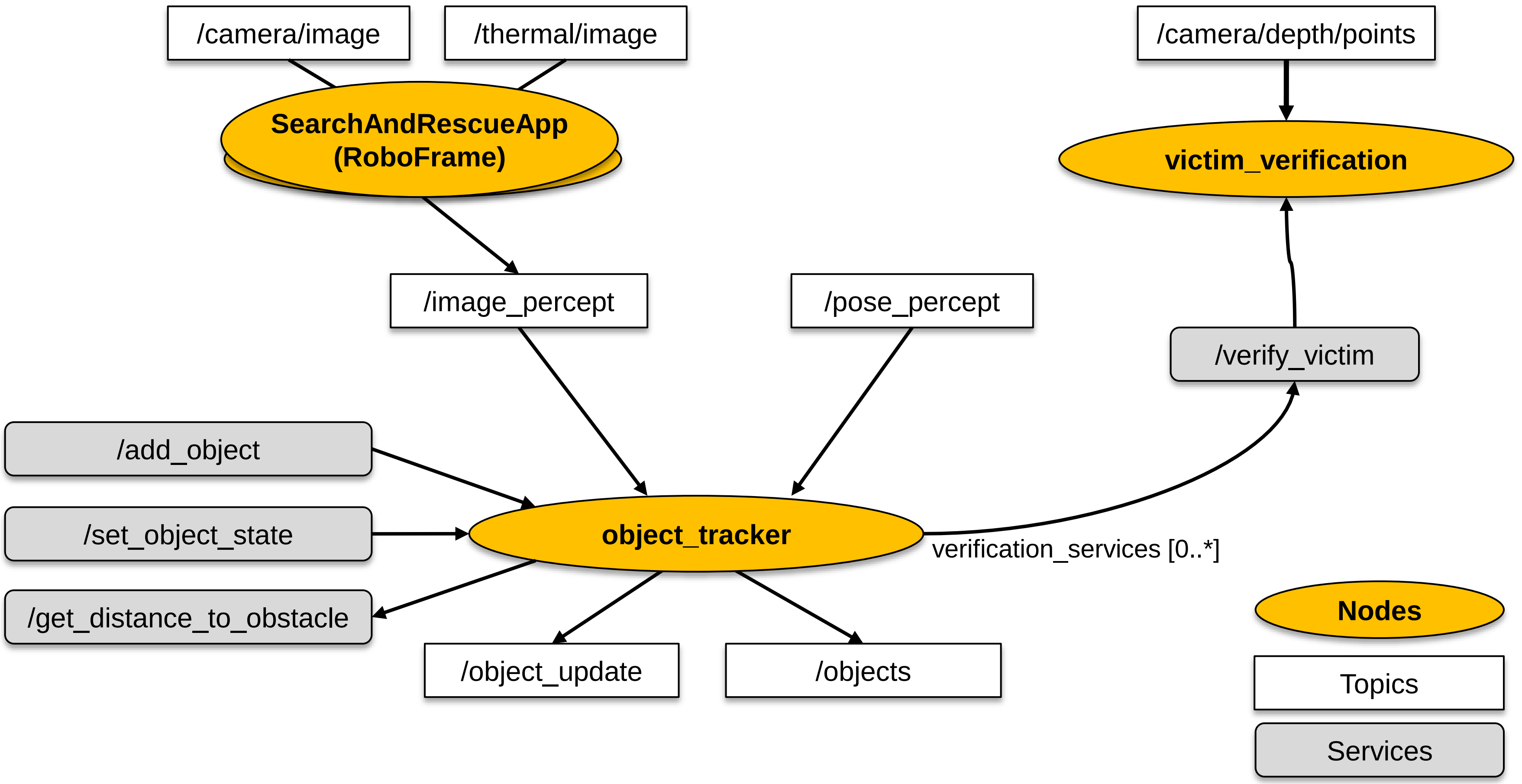
Low-Level Hypotheses:

- A valid victim is measurable by a depth camera (point cloud)
- A valid victim is not flat


Verification Request (x,y,z)
Check if there are enough valid depth points at (x,y,z)
Check if all depth points lie in a plane
no
yes
Victim verified
Victim cancelled

