Leveraging 3D Perception for RoboCup Rescue and the DARPA Robotics Challenge

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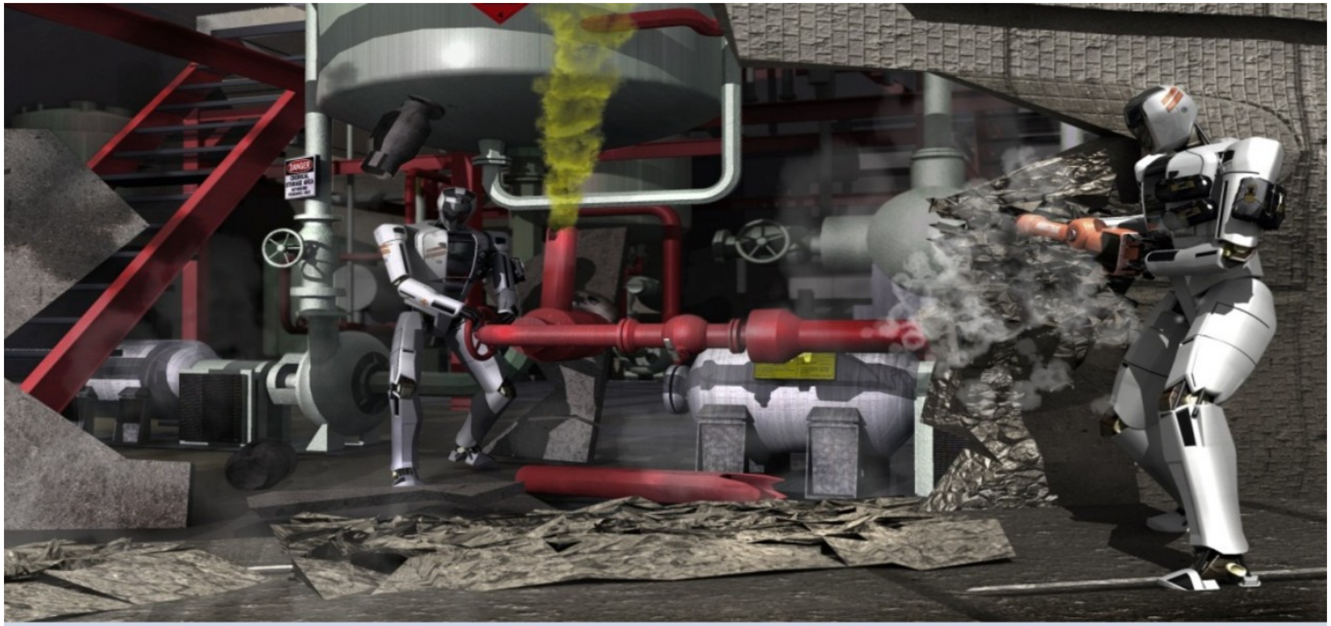
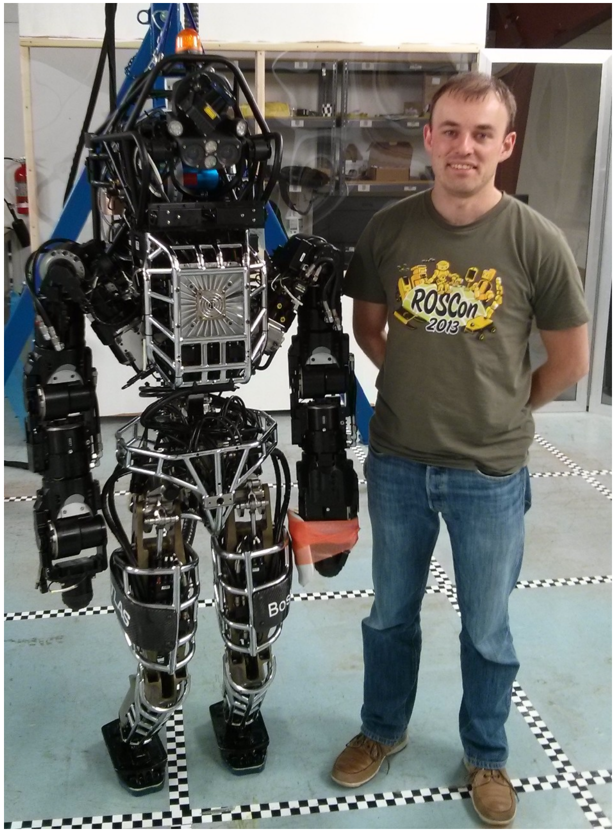


Short Introduction

- Researcher/PhD student with Simulation, Systems Optimization and Robotics group at TU Darmstadt
- Team leader Team Hector Darmstadt
- Onboard software lead DRC Team ViGIR
- Author/co-author
  - hector_slam
  - hector_quadrotor
  - hector_exploration_planner
- Interested in
  - Autonomy for USAR scenarios
  - Operator support through autonomous capabilities
  - Advancing robotics through open source software

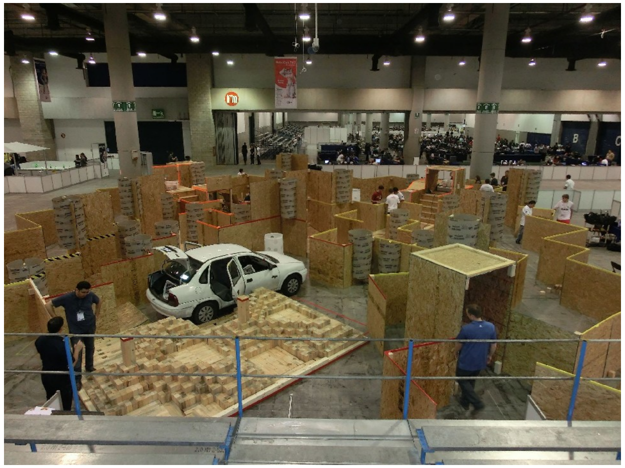


Overview

- Present two applications of 3D perception in competitive environments:
  - RoboCup Rescue
    - Team Hector Darmstadt
  - DARPA Robotics Challenge
    - Team ViGIR
- Focus
  - Give overview of competitions
  - Leveraging 3D geometry also for tasks other than robot localization/mapping

RoboCup Rescue RRL

- RRL stands for “Real Robot League”
- Goals of the urban search and rescue (USAR) robot competitions:
  - Increase awareness of the challenges involved in search and rescue applications
  - Provide objective evaluation of robotic implementations in representative environments
  - Promote collaboration between researchers.
- Requires robots to demonstrate their capabilities in
  - Mobility
  - Sensory perception
  - Planning
  - Mapping
  - Practical operator interfaces
- http://wiki.robocup.org/wiki/Robot_League



RoboCup Rescue - Details

- Tasks:
  - Find victims (simulated by baby dolls, heat blankets)
  - Create arena map
  - Detect and map QR codes
  - Deliver supplies to victims
- Different kinds of arenas
  - Yellow
    - Medium difficulty terrain
    - Only autonomous robots allowed
  - Orange arena
    - Harsh terrain
  - Red arena
    - Extremely difficult terrain
  - Blue arena
    - Manipulation
- Different Control Modes
  - Teleoperation
  - Autonomous

Team Hector Darmstadt

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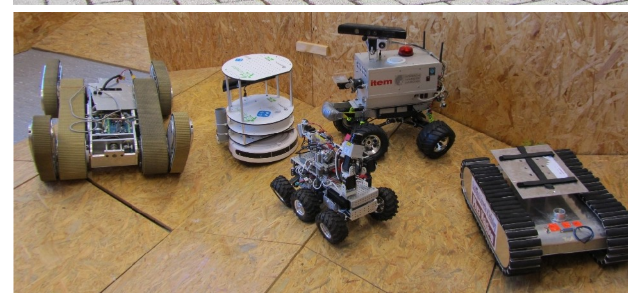
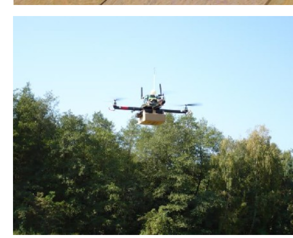
- **He**terogeneous **C**ooperating **T**eam **o**f **R**obots
- Part of GRK 1362 “Cooperative, Adaptive and Responsive Monitoring in Mixed Mode Environments”
- Focus on autonomous systems for monitoring/exploration in disaster scenarios
  - Example/validation scenario RoboCup Rescue
- People
  - ~4 PhD students
  - Many highly motivated grad/undergrad students
- Robots
  - 5 Unmanned ground vehicles (UGVs)
  - 4 Unmanned aerial vehicles (UAVs)
- Successful participation in international competitions
- Major parts of developed software available to the research community

