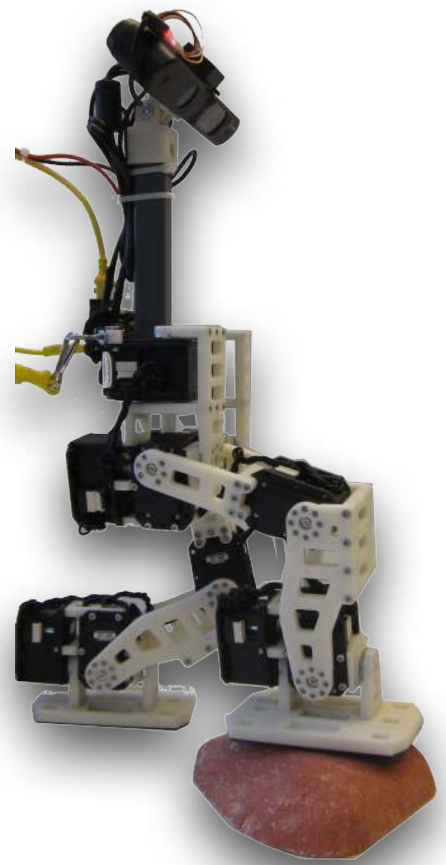
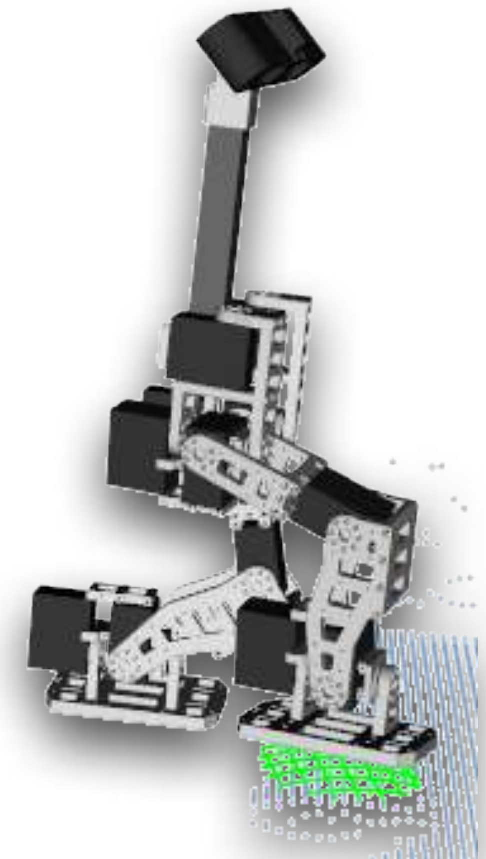
Ph.D. Thesis Defense



Curved Surface Patches *for* Rough Terrain Perception



Dimitrios Kanoulas

G P C

Geometric and Physical Computing Lab

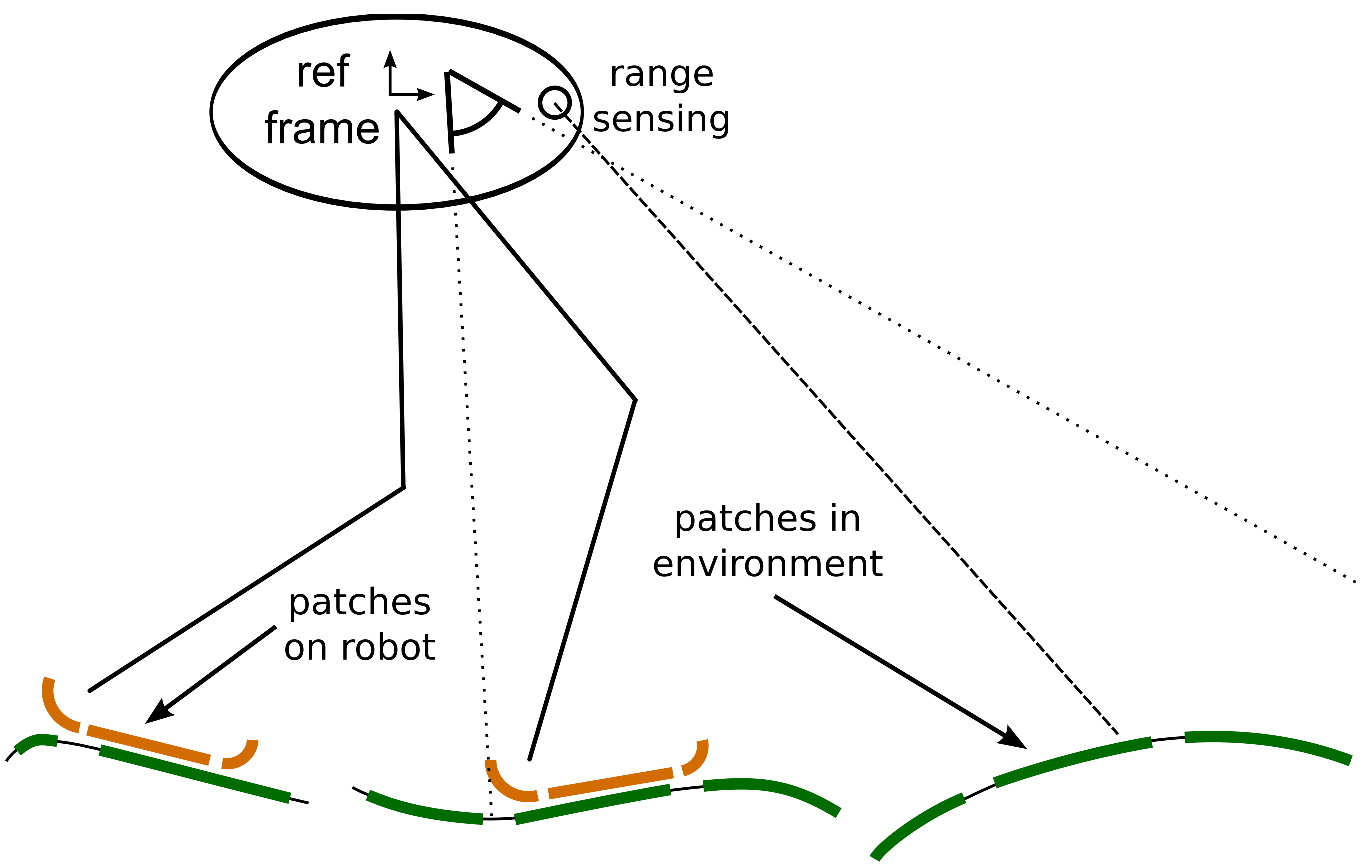
Northeastern University
College of Computer & Information Science

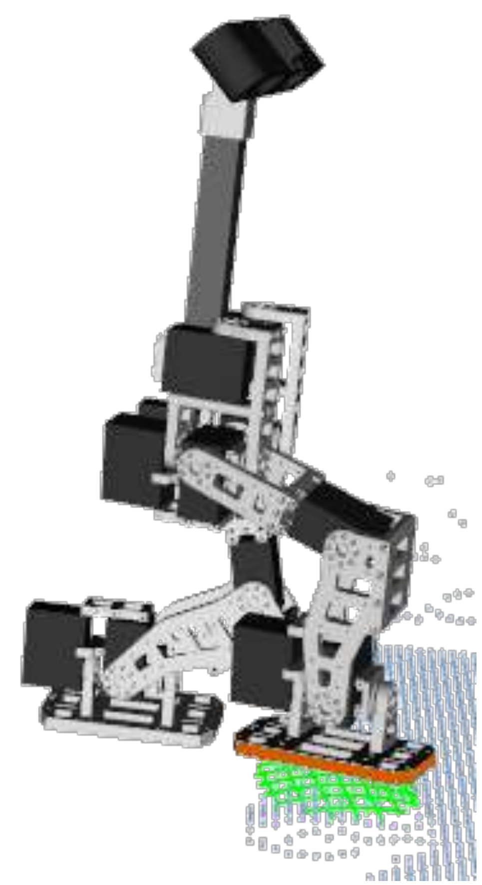
Thursday, July 24, 2014

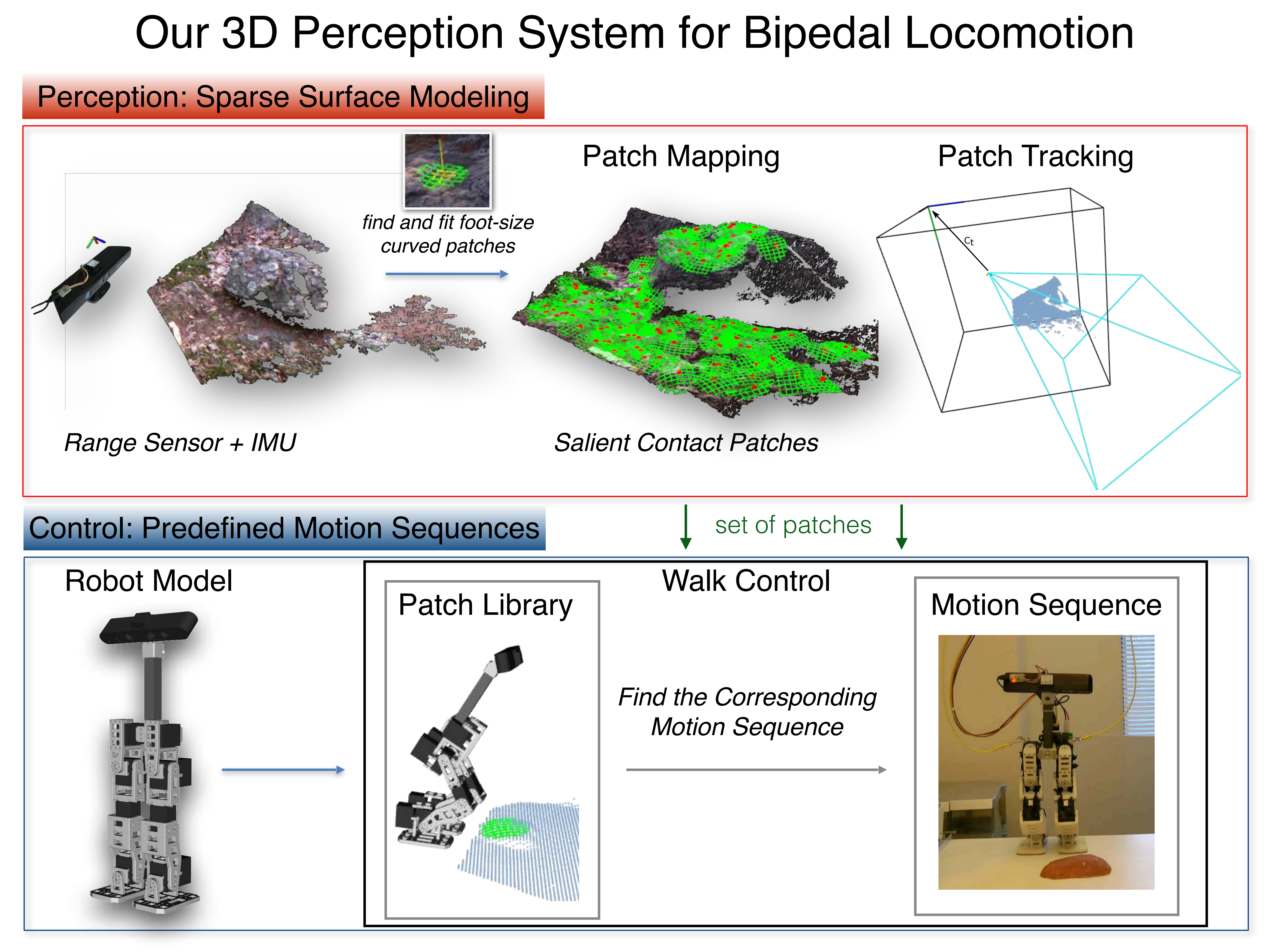
3D Perception for Contact in Rough Terrain

Thesis Statement
Robots operating in many unstructured environments need to perceive areas for potential contact. These can be **detected** and **modeled** using **curved surface patches**, and spatially **mapped** in real-time.