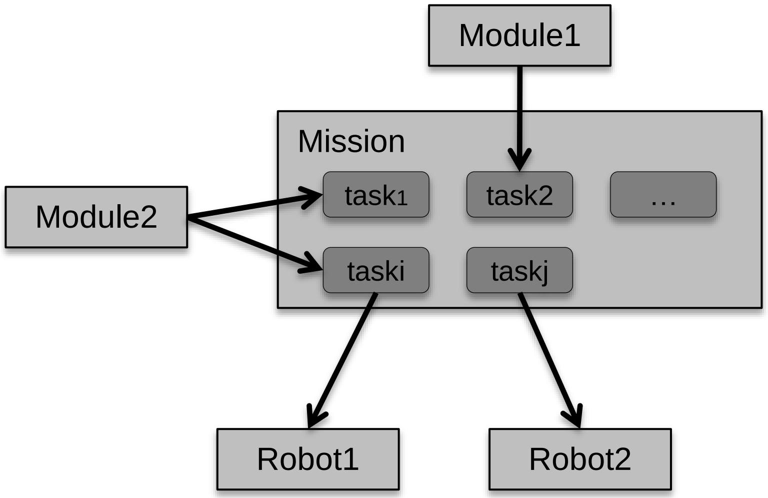
Victim and Object Detection

ROS Graph



High-Level Control
Task Allocation

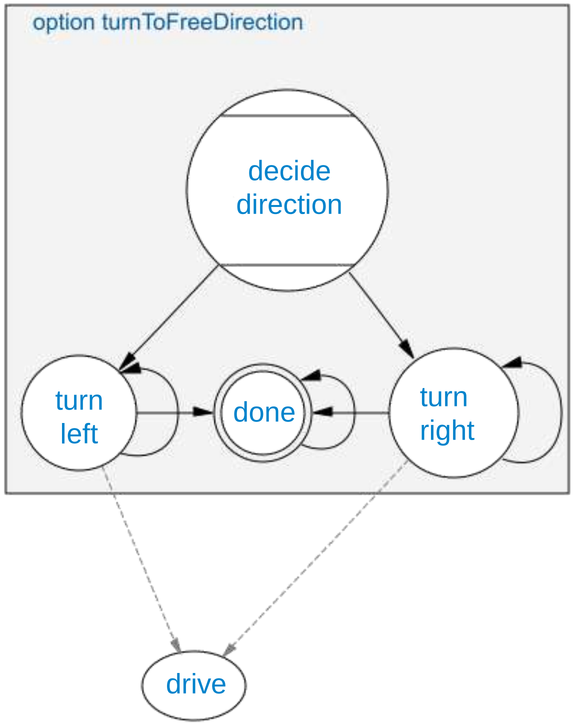
- Modules generate tasks for desired actions
  - Explore area
  - Verify victim hypotheses
- Calculate cost to execute tasks
  - Metric can include
    - Estimated duration to accomplish a task
    - Assumed gain of task execution
    - Expected quality of solution
  - Scale with task priority
- Task Allocation
  - Single robot: Greedily allocate task with lowest cost
  - Multiple robots: Use more sophisticated task allocation algorithm, for example market-based
  - Allow re-allocation if high-priority tasks emerge



High-Level Control
Behavior with XABSL

- Details on how to execute specific tasks
  - Request desired position + orientation of robot
  - Move camera

- Realized with XABSL (eXtensible Agent Behavior Specification Language)
  - Hierarchical finite state automata
  - Each state machine is called **option**
  - Each state can execute other options or low-level behaviors
  - Intermediate code is interpreted by the XABSL-Engine