  Team Hector website

  Team Hector on Facebook

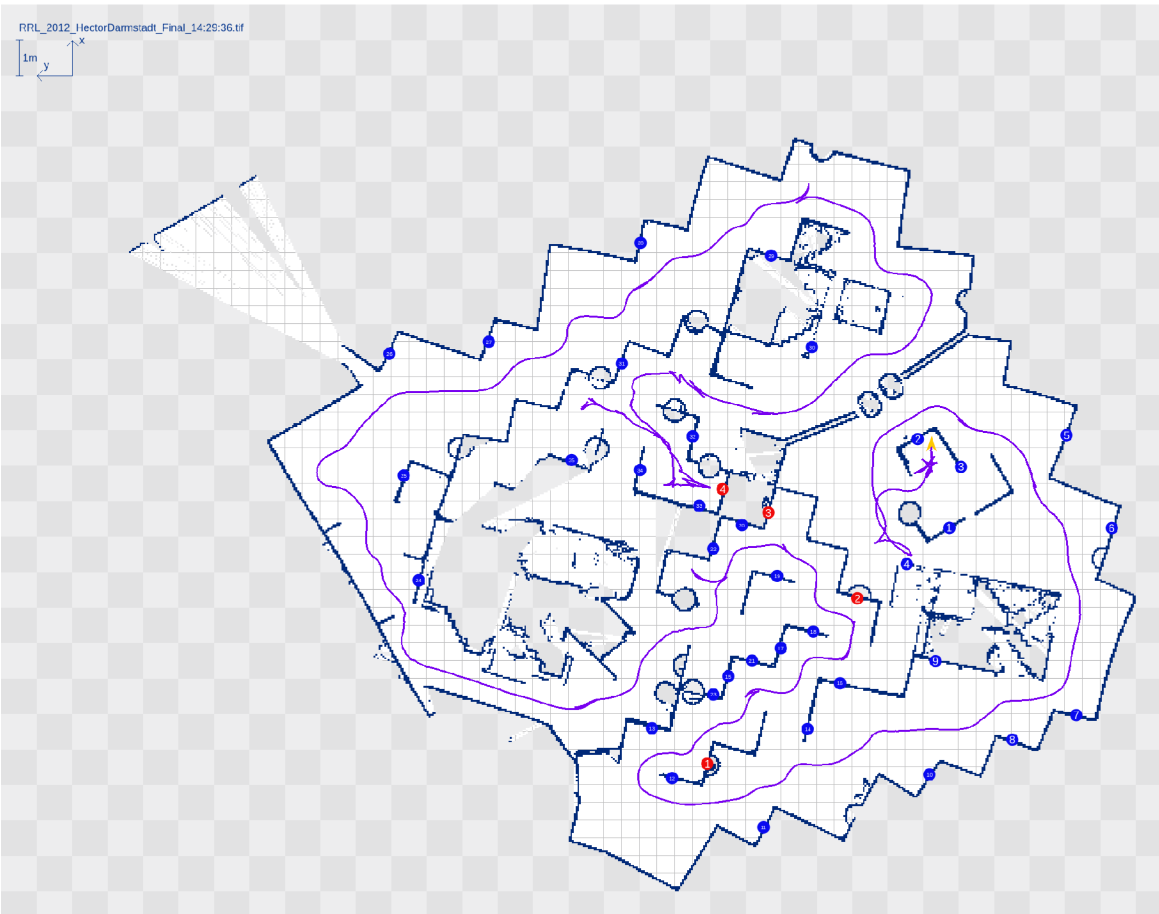




Team Hector - Some History

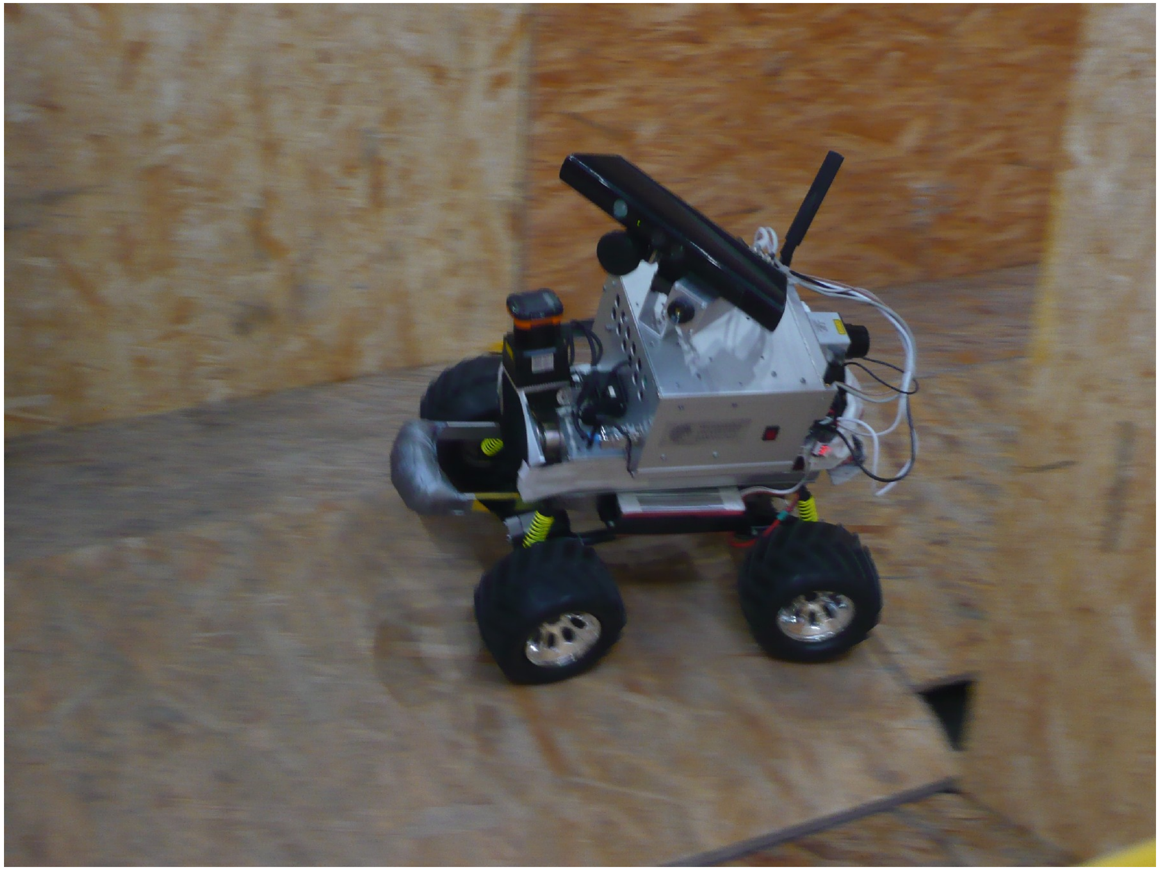
- EMAV 2009
  - Winner outdoor competition (quadrotor)
- RoboCup German Open
  - Winner 2011, 2012, 2013
  - Best in Class Autonomy 2011, 2012, 2013
- RoboCup
  - 2nd place overall 2012
  - Best in Class Automony 2012, 2013
- RoboCup standard software effort
  - Contributed software, see RoboCup Rescue on ros.org
  - Participation in summer schools and camps

Results – RoboCup 2012



- 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 UGV



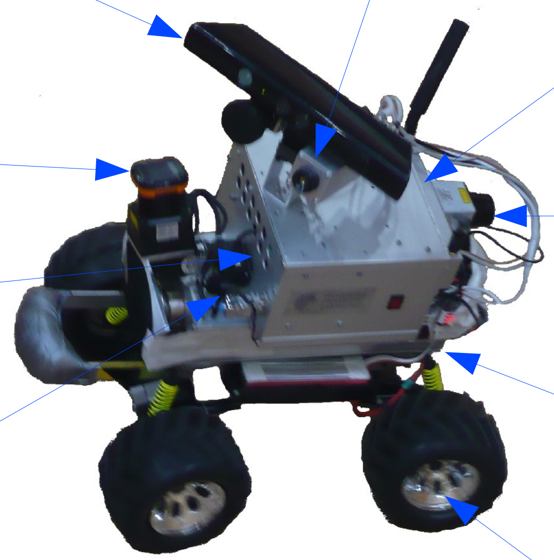
Hector UGV - Hardware

RGB-D Camera
-4m range
-30Hz

Thermal Camera
-10Hz
-160x120 resolution

2 x PS Eye Camera
(not pictured)
-up to 60Hz
-640x480

Hokuyo UTM-30LX LIDAR
-30m range
-40Hz scan rate
-roll-/pitch-stabilized



Hokuyo URG-04LX LIDAR
-4m range
-10Hz scan rate

CO2 Sensor

Navigation & Control Unit
-3 Axis Accelerometer
-3 Axis Gyroscope
-2 Axis Magnetometer
-Barometer