For footfall contacts: Detect **bounded curved surface patches** of the same scale as surfaces on robot's foot.







Our 3D Perception System for Bipedal Locomotion
Perception: Sparse Surface Modeling
find and fit foot-size curved patches
Patch Mapping
Patch Tracking
Ct
Range Sensor + IMU
Salient Contact Patches
set of patches
Control: Predefined Motion Sequences
Robot Model
Walk Control
Patch Library
Motion Sequence
Find the Corresponding Motion Sequence

Contributions

1. A new sparse environment surface representation using a set of **bounded curved patches** suitable for modeling local contact regions both in the environment and on the robot.

2. A **fast algorithm to fit** these patches to 3D point samples of a surface, with quantified uncertainty both in the input points and in the output patch.

3. Fast residual, coverage, and curvature **patch validation** tests for evaluating the fidelity of fitted patches.

4. **Bio-inspired rules for finding patches** statistically similar to those selected by humans for hiking in rough terrain.

5. **Real-time mapping** of hundreds of patches near a **walking biped** in combination with dense volumetric depth map fusion and inertial sensing.

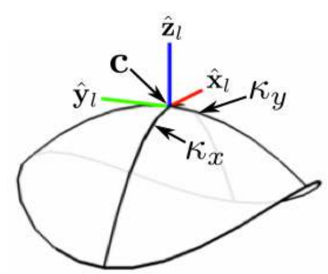
<u>**Conference/Workshop Papers and Posters:**</u>

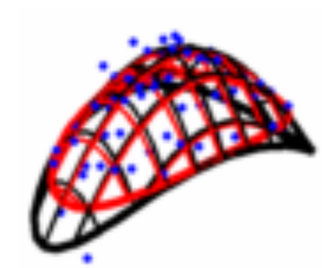
- Kanoulas, Vona. *Bio-Inspired Rough Terrain Contact Patch Perception.* **[ICRA '14]**
- Kanoulas, Vona. *The Surface Patch Library (SPL).* **[ICRA '14]**
- Kanoulas. *Surface Patches for Rough Terrain Perception.* **[NERC '13]**
- Kanoulas, Vona. *Sparse Surface Modeling with Curved Patches.* **[ICRA '13]**
- Vona, Kanoulas. *Curved Surface Contact Patches with Quantified Uncertainty.* **[IROS '11]**

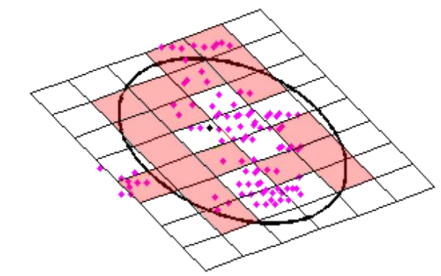
Outline

- Related Work

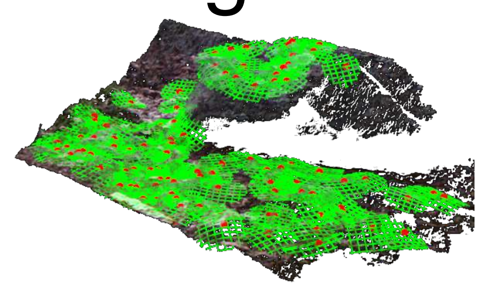
- Sparse Surface Modeling with Curved Patches
  - Patch Modeling
  - Patch Fitting
  - Patch Validation

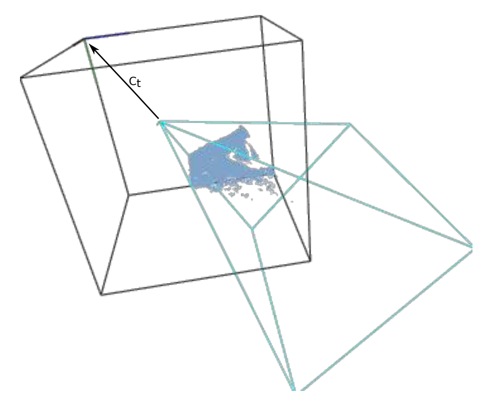


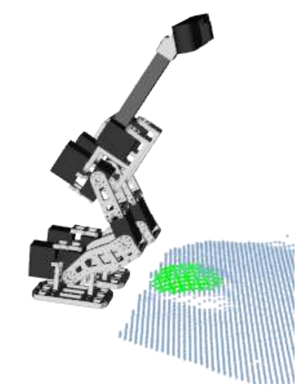




- Curved Patch Mapping and Tracking
  - Patch Mapping
  - Patch Tracking
  - Application to Biped Locomotion







- Conclusions and Future Work

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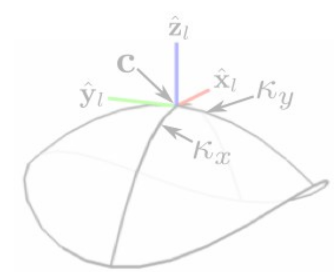


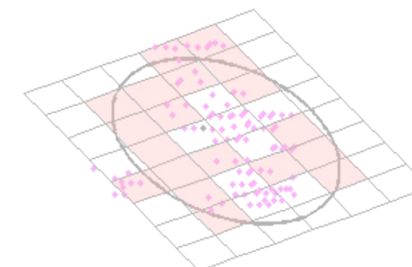

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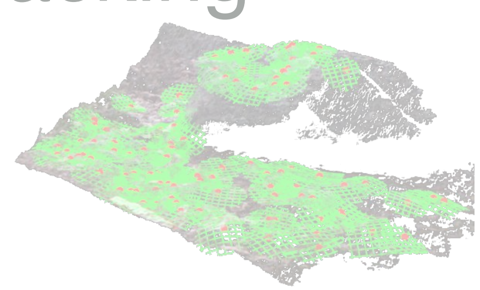
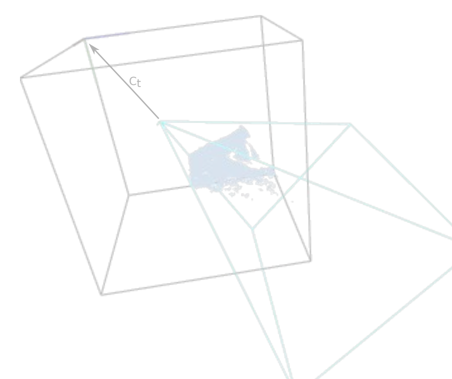
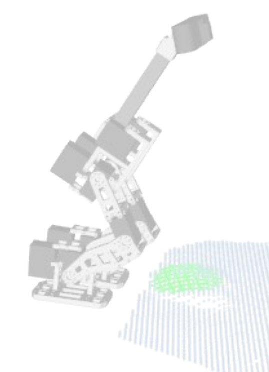
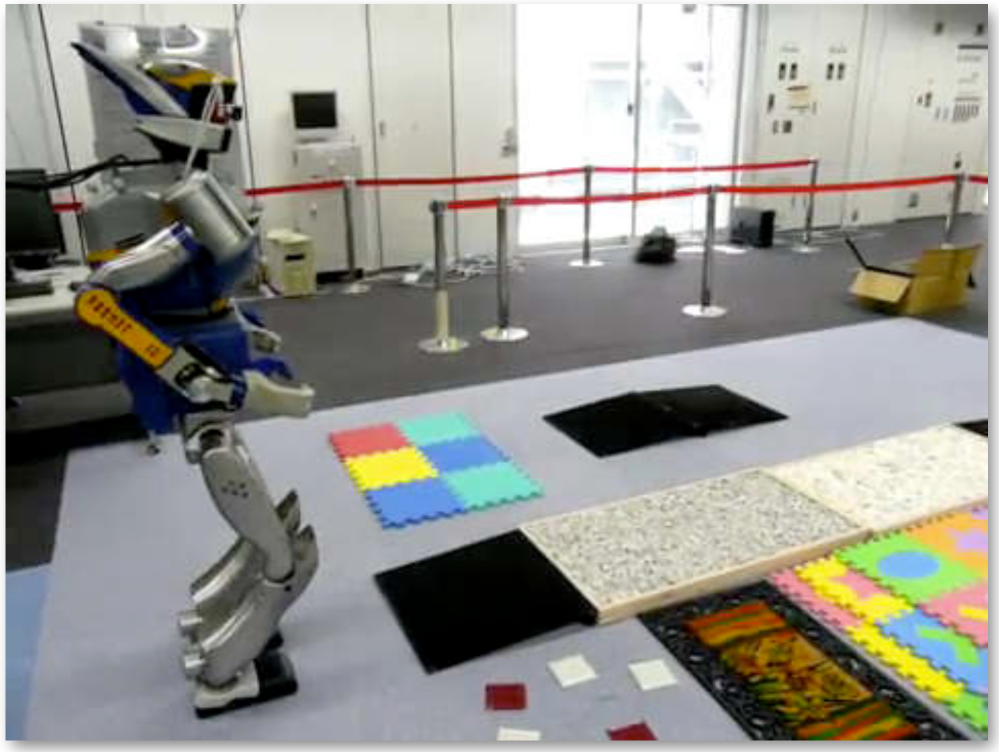
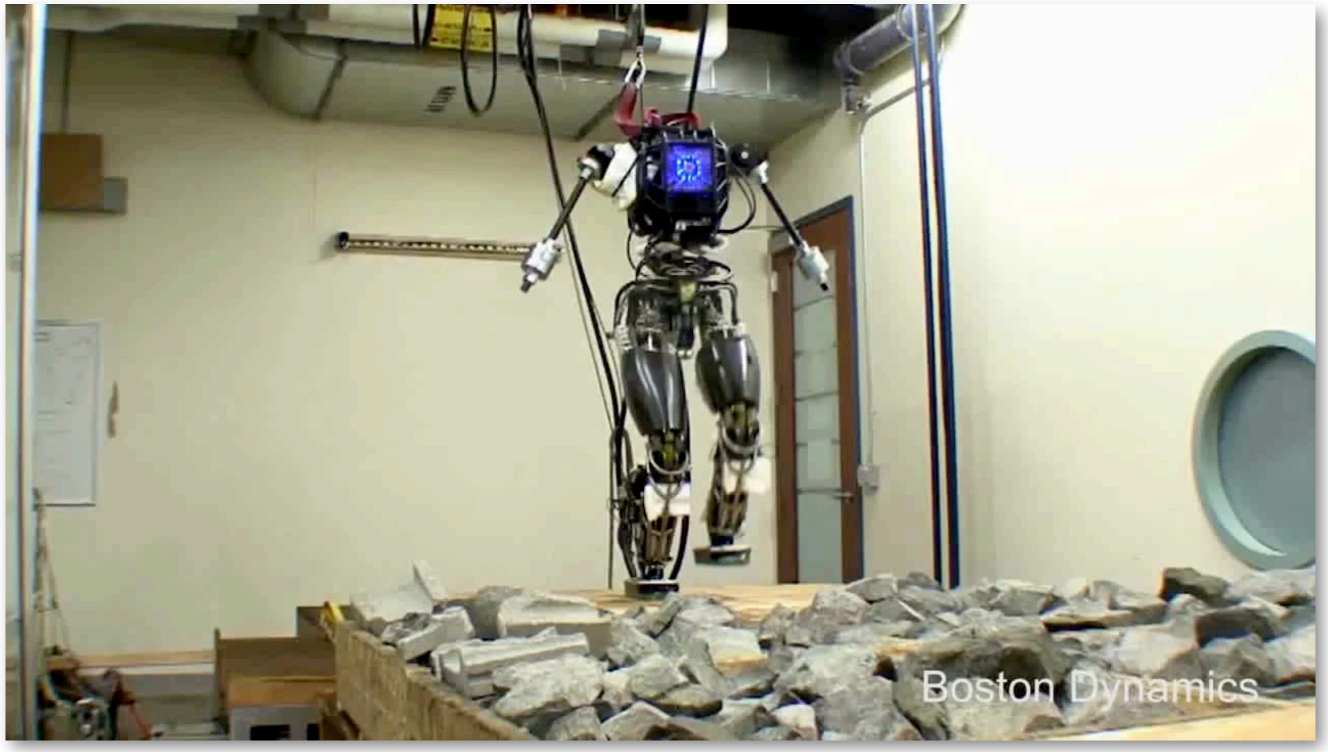