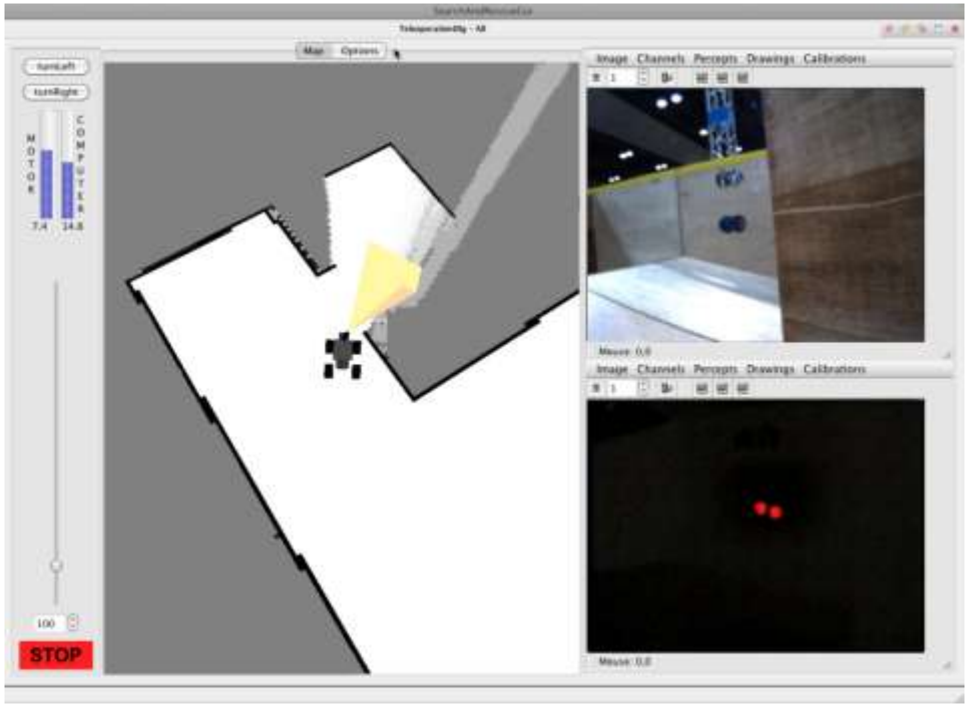


➢**Reusability of fine-tuned behavior in many high-level options**

➢**Behavior can be modified during runtime**

Human-Robot Interaction

- Teleoperation
  - Direct control of robot motions
  - Control of cameras
- Semi-autonomous operation
  - Goal selection via point-and-click
  - Autonomous path planning
- Supervision of robot teams
  - Control team coordination
  - Modify mission details
  - Influence task allocation