Bi-Directional Audio

Wheel Encoders
(one per wheel)

Processing:
-Geode 500 MHz (low level control)
-Core i7 2.6 GHz Mini-ITX
-Nvidia CUDA GPU optional

3D Perception for RoboCup Rescue

- 2D environment representations sufficient in some situations
  - Will fail in many real world environments
  - Will work less and less also in RoboCup Rescue RRL due to changes in arena
- Multitude of 3d environment representations available
  - Point clouds
    - Well suited for many SLAM approaches (see previous talks)
  - Polygonal maps
    - Need for significant preprocessing
  - Volumetric Representations
    - Compact
    - Probabilistic representation easy to achieve

SLAM in RoboCup Rescue

- 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
  - Stop an go not desirable
- Georeferenced Map with robot trajectory and objects of interest
  - Saving GeoTiff maps

3D Perception Setup used by Team Hector

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- Generate 2D map using hector_slam
- Fuse 2D SLAM pose in INS to get 6DOF state estimate using hector_pose_estimation
- Use RGB-D point clouds data to create elevation map using hector_elevation_mapping
- Generate costmap from elevation map and 2D SLAM map using hector_costmap
- Create 3D octomap environment model using RBG-D sensor
- Use octomap for raycasts to determine object of interest 3D positions

Basic system setup

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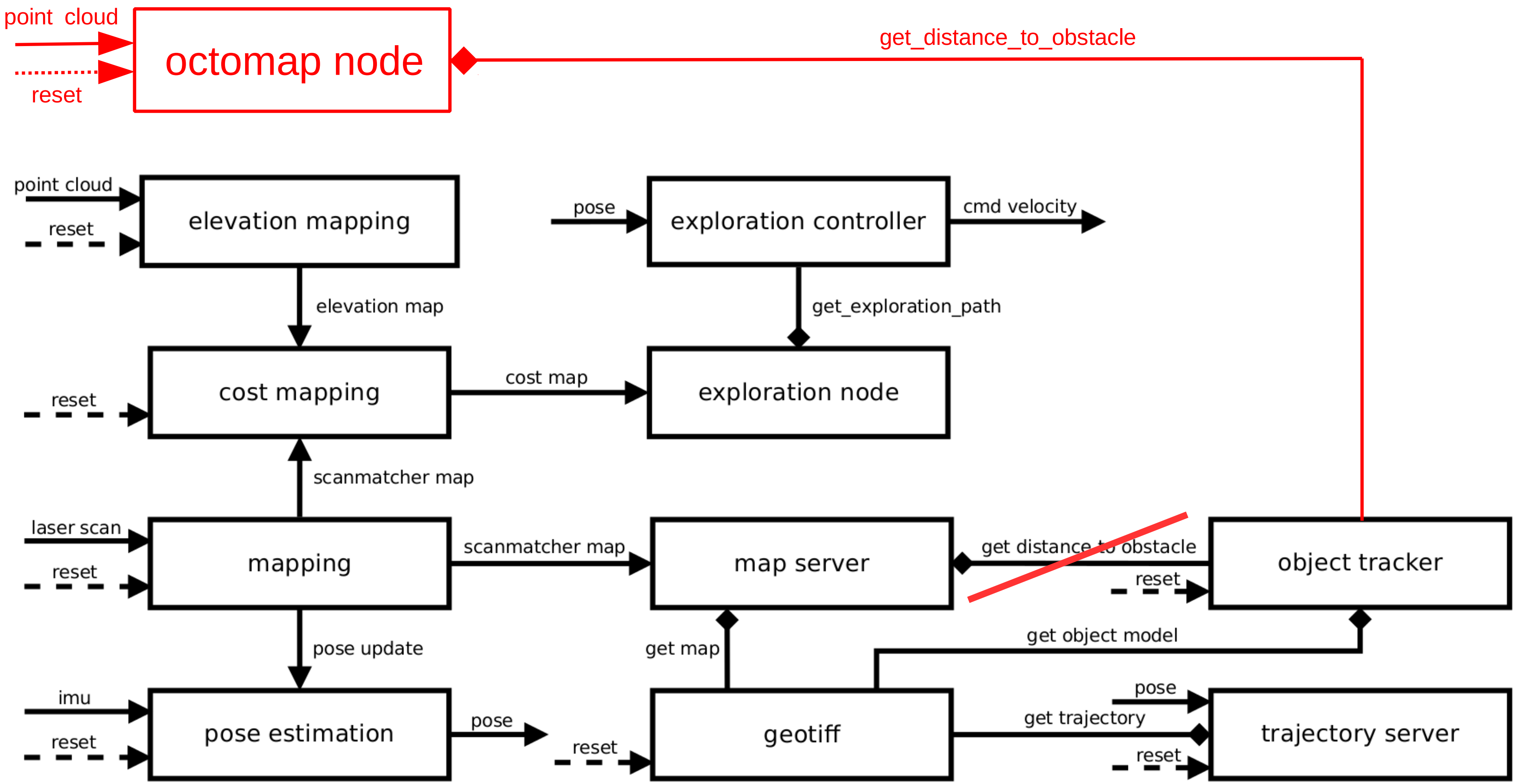

6DOF Pose Estimation

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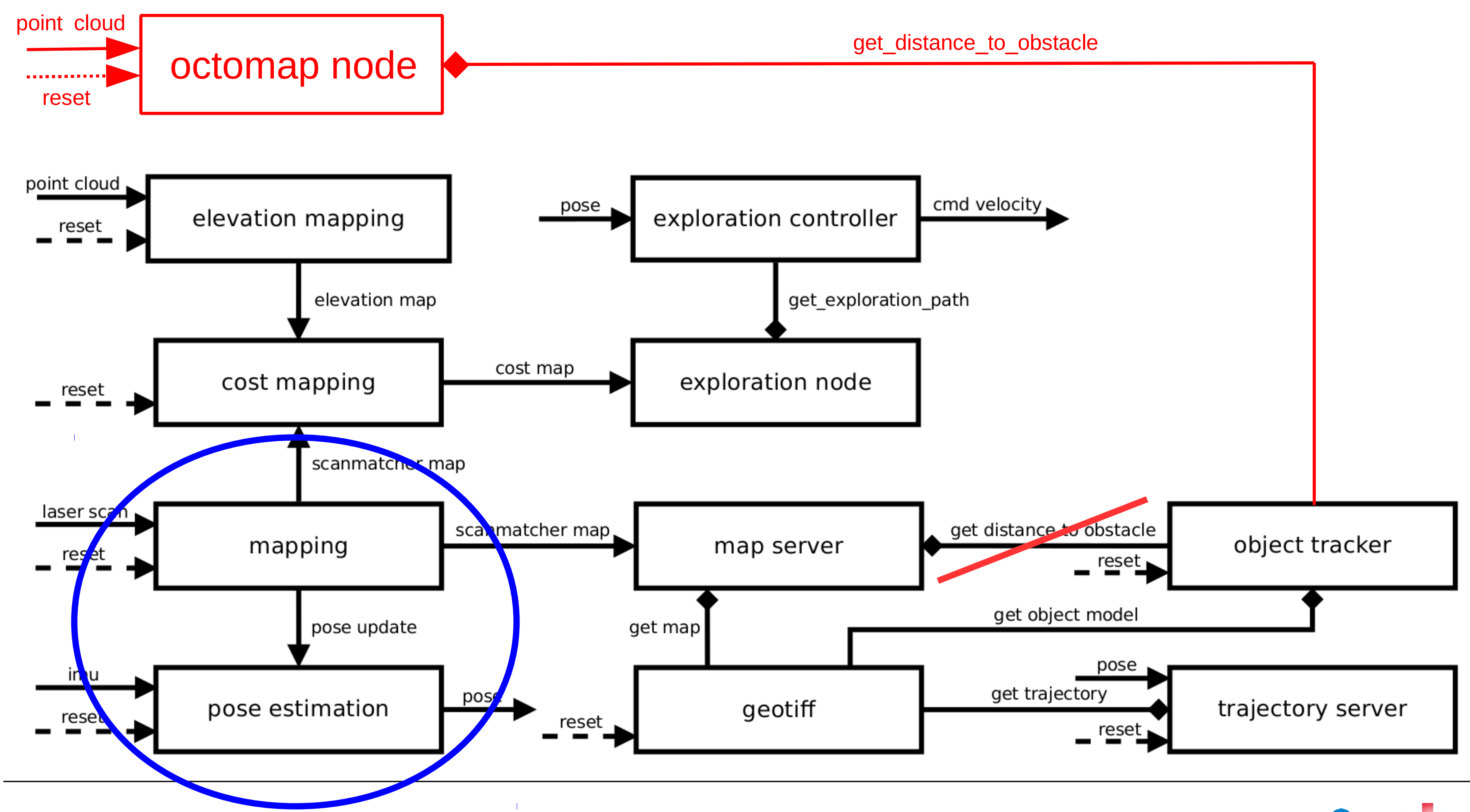
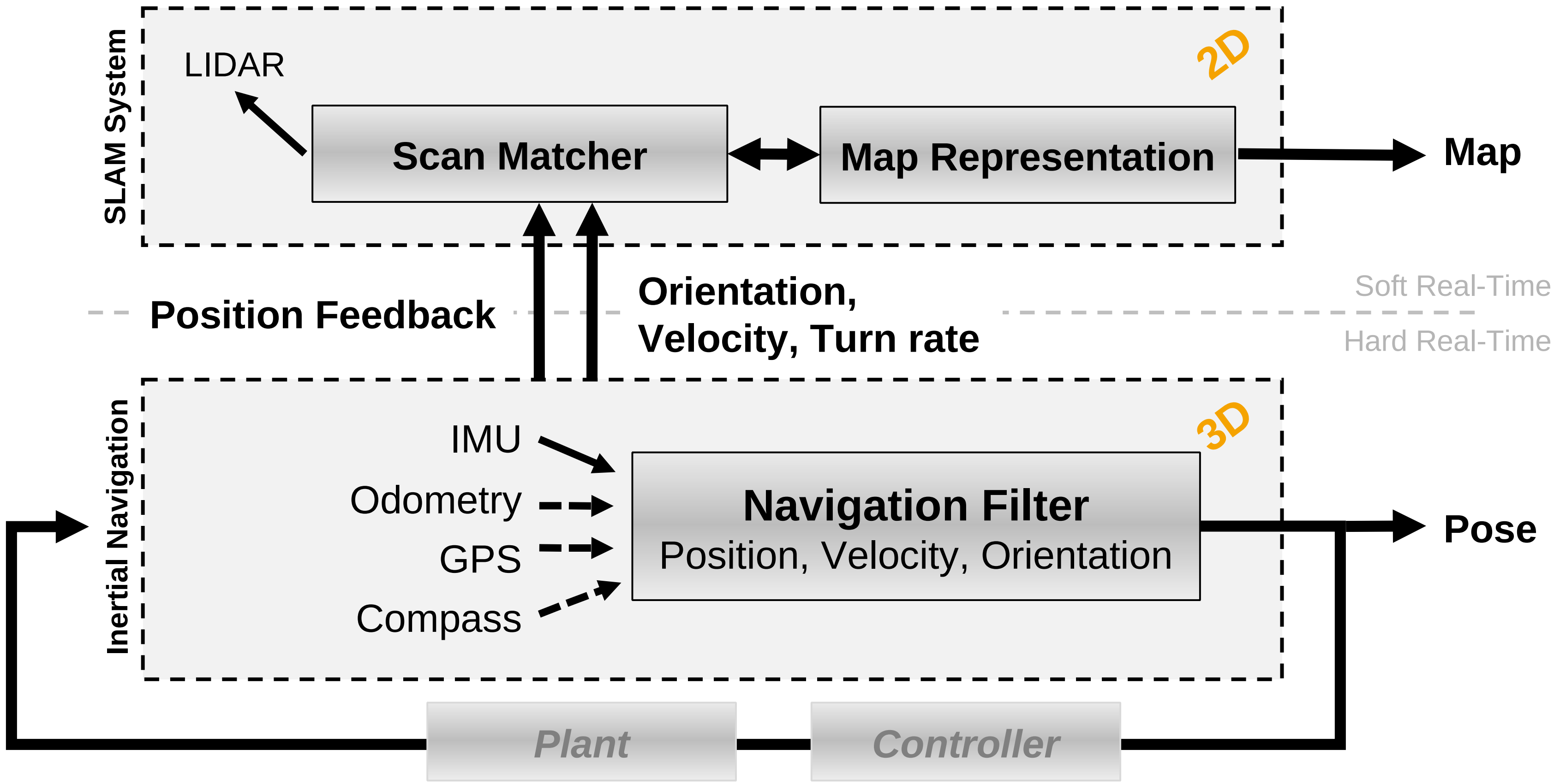
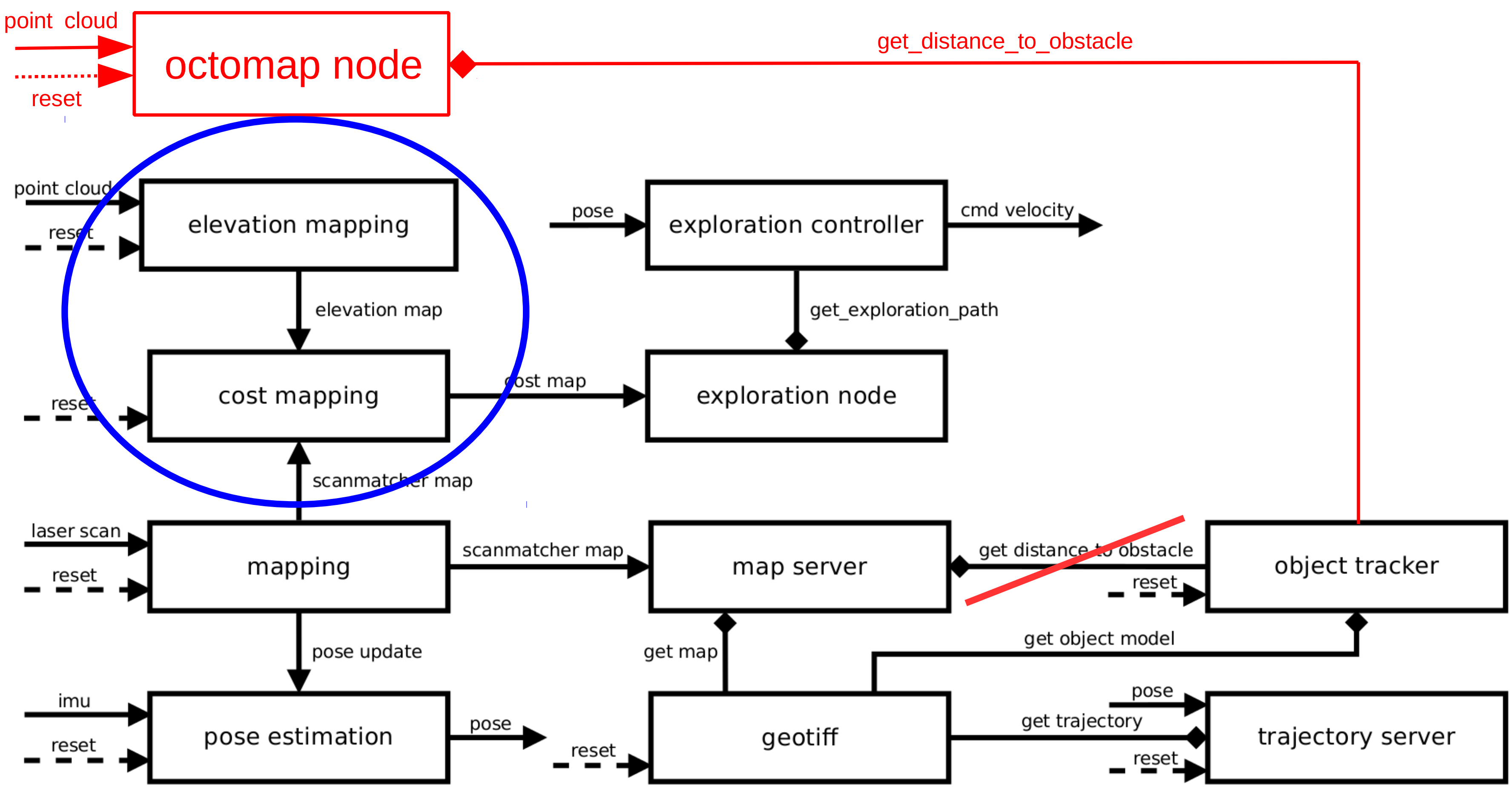


6DOF Pose Estimation



Generating Elevation/Cost Maps



Generating Elevation/Cost Maps

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- Goal: Binary classification of map cells for planner into
  - Traversable
  - Non-Traversable
- Perform mapping with known poses using previously estimated 6DOF pose estimate
- Generate elevation map
- Fuse with 2D SLAM map
- Result: Cost map for planner

Generating Elevation Maps

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Kalman Filter based Approach:

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

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

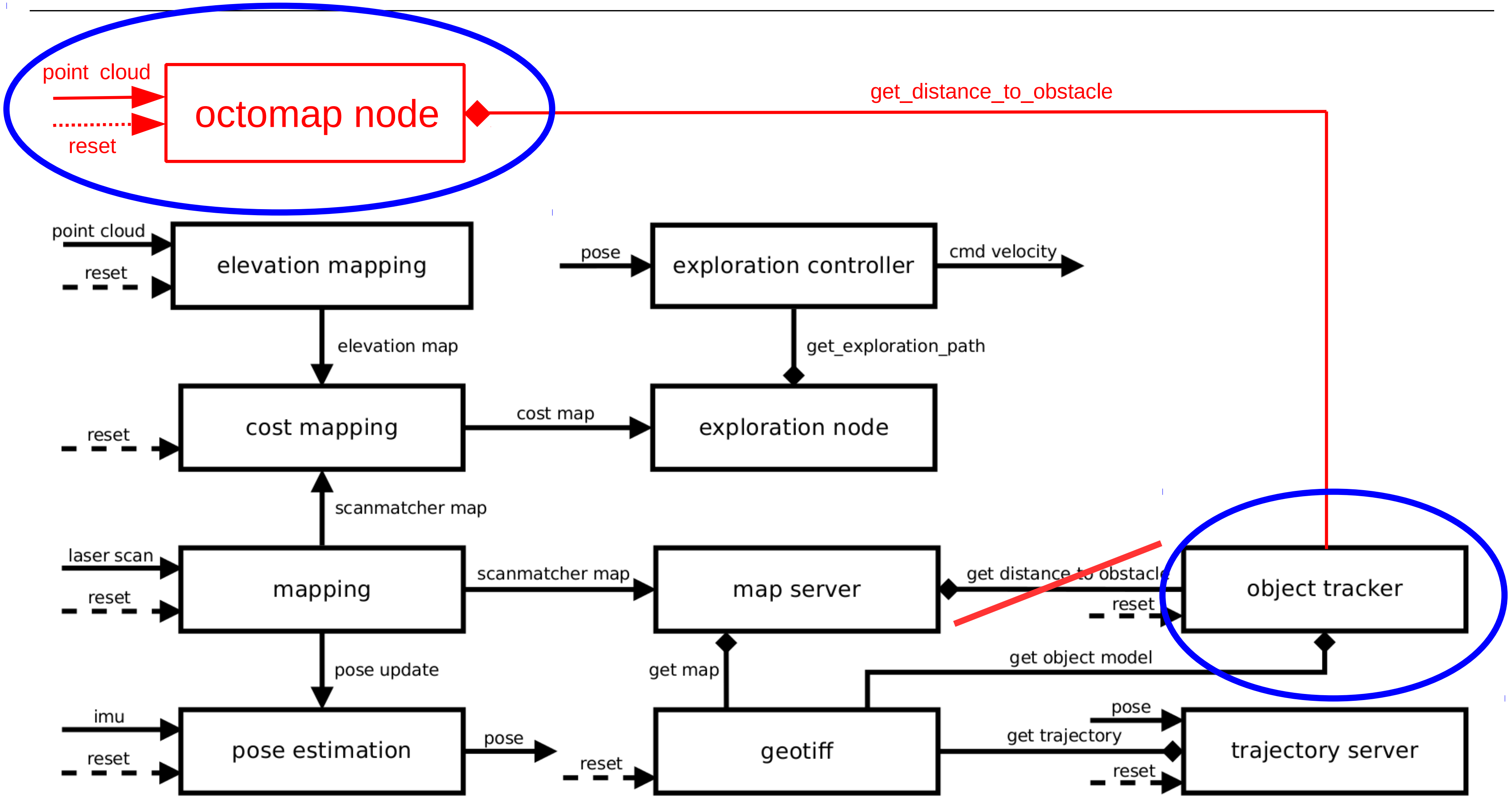
More precisely:

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

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.

Localizing Objects of Interest in 3D



Localizing Objects of Interest in 3D

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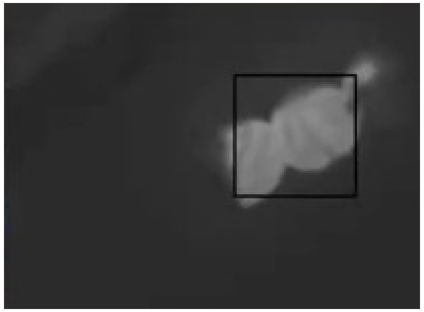
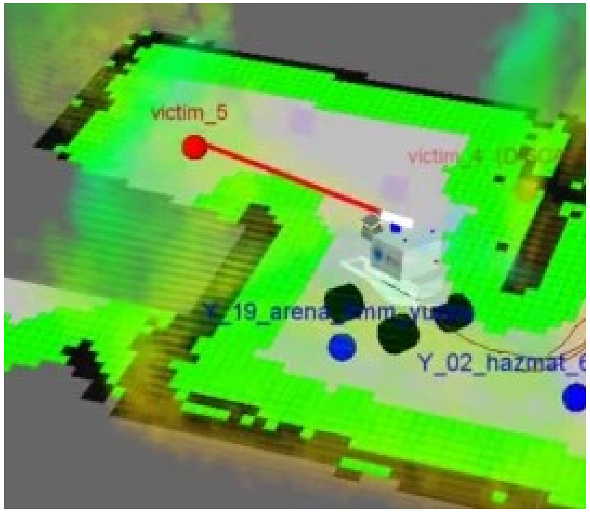
- Multiple camera systems
  - 3 x visual spectrum cameras
  - 1 x thermal camera
- 2D detection on image plane
  - Blob detection
  - HOG based object detection
- Determine 3D world position by lookup in onboard enviroment maps
  - Previously 2D raycasting into 2D map
  - Now using Octomap representation for 3D distance lookup
  - Trivial change due to modular system architecture





Localizing Objects of Interest in 3D

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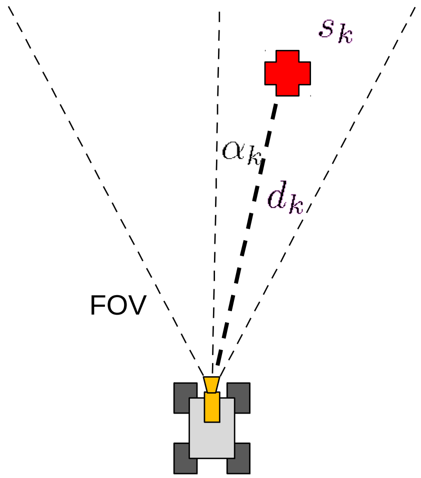
- Tracking of uncertain victim/object estimates $\{\mathbf{x}_k^j, P_k^j, \pi_k^j\}$ over time
  - $\mathbf{x}_k^j, P_k^j$ 3D position vector and covariance
  - π_k^j Confidence (1 – error probability)
- Robot position and camera transformation are assumed to be known

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)



What to watch out for

- Octomap updates are relatively slow (especially when using RGB-D sensors)
  - Compared to just aggregating point clouds
  - Lookups are much faster
  - 1-2 Hz RGB-D based should be fine
- RGB-D data bad when sensor moves
  - Rolling Shutter and approximate timestamps
  - Only update map when sensor sufficiently stable
- Don´t forget to self filter your robot
  - Easily done for LIDAR data
  - Some special treatment needed for filtering hot robot parts from thermal images

Video – RoboCup German Open 2013 Final

http://www.youtube.com/watch?v=PKI378kadp8

Future Work

- Going 3D also for SLAM front-end
  - Experiments on extending hector_slam with exchangable map representation backend (“Hector SLAM 2”)
    - Grid maps
    - 3D representations
  - Evaluate other existing solutions
- Multi-robot exploration
  - Map registration/sharing
  - Exploration planning for multiple robots
- Motion planning based on true 3D environment representation (What we do at this camp)
- Manipulation leveraging DRC developments

Future Work: Introducing New Mobile Robots

http://www.youtube.com/watch?v=ztGgMSmWP8A

Future Work: Introducing New Mobile Robots

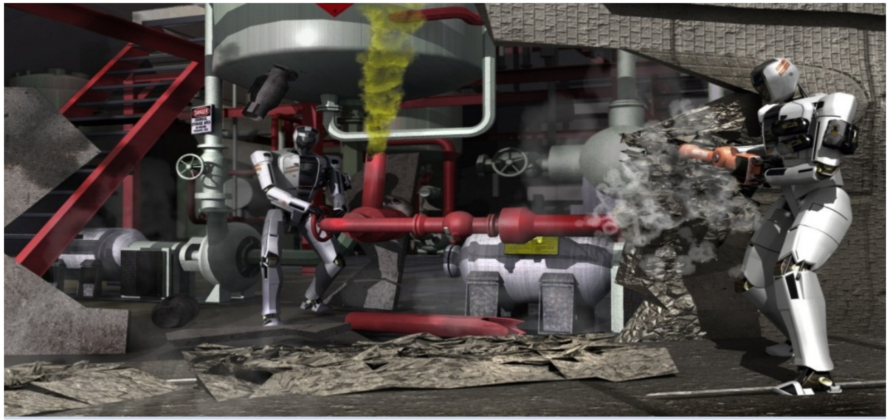
- Huge thanks to Team Stabilize (RMUTP) from Thailand for working with us

References

- RoboCup Rescue wiki page on ros.org
- tu-darmstadt-ros-pkg on ros.org
- J. Meyer, P. Schnitzspan, S. Kohlbrecher, K. Petersen, O. Schwahn, M. Andriluka, U. Klingauf, S. Roth, B. Schiele and O. von Stryk: A Semantic World Model for Urban Search and Rescue Based on Heterogeneous Sensors. RoboCup 2010: Robot Soccer World Cup XIV
- S. Kohlbrecher, J. Meyer, 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
- S. Kohlbrecher, K. Petersen, G. Steinbauer, J. Maurer, P. Lepej, S. Uran, R. Ventura, C. Dornhege, A. Hertle, R. Sheh and J. Pellenz: Community-Driven Development of Standard Software Modules for Search and Rescue Robots. IEEE International Symposium on Safety, Security and Rescue Robotics 2012
- S. Kohlbrecher and J. Meyer and T. Graber and K. Petersen and O. von Stryk and Uwe Klingauf: Hector Open Source Modules for Autonomous Mapping and Navigation with Rescue Robots. RoboCup 2013: Robot Soccer World Cup XVII
- A. Hornung, K. M. Wurm, M. Bennewitz, C. Stachniss, and W. Burgard: OctoMap: An efficient probabilistic 3D mapping framework based on octrees. Autonomous Robots, 2013

DARPA Robotics Challenge (DRC)

- Initiated by DARPA in the beginning of 2012
- Motivated by limited ability of responding to disasters using robot systems
  - Fukushima
- Robots have to perform tasks inspired by those encountered by responders in disaster scenarios



DRC - Tasks

- Task 1: Drive car to destination, get out
- Task 2: Traverse rough terrain
- Task 3: Climb industrial ladder
- Task 4: Remove debris
- Task 5: Enter door(s)
- Task 6: Break through wall
- Task 7: Open valves
- Task 8: Connect hose

Trial Task Description Document

DRC – Key Facts

- Operator in the loop
  - Can leverage human expertise and capabilities to fulfill tasks
  - Assisted autonomy
- Limited bandwidth between operator and robot
  - Compression and data selection required
- Robot may be tethered
  - Allows use of a larger variety of actuation systems

DRC - Why emphazise human capabilities?

- Environment, even degraded, has been engineered for humans
- No shortage of human tools
- Human-like robot capabilites are easier for domain experts to understand






Team ViGIR

- Team ViGIR (**Vi**rginia **G**ermany **I**nterdisciplinary **R**obotics)
  - TORC Robotics (Blacksburg, VA, US)
    - Project Management and Coordination
  - TU Darmstadt, SIM (Darmstadt, Hesse, Germany)
    - Onboard Software
  - Oregon State University, RHCS (Corvallis, OR, US)
    - Grasping
  - Virgina Tech, CHCI (Blacksburg, VA, US)
    - Operator Control Station (OCS)
- Team has significant challenge experience and success in their fields
  - DARPA Urban Challenge
  - RoboCup Rescue & Humanoid Leagues
  - IEEE 3DUI contest
- Publication of software as open source planned

  teamvigir.org

  Team ViGIR on Facebook

Timeline

- Spring 2012: Team ViGIR hands in proposal for Track B participation in DRC program
- Autumn 2012: Team ViGIR is selected as one of 11 teams funded in Track B
  - Number of original proposals unknown, but hinted at being high
- October 2012: DRC Kick-off
- June 2013: Virtual Robotics Challenge (3 Tasks)
  - Team ViGIR achieves 6th place in ranking
  - From 23 qualified teams
  - Originally >100 teams registered for VRC
- December 2013: DRC Trials
  - 8 of 13 teams advance
- December 2014: DRC Finals
  - 2 Million US$ for winning team

Big Picture

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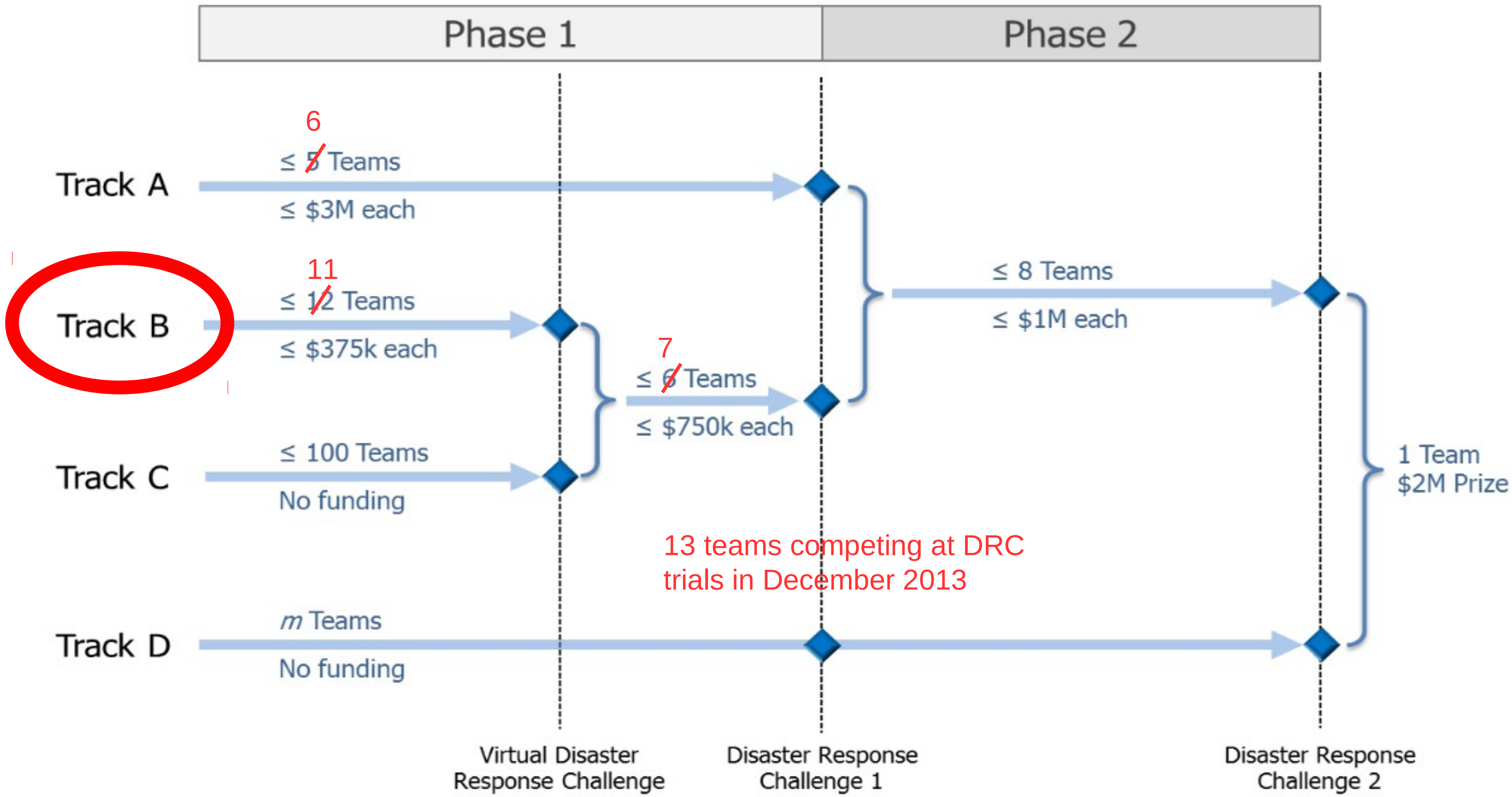


Challenges

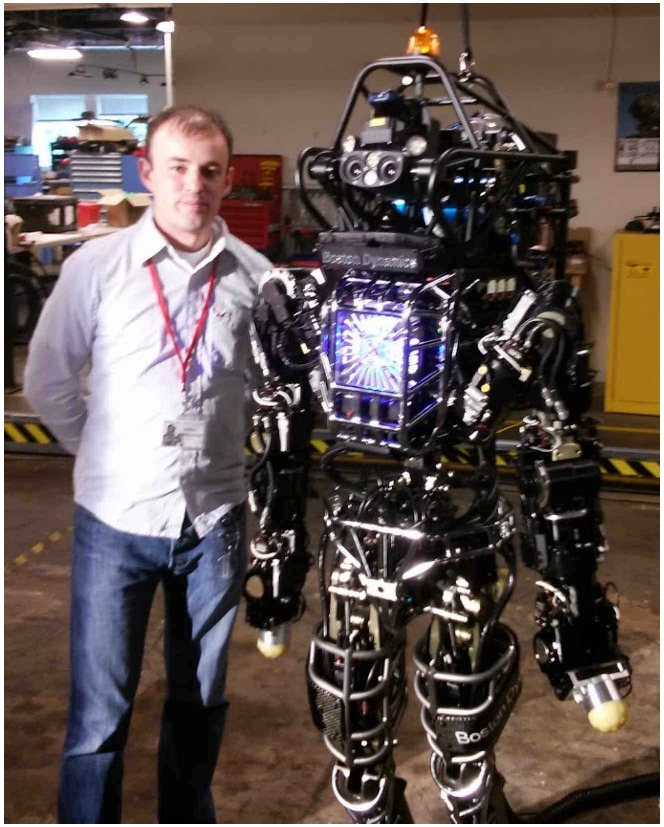
- Multiple research challenges
  - Perception/planning
  - Reliable bipedal locomotion
  - Human-robot cooperation
  - Forceful manipulation
  - Whole body control
- "Meta challenge"
  - Extremely tight schedule
    - 8 months from DRC kick-off to VRC
    - 6 months from VRC to DRC Trials with real Atlas system

Optimizing System Performance

- Strengths:
  - Robot:
    - Low level control
    - Sensor data processing
    - Collision avoidance
  - Human:
    - Object recognition
    - Scene understanding
    - High level decision making
- How to leverage these strengths best?

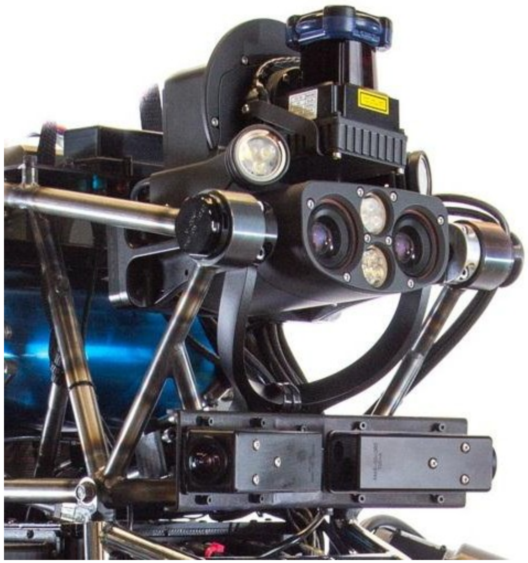
Atlas Robot - Overview

- 28 DOF
- 1.88m tall
- ~150 kg
- Hydraulically driven
  - > 7kW hydraulic pump onboard
- Capable of forceful manipulation
- High performance actuation
  - Safety critical
- In many ways most advanced humanoid robot system in the world



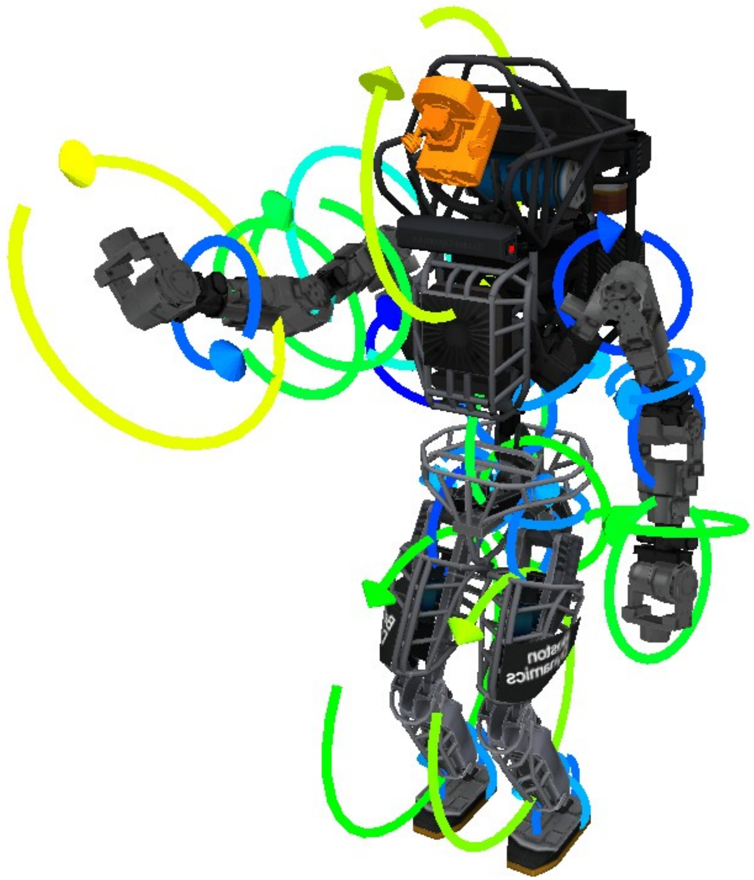
Atlas Robot – External Sensing

- Carnegie Robotics Multisense-SL sensor head
  - Stereo Camera (2 Megapixel, FPGA stereo processing onboard)
    - Up to 15Hz @ 15 fps
    - Up to 30 Million Points/second
  - Spinning Hokuyo LIDAR
    - 40Hz
    - 30m range
  - Saturates 1Gbit Ethernet connection if set to max resolution
- 2 x Stereo Camera in Sandia hands
- 2 x Situational awareness fisheye lens cameras below head



Atlas Robot – Internal Sensing

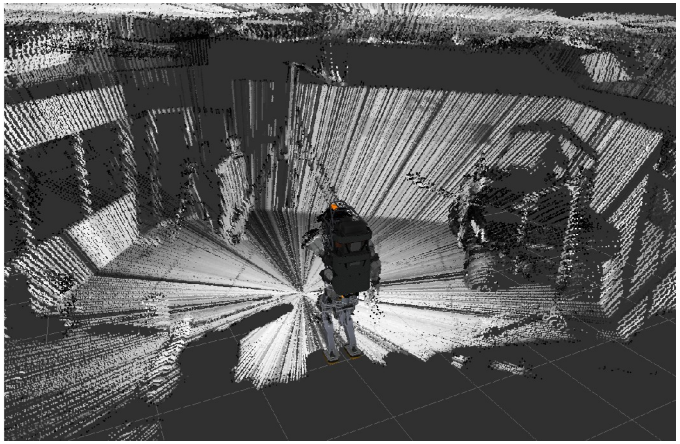
- IMU
  - Fiber optic ring gyros
  - Highly accurate MEMS accelerometers
- Joint sensors
  - Position, torques, velocities
- Wrist and ankle mounted force/torque sensing
- Motion while walking can estimated using kinematics/IMU
  - Very little slip during walking

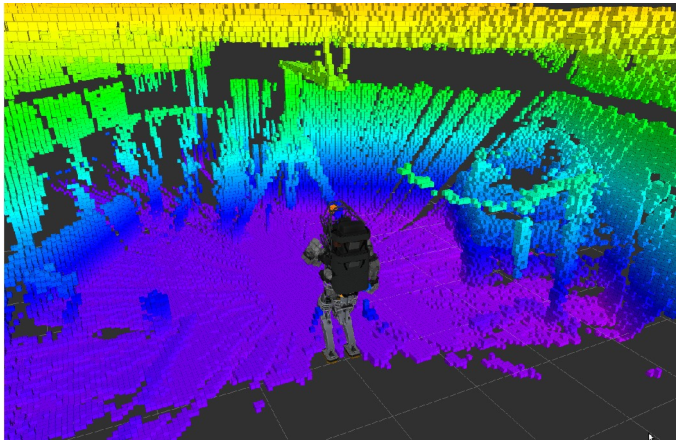


Video – Atlas Sensor Data

Environment Modeling

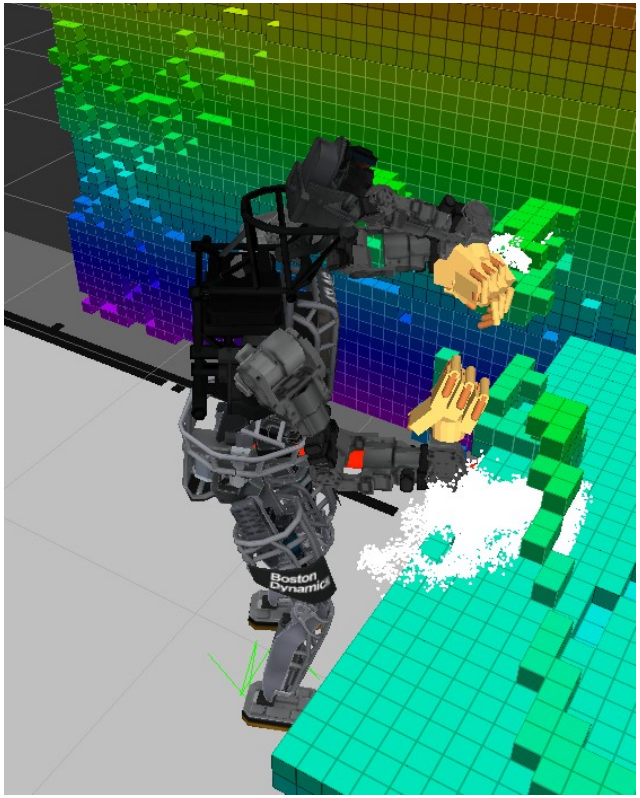
- Save point cloud Data from sensors in circular buffer along with tf frame snapshots. Allows to reconstruct point clouds on demand, for example
  - in fixed world frame when robot localization is reliable
  - in pelvis frame (i.e. robot coordinates) when localization is unreliable
- Generate Octomap 3D representation of environment based on point cloud data
  - Probabilistic representation
  - Fuses noisy distance/point cloud data
  - Compact
- Used to generate collision checking models for planners:
  - Footstep planner
  - Upper body motion planner
- Internally using PCL tools





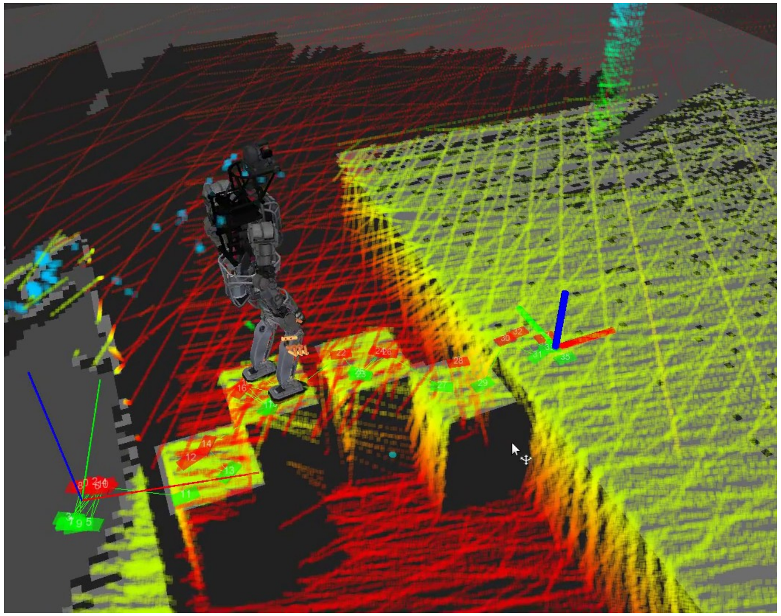
3D Perception for Manipulation Planning

- Use MoveIt! Library For upper body motion planning
  - Arms (6 DOF)
  - Arms + torso (9DOF)
- Has native octomap support
- Use MoveIt! Low level API to have more control over planning system
  - Collision avoidance settings
  - Joint angle constraints
- On planning request, environment model region of interest octomap gets transferred to planner



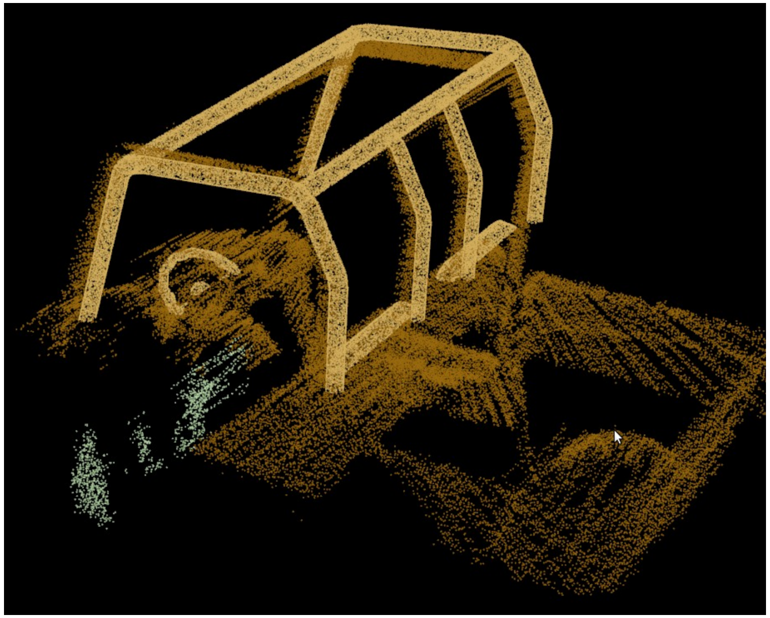
3D Perception for Footstep Planning

- Two approaches
  - Selectable by operator depending on situation
- Flat ground
  - Slice octomap into 2D grid maps
  - One low slice for footstep planning
  - One high slice for upper body collision avoidance
- Rough Terrain
  - Additional plane detection in point clouds



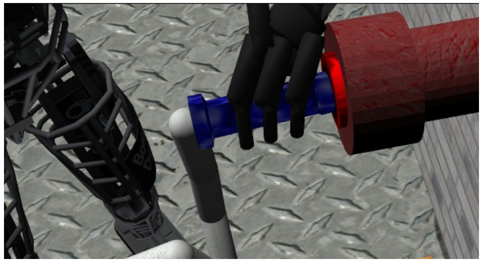
3D Perception for Object Detection

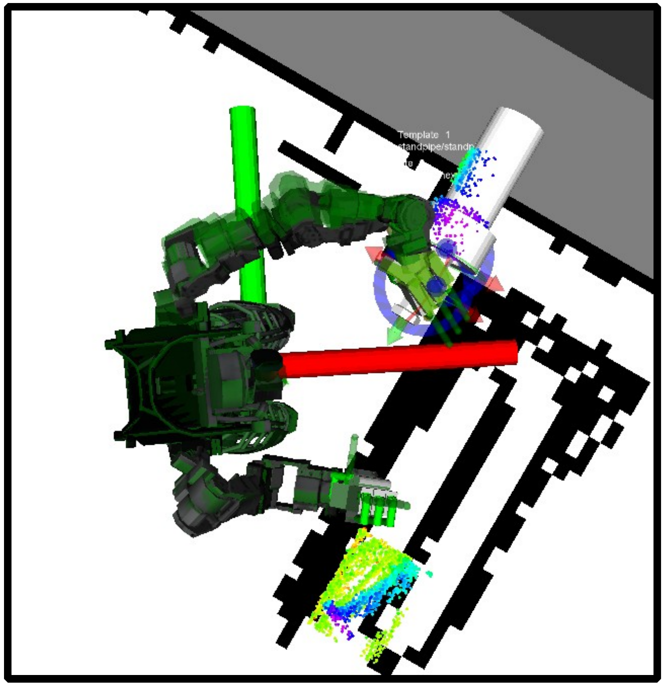
- Pointcloud regions of interest for environment segmentation
  - Matching templates against sensor data for object of interest pose estimation
- Results from mobile manipulation of limited utility, as appearance of objects not known
  - No training possible
- Outdoor conditions likely to degrade especially visual spectrum sensor data



Environment Modeling – Operator Control Station (OCS)

- Remote distance queries by raycasting onboard Octomap
- Query 2D slices of Octomap data (very good compression)
- Query pointcloud regions of interest for object template alignment





Video - Walking

Video – First Grasping Test

Video – Grasping Drill

References

- S. Kohlbrecher, D. Conner, A. Romay, F. Bacim, D. Bowman and O. von Stryk: Overview of Team ViGIR's Approach to the Virtual Robotics Challenge. IEEE International Symposium on Safety, Security and Rescue Robotics 2013
- S. Chitta, I. Sucan, and S. Cousins: Moveit!. IEEE Robotics Automation Magazine, vol. 19, no. 1
- R. B. Rusu and S. Cousins, 3D is here: Point cloud library (pcl). ICRA 2013

Conclusions/Some Lessons Learned

- Leverage existing open source tools as much as possible
  - Some customization might be needed
  - Focus on your research
- Document development using tools
  - Redmine/TRAC
    - Issue tracker
    - Wiki
  - Gitlab
- Use continuous integration