- Conclusions and Future Work

Rapid advancements in actuation and control



HRP-2 [AIST, 2010]



ATLAS [Boston Dynamics, 2013]

Why Bipedal Robots?

- replace humans in hazardous tasks
- operate in human-traversable rough terrain

Recent legged robots are gaining capability mostly without using 3D perception.

<u>But under the assumptions that:</u>

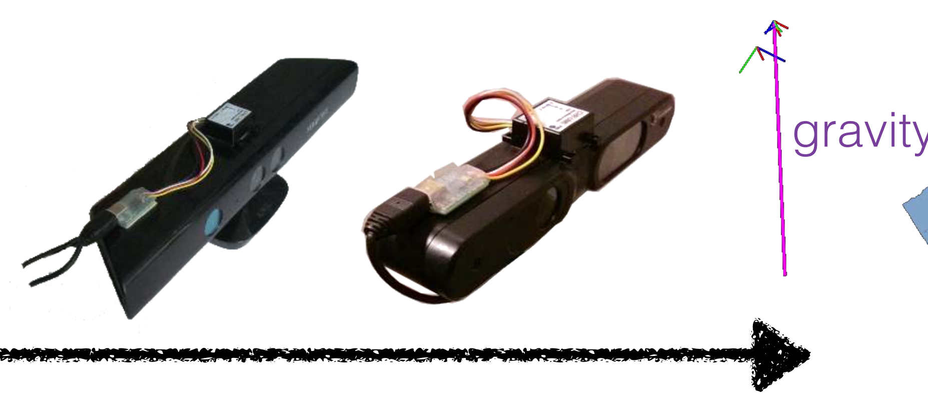
- either the environment is mostly known or well structured
- or uncertainty can be tolerated by low-level feedback control
- or tactile sensing & proprioception is sufficient

still many open problems in **3D perception** for rough terrain contact

Perception

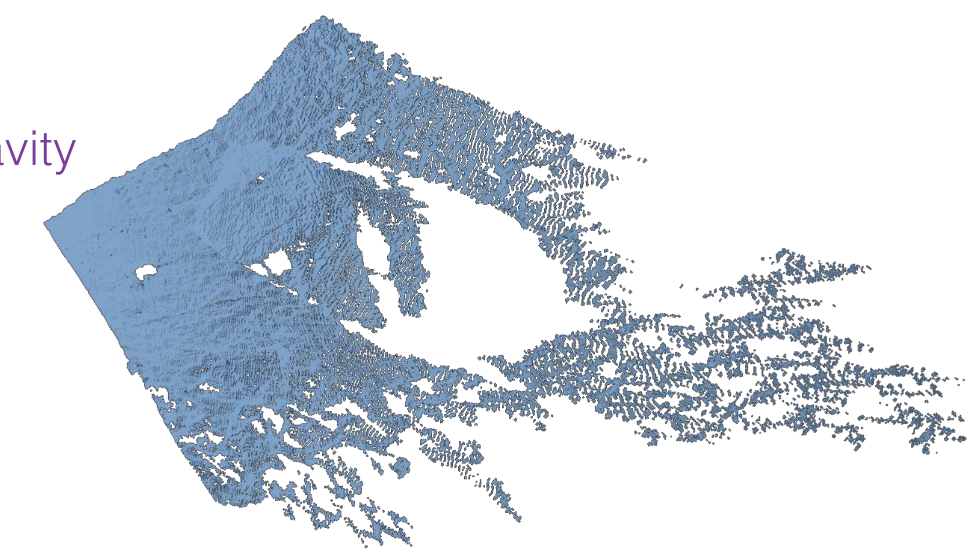
exteroceptive (sensing the environment)	**proprioceptive** (sensing robot’s own state)
range sensor: detect upcoming terrain contacts from a distance, but with relatively high uncertainty	**IMU sensor:** sense the velocity, orientation, and gravity
tactile sensors: detect contacts with terrain	**kinematics:** sense the pose of contact areas on the robot itself-e.g. heel, toe, foot sole- potentially with relatively low uncertainty

Range and IMU Sensing



range sensing + IMU

- **PrimeSense Microsoft Kinect / Carmine 1.09**
- **CH Robotics UM6 9-DoF IMU**



Range Sensor: 640x480 pixels, i.e. 307,200 point cloud [~30Hz framerate]
IMU Sensor: gravity vector [~100Hz framerate]

Quadrupeds using 3D Perception

using MoCap only

Little Dog [Boston Dynamics]

using stereo camera

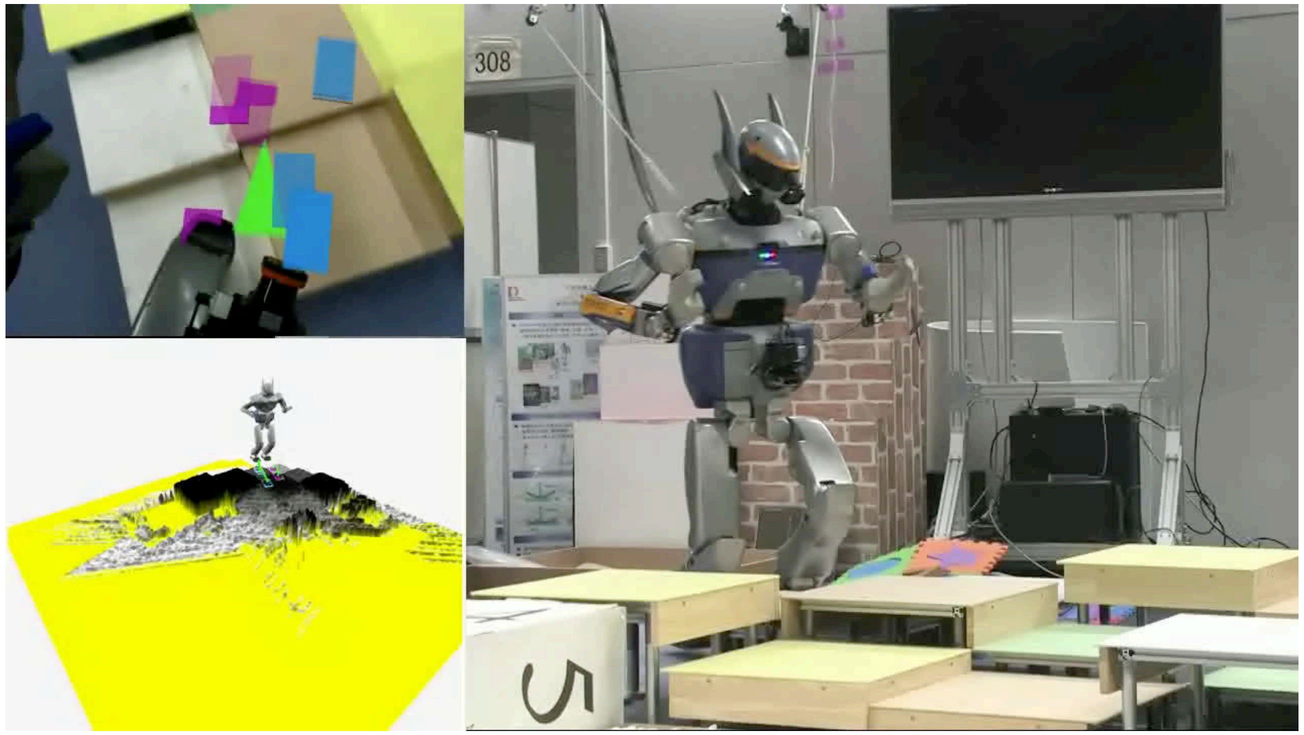
[Kalakrishnan et al – IROS 2009]

[Plagemann et al – IROS 2008]
[Kolter et al – IROS 2009]

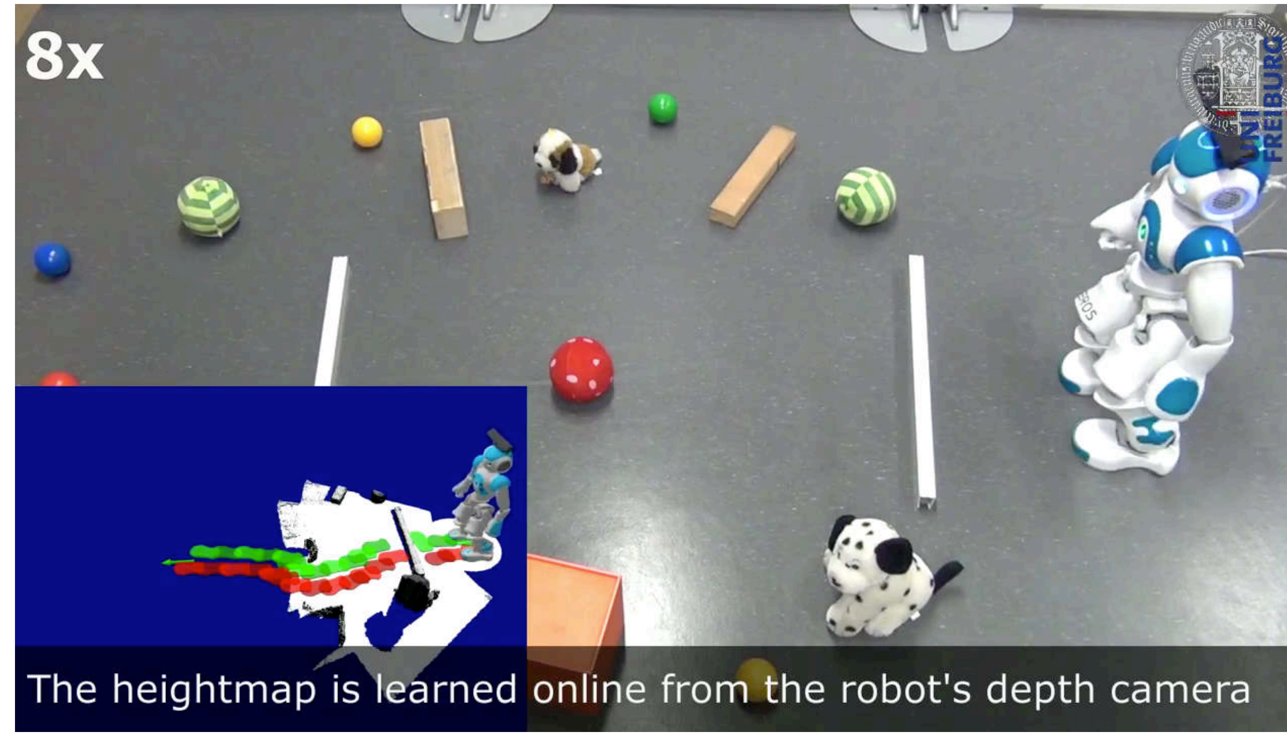
- detailed environment representation
- robot position in the environment

- not designed to reason about contact for non-point feet
- not in real-time

Humanoids using 3D Perception



[Nishiwaki et al – IJRR 2012]



[Maier et al – IROS 2013]

- they are designed to reason about contact only with **flat surfaces**
- they do not always work in real-time

Environment representation

- **dense** volumetric maps; useful for obstacle avoidance
- **dense** surface maps, e.g. triangle meshes, heightmaps

How to reason about contact with a complex **dense map**, e.g. mesh of 100k+ triangles?

Context in Surface Fitting

- Range Image Segmentation [Jiang & Bunke '94]
  - *partition the environment in non-overlapping but potentially irregularly bounded regions*
- Tiny Patches [Murray & Little '05]
  - *dense modeling approach with small planar patches*
- Flat Patches [Gutman et al 08, Pathak et al '09, Vaskevicius et al '10]
  - *sparse modeling approach with large planar patches*
- Curved Patches & Paraboloids [Powell et al '98, Petitjean '02, Dai et al '07]
  - *curved patches, but without considering uncertainty and bounds*

<u>Our contributions</u>: bounded curved contact patches with quantified uncertainty

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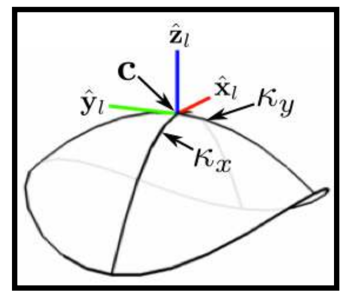

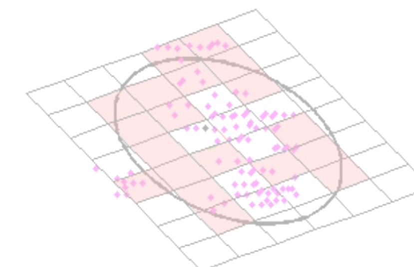

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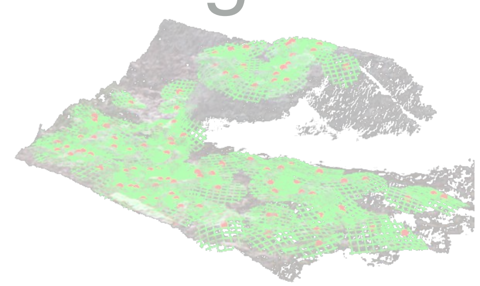
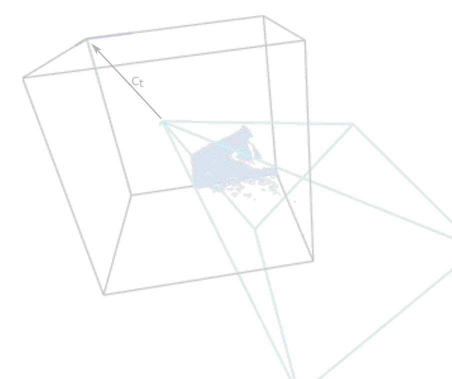
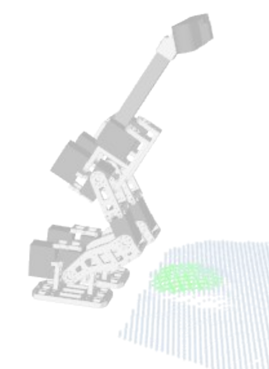
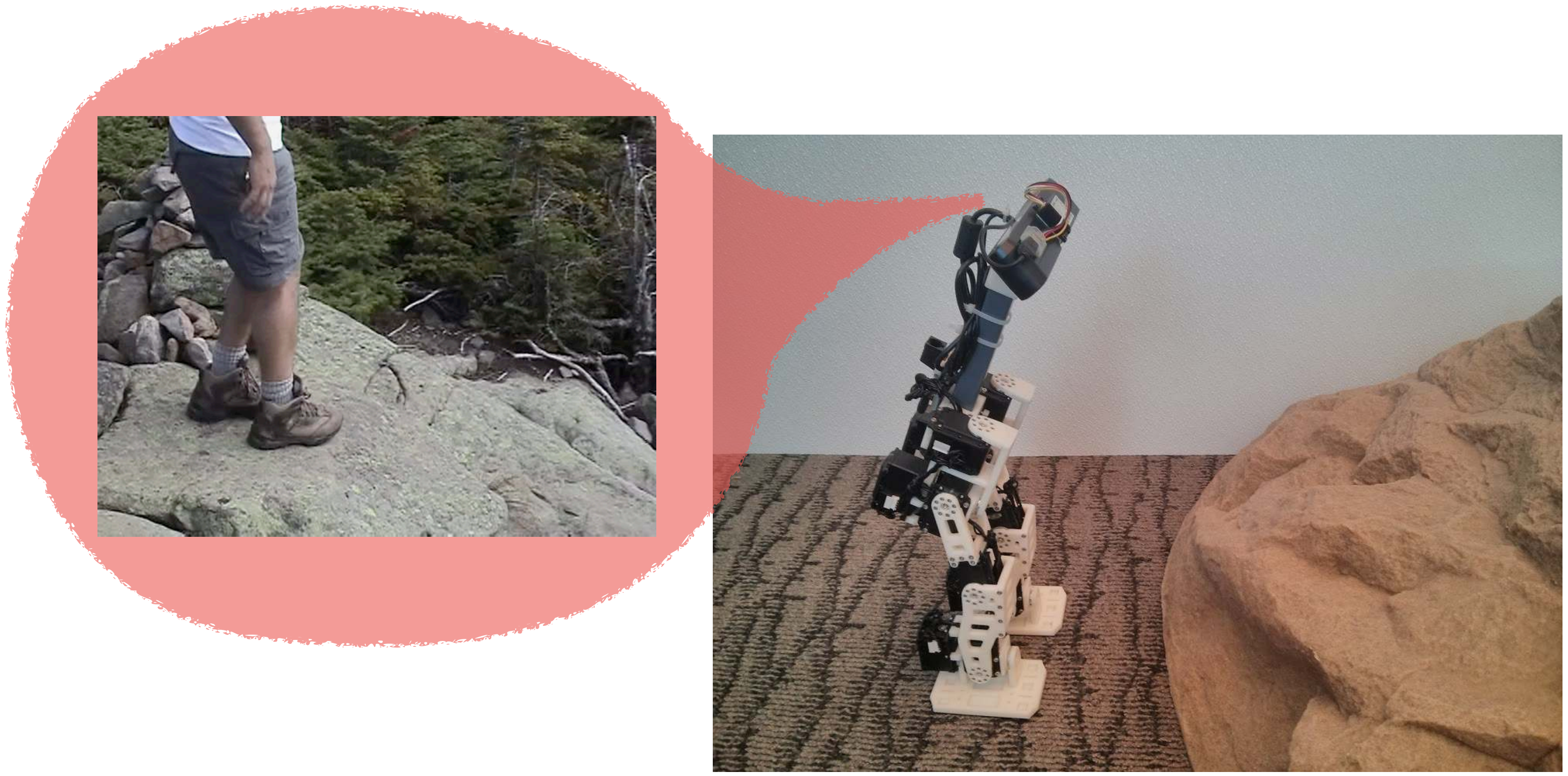






- Conclusions and Future Work

Perceiving Rough Terrain



How should bipedal robots **perceive** and **model** an unknown rough terrain for potential navigation on it?

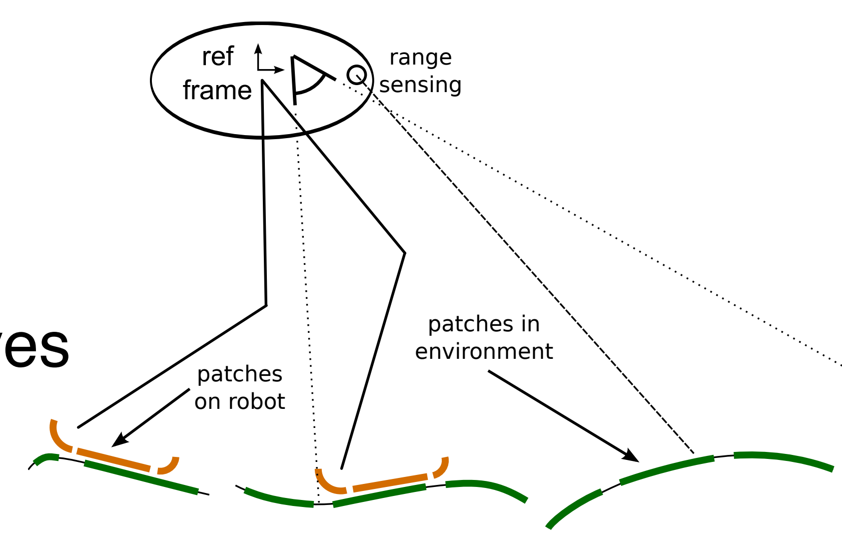
Intuition: *when humans are hiking on 3D rock surfaces, they may consider a* ***sparse*** *set of footholds.*

we present a new perception approach
using a sparse representation of the environment

Instead of a dense map, we represent only a sparse set of patches sampling environment surfaces potentially suitable for contact.

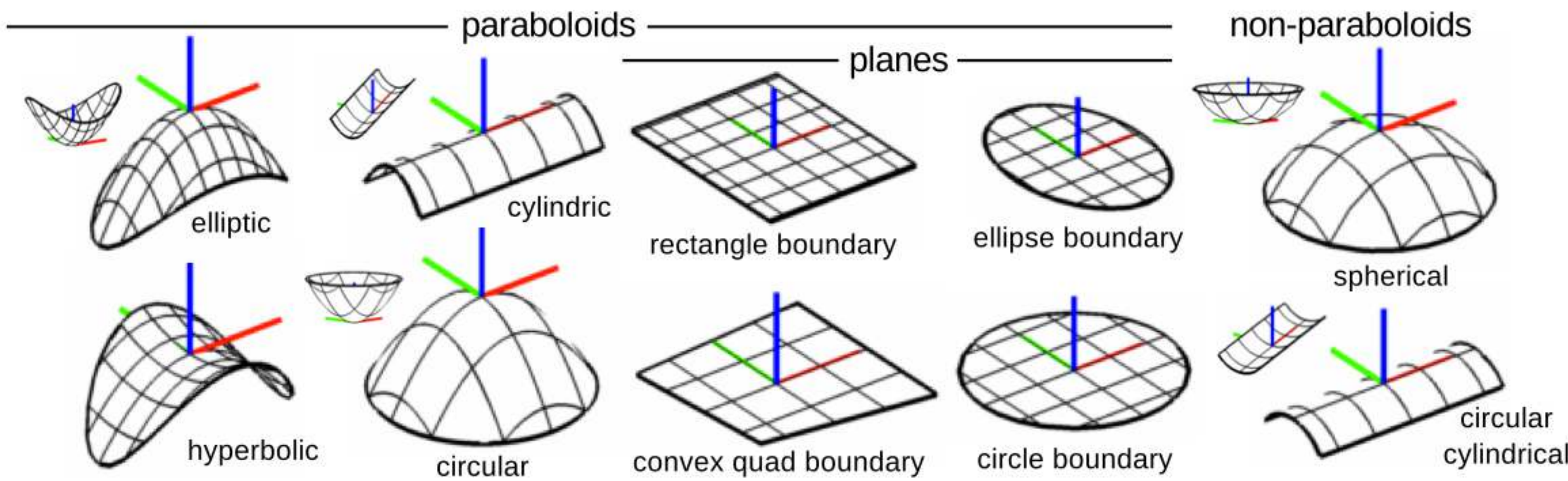
Sub-problems:

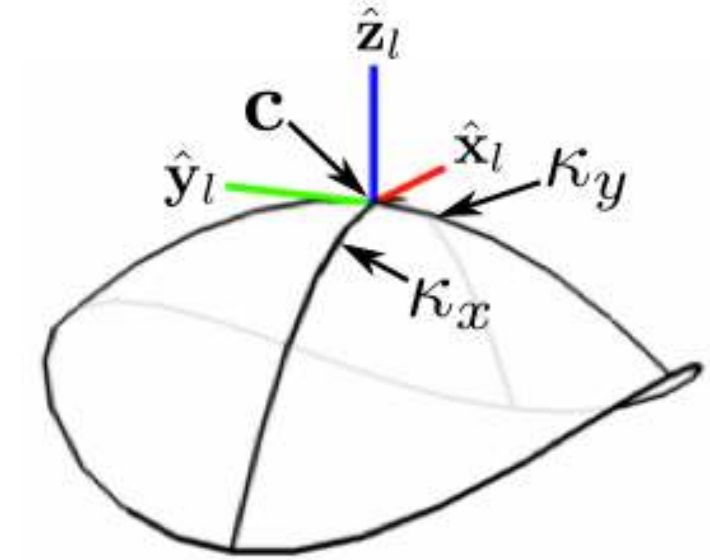
- detect and model local contact surface areas
- maintain a dynamic map of patches as the robot moves



Representing Curved Patches

10 bounded curved-surface patch types for contact regions





paraboloid in patch local frame

$$0 = p_{li}(\mathbf{q}_l, \mathbf{k}) \triangleq \mathbf{q}_l^T \operatorname{diag}([\mathbf{k}^T \ 0]^T)\mathbf{q}_l - 2\mathbf{q}_l^T \hat{\mathbf{z}}$$

$$\mathbf{q}_l = p_{le}(\mathbf{u}, \mathbf{k}) \triangleq [\hat{\mathbf{x}} \ \hat{\mathbf{y}}]\mathbf{u} + \frac{1}{2}\mathbf{u}^T \operatorname{diag}(\mathbf{k})\mathbf{u}\hat{\mathbf{z}}$$

curvature
$\mathbf{k} \in R^2$

paraboloid in world frame

$$0 = p_{wi}(\mathbf{q}_w, \mathbf{k}, \mathbf{r}, \mathbf{c}) \triangleq p_{li}(X_r(\mathbf{q}_w, \mathbf{r}, \mathbf{c}), \mathbf{k})$$

$$\mathbf{q}_w = p_{we}(\mathbf{u}, \mathbf{k}, \mathbf{r}, \mathbf{c}) \triangleq X_f(p_{le}(\mathbf{u}, \mathbf{k}), \mathbf{r}, \mathbf{c})$$

pose
$(\mathbf{r},\mathbf{c}) \in R^3 \times R^3$

ellipse bounds

$$\mathbf{u} \triangleq \Pi_{xy}\mathbf{q}_l = \Pi_{xy}X_r(\mathbf{q}_w, \mathbf{r}, \mathbf{c}), \ \Pi_{xy} \triangleq [\hat{\mathbf{x}} \ \hat{\mathbf{y}}]^T$$

$$0 \geq e(\mathbf{u}, \mathbf{d}_e) \triangleq \mathbf{u}^T \operatorname{diag}([1/d_x^2 \ 1/d_y^2])\mathbf{u} - 1$$

bounds
$\mathbf{d} \in R^2$

Patch Modeling:

1. curved, (foot-sized) bounded
2. geometrically meaningful minimal parameterization
3. quantified uncertainty

Vona, Kanoulas – IROS 2011

Uncertainty Representation

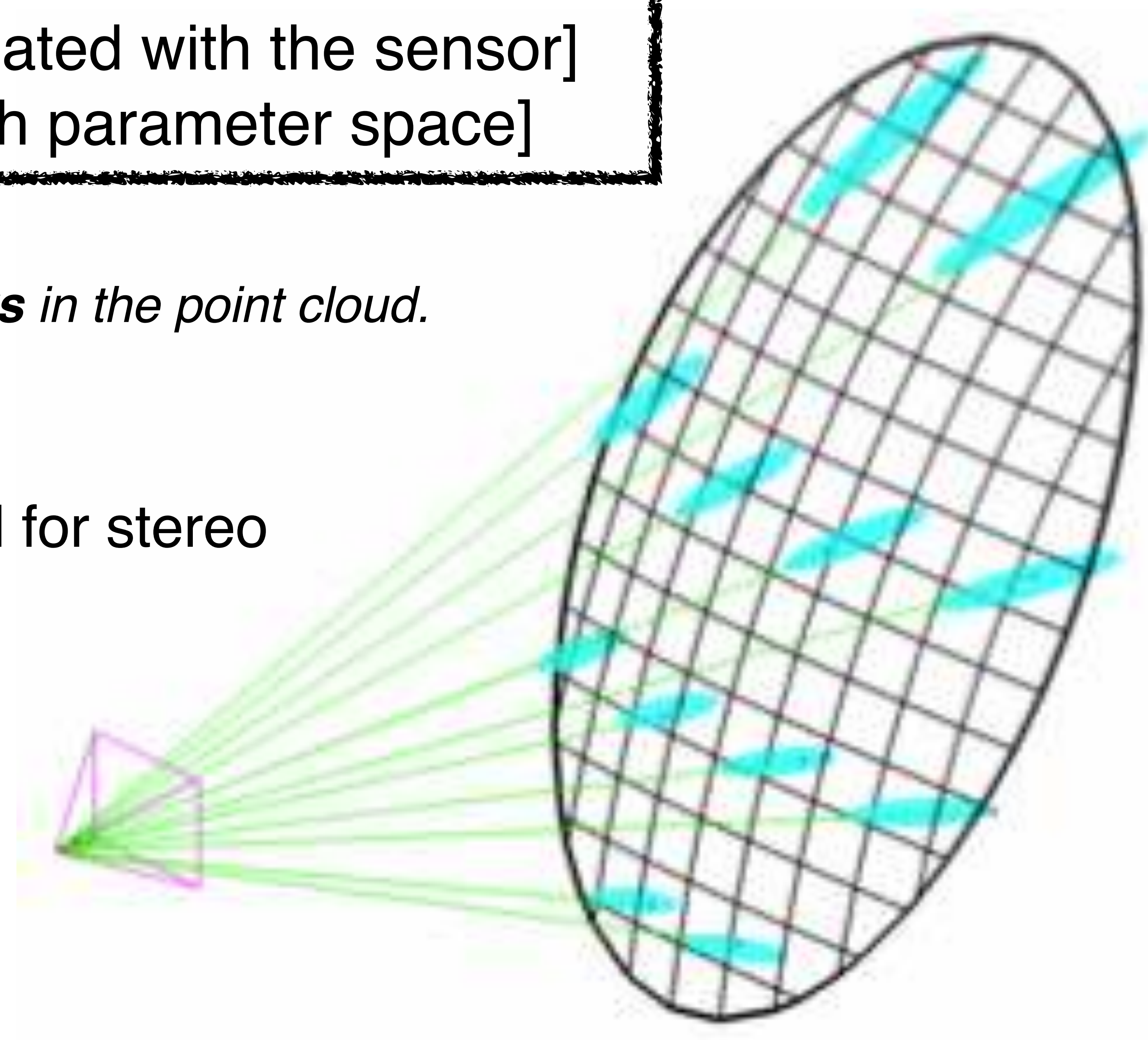
Gaussian modeling with covariance matrices.

Two kinds of uncertainty:

- of the input points [associated with the sensor]
- of the fitted patch [in patch parameter space]

*Note that there are also **outliers** in the point cloud.*

95% probability error ellipsoid for stereo range sensing.



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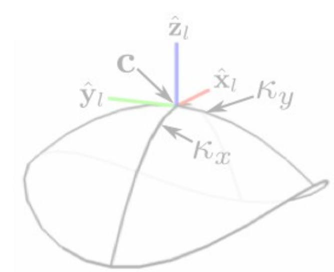

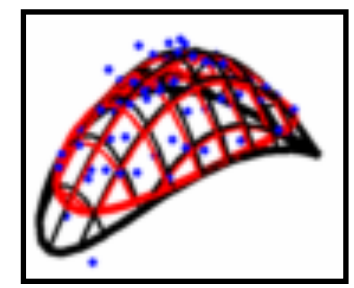

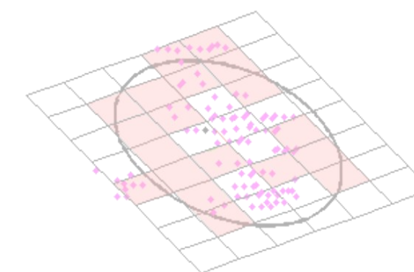

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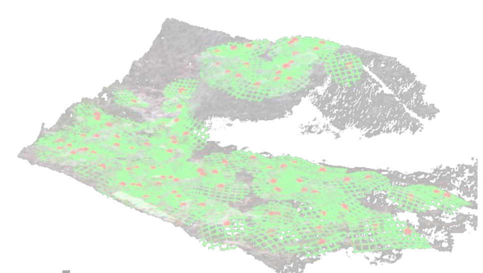
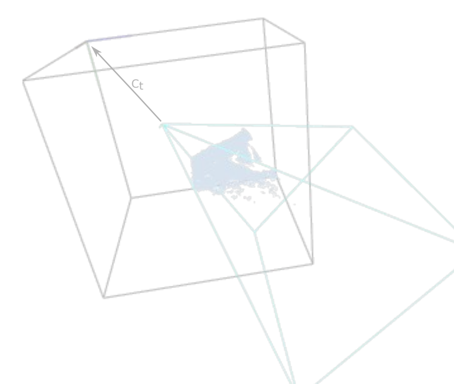
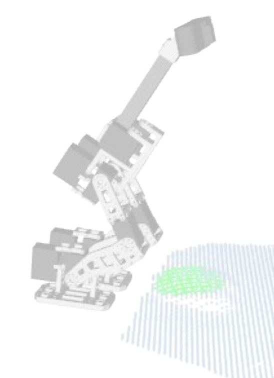


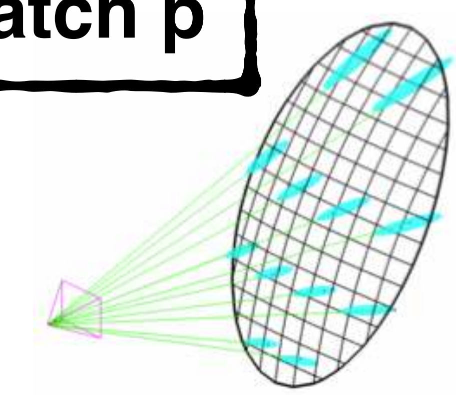




- Conclusions and Future Work

Patch Fitting with Uncertainty Propagation

Given a set of 3D points q_i with uncertainty Σ_i, fit a patch p



elliptic paraboloid
(original patch)

Levenberg-Marquardt Least Squares

$$\mathbf{p}_{\text{opt}} = \underset{\mathbf{p}\text{ near }\mathbf{p}_0}{\operatorname{argmin}}\ r,\ \ r \triangleq \sum_{i=1}^{N} e_i^2,\ \ e_i \triangleq f(\mathbf{q}_i, \mathbf{p})$$

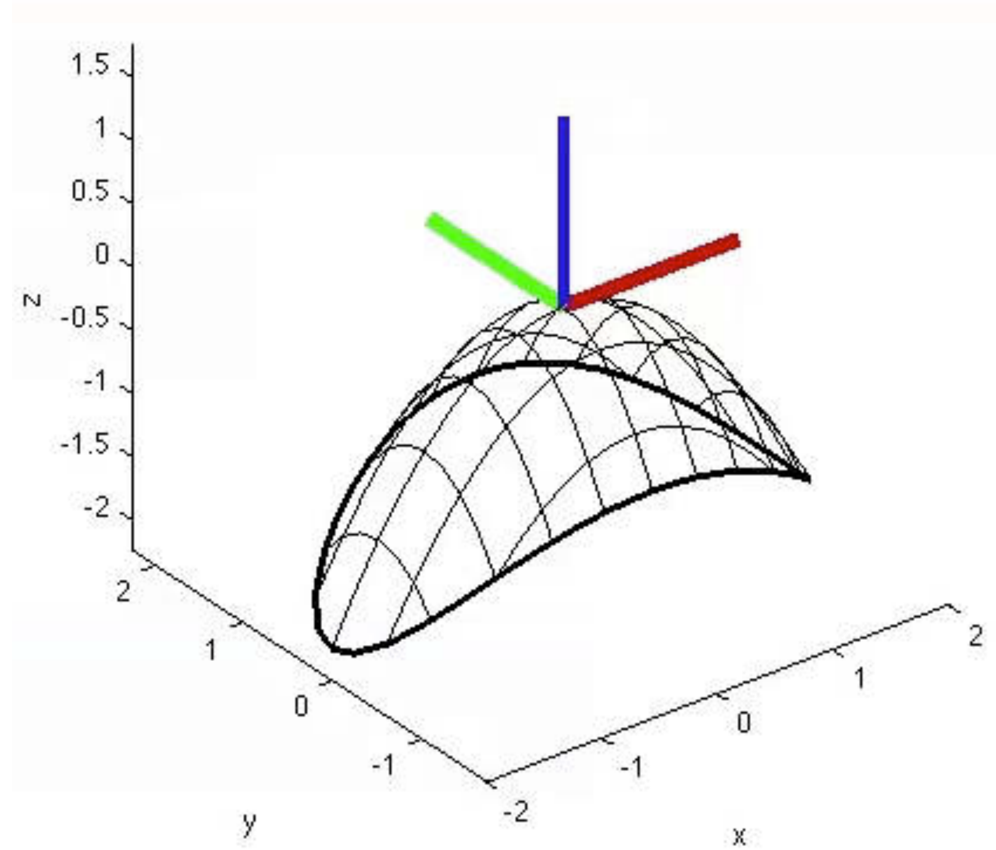
weighted Levenberg-Marquardt

$$F(i, \mathbf{p}) \triangleq f(\mathbf{q}_i, \mathbf{p})/\sigma_i = f(\mathbf{q}_i, \mathbf{p})/\sqrt{v_f(i, \mathbf{p})}$$

uncertainty propagation

$$\sigma_i = \sqrt{\operatorname{var}(f(\mathbf{q}_i, \mathbf{p}))} \triangleq \sqrt{v_f(i, \mathbf{p})}$$

$$v_f(i, \mathbf{p}) \triangleq \left(\frac{\partial f}{\partial \mathbf{q}}(\mathbf{q}_i, \mathbf{p})\right) \Sigma_i \left(\frac{\partial f}{\partial \mathbf{q}}(\mathbf{q}_i, \mathbf{p})\right)^T$$

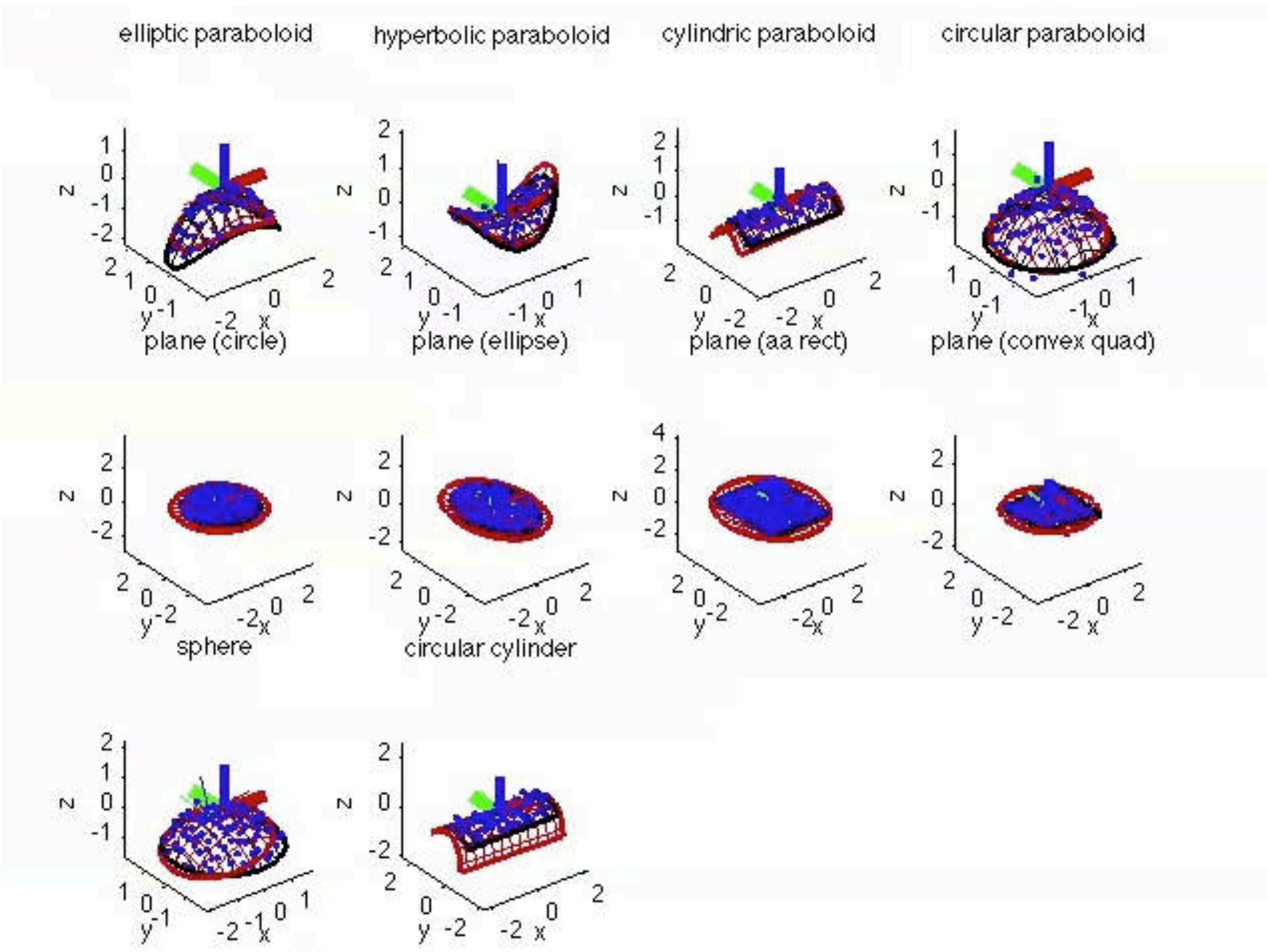


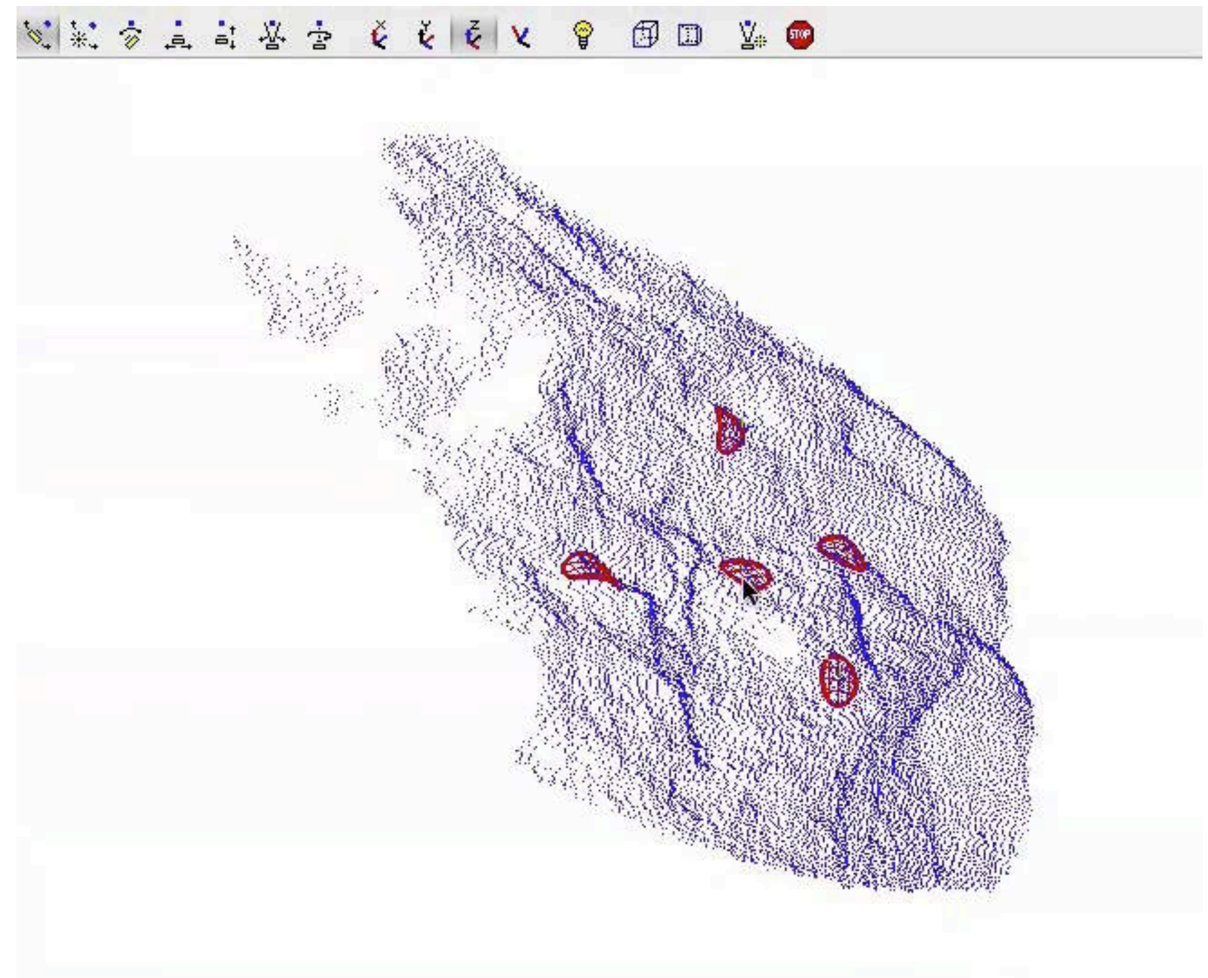
Real-time non-linear fitting algorithm including quantified uncertainty.

Manual Patch Fitting Algorithm

fit the 10 types of patches
in noisy simulated data

manually pick sample points;
automatically fit patches





Fitting algorithm speed: ~0.6ms per patch (50 neighbors) in C++

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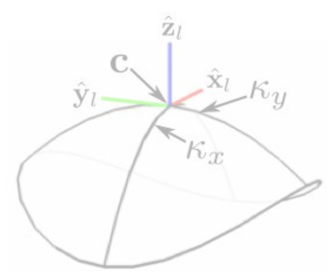

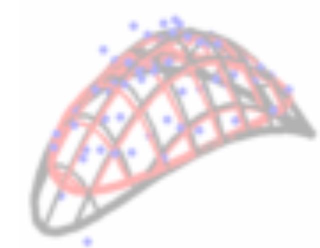

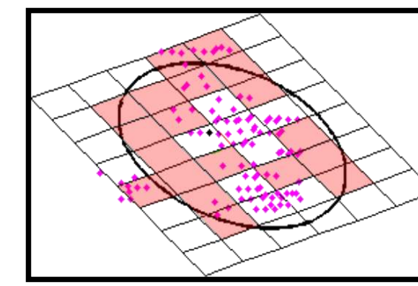

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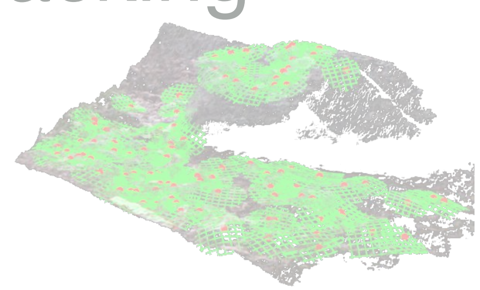

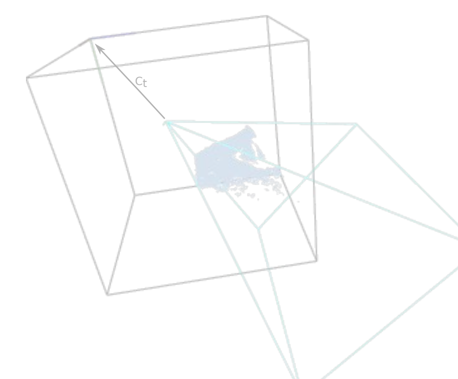

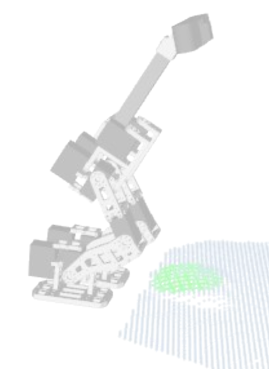

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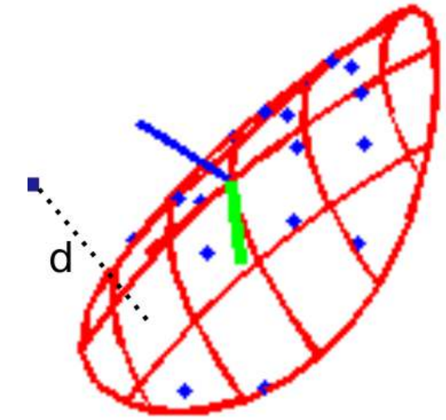
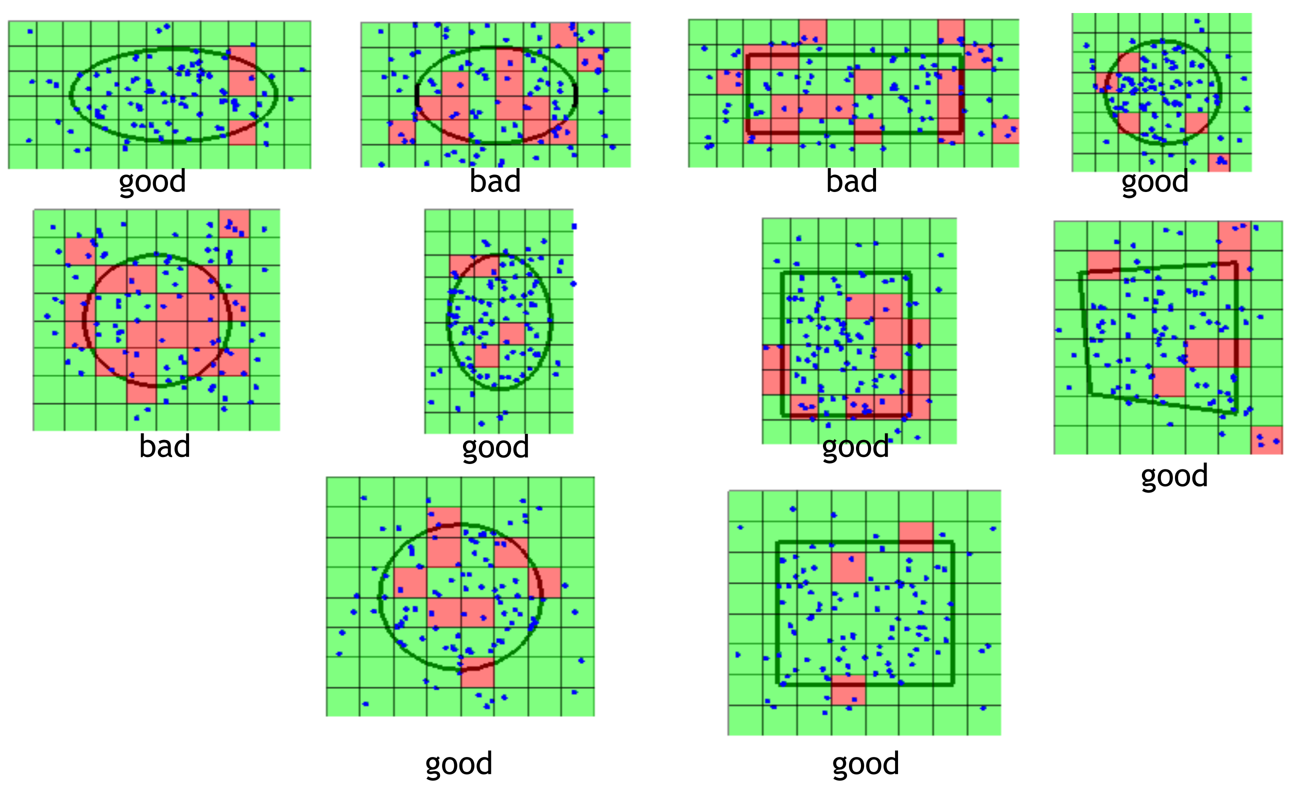
Patch Validation

Kanoulas, Vona – ICRA 2013

First check the geometric residual (patch fit quality): $res = \Sigma_{i=1}^{N} d_i^2$
The residual can be bad due to: 1) outliers, or 2) local minima in LM.

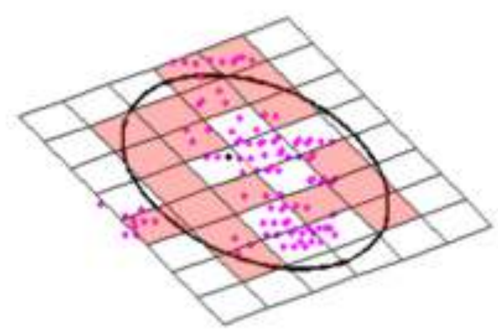


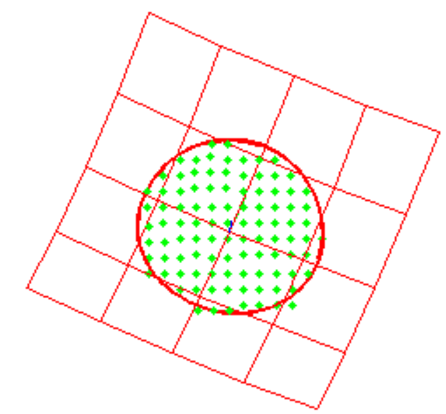
Second check the coverage vs the boundary (fidelity to data):
a patch may fit the data but still not faithfully represent the surface.



100 pts/patch, 50 cells/patch

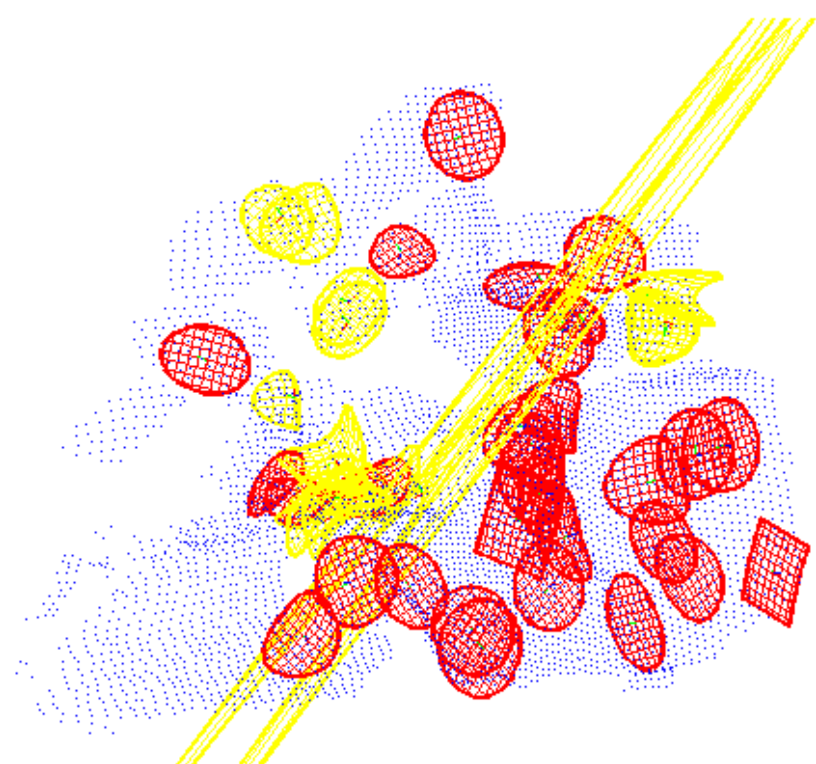
Good cell: 5 pts threshold **Bad patch:** less than 20% good cells
Green: good cells **Red**: bad cells





Third check the curvature:

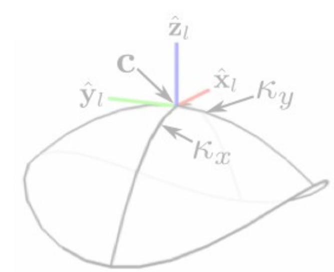
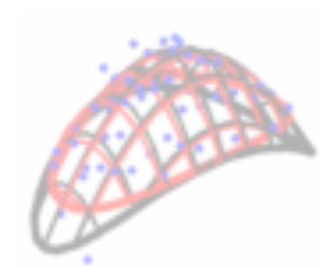
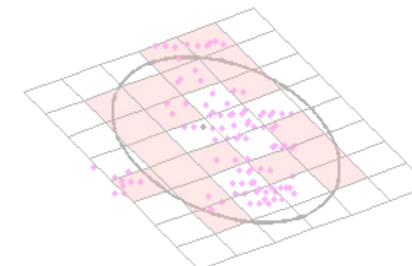
1) very curved surfaces
2) local minima in LM



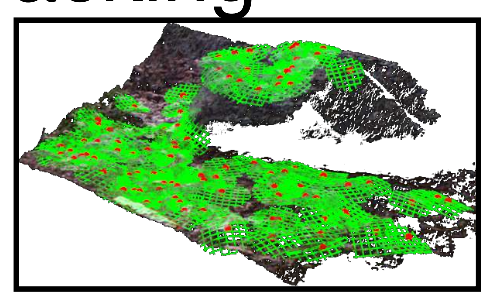
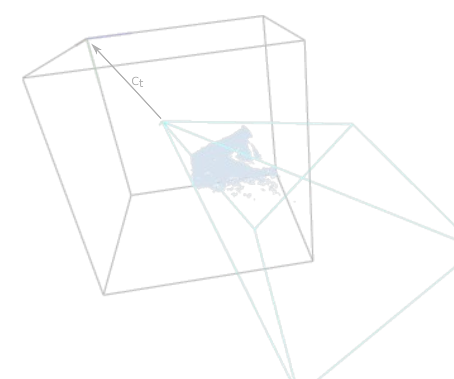
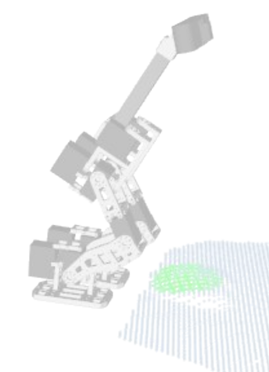
Outline

- Motivation and Related Work

- Sparse Surface Modeling with Curved Patches
  - Patch Modeling
  - Patch Fitting
  - Patch Validation

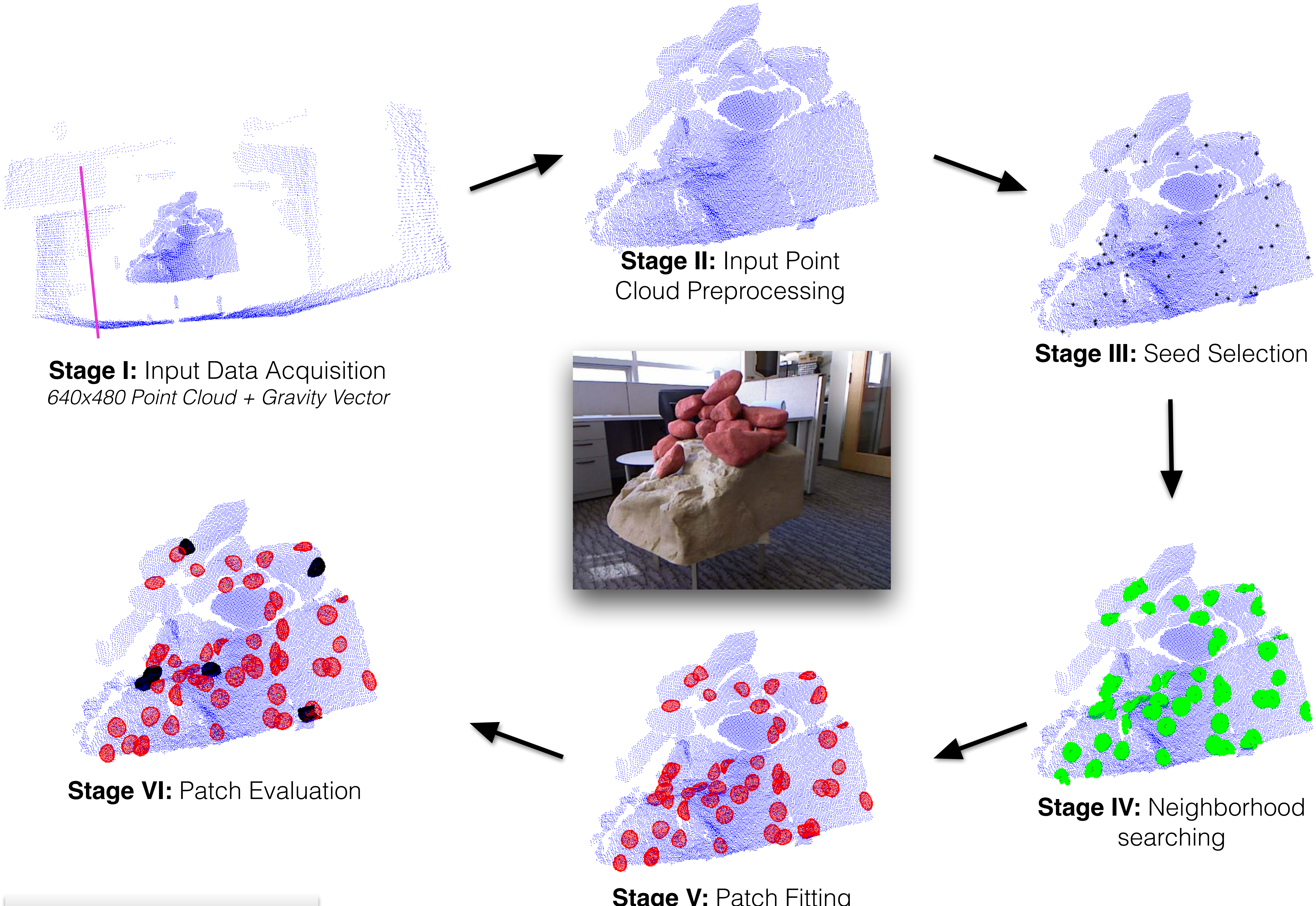




- Curved Patch Mapping and Tracking
  - Patch Mapping
  - Patch Tracking
  - Application to Biped Locomotion

- Conclusions and Future Work

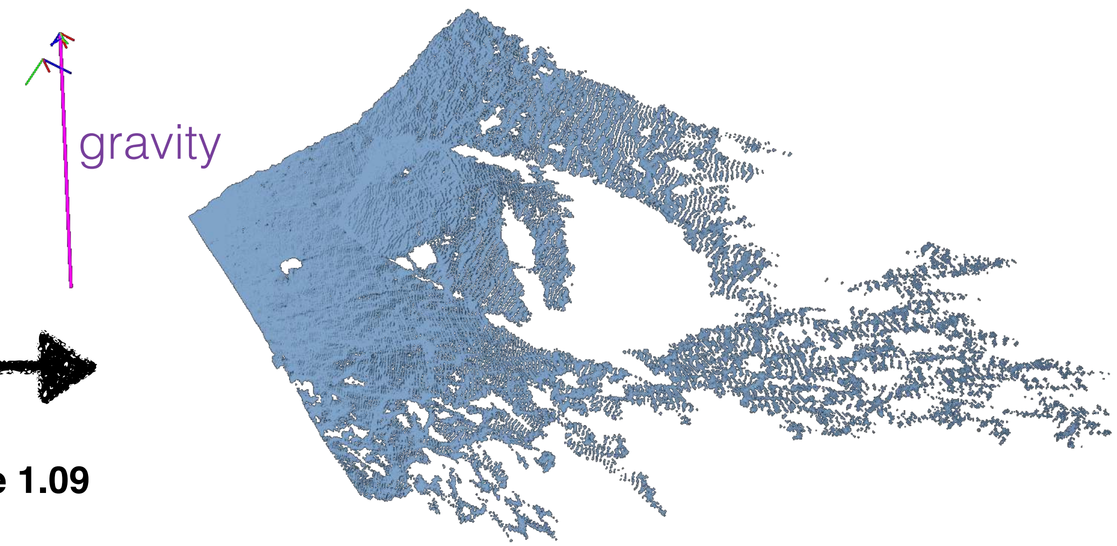
Patch Mapping with Curved Patches