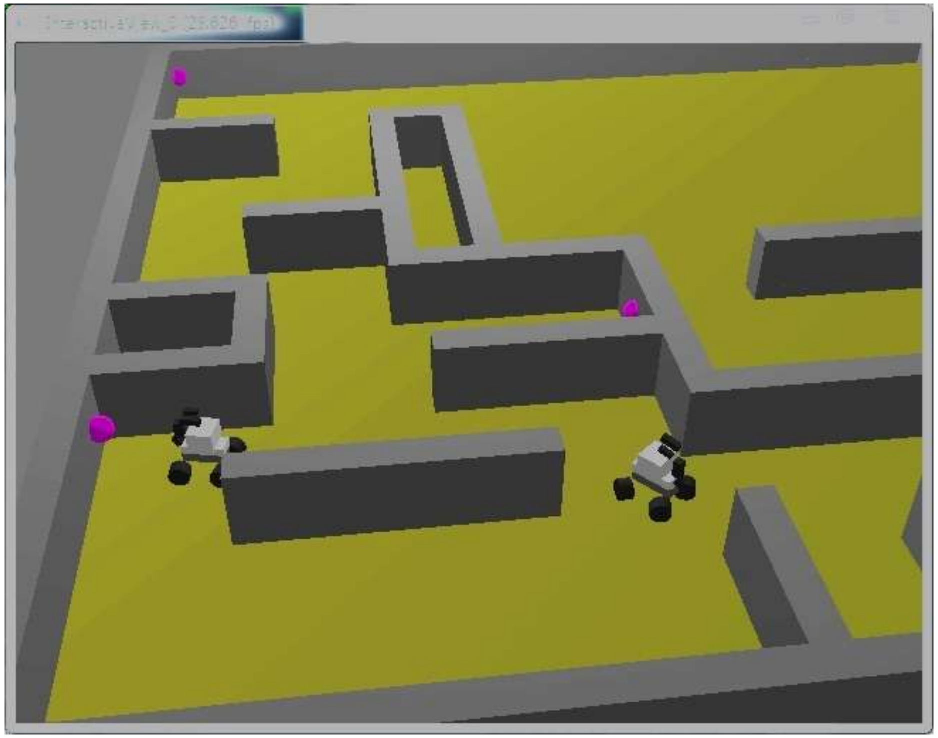


- GUI so far based on RoboFrame

→ New solution will be presented after lunch

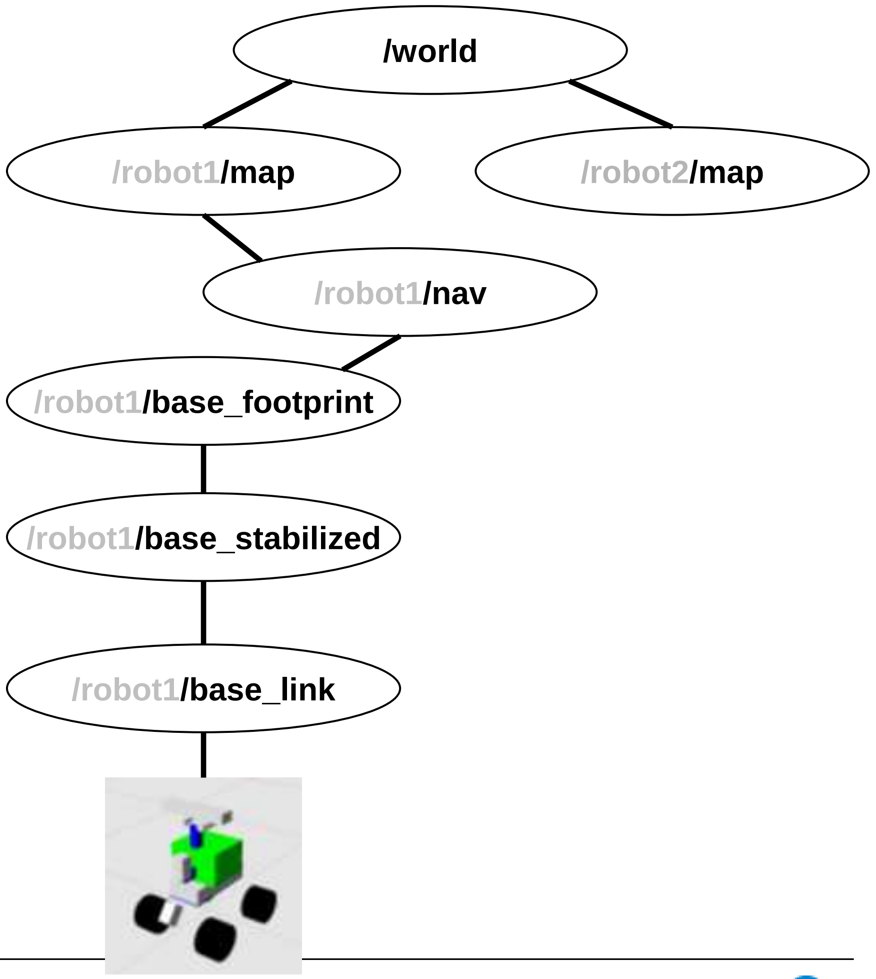
Simulation

- Based on the Multi-Robot-Simulation-Framework MuRoSimF
  - Software-in-the-loop testing
    - Run same code as on real robots
    - Test software functionality without hardware
  - Arbitrary mazes and robots
  - Simulation of various sensors
    - Camera
    - Thermal camera
    - Laser range finder
  - Ground-truth data
    - Simplifies evaluation and tuning of algorithms
- Communication between ROS and robot firmware



Some Additional Considerations

- **/syscommand**
  - Reset internal state of all nodes simultaneously
- **tf package**
  - No clear definition of frames



Open Questions

- **Simulation environment** providing a complete Rescue arena
  - Gazebo
  - USARsim
  - Morse
- **Multi-robot scenarios**
  - Multi-master
  - Map merging
- **Integrated GUI solution**
  - RViz + Tools
  - General Rescue GUI

Current State of ROS packages

Package	Release	Generality	Document.
monstertruck_driver	✘	✘	✘
hector_pose_estimation	(✓)	✓	●
hector_mapping	✓	✓	●
hector_trajectory_server	✓	✓	●
hector_geotiff_node	✓	✓	●
hector_elevation_mapping	●	✓	✘
hector_move_base (+ Plugins)	●	●	✘
object_detection	●	●	●
object_tracking	●	✓	●
victim_depth_verification	●	✓	✘
SearchAndRescueApp	✘ **(Roboframe)**	✓	●
SearchAndRescueGui	✘ **(Roboframe)**	●	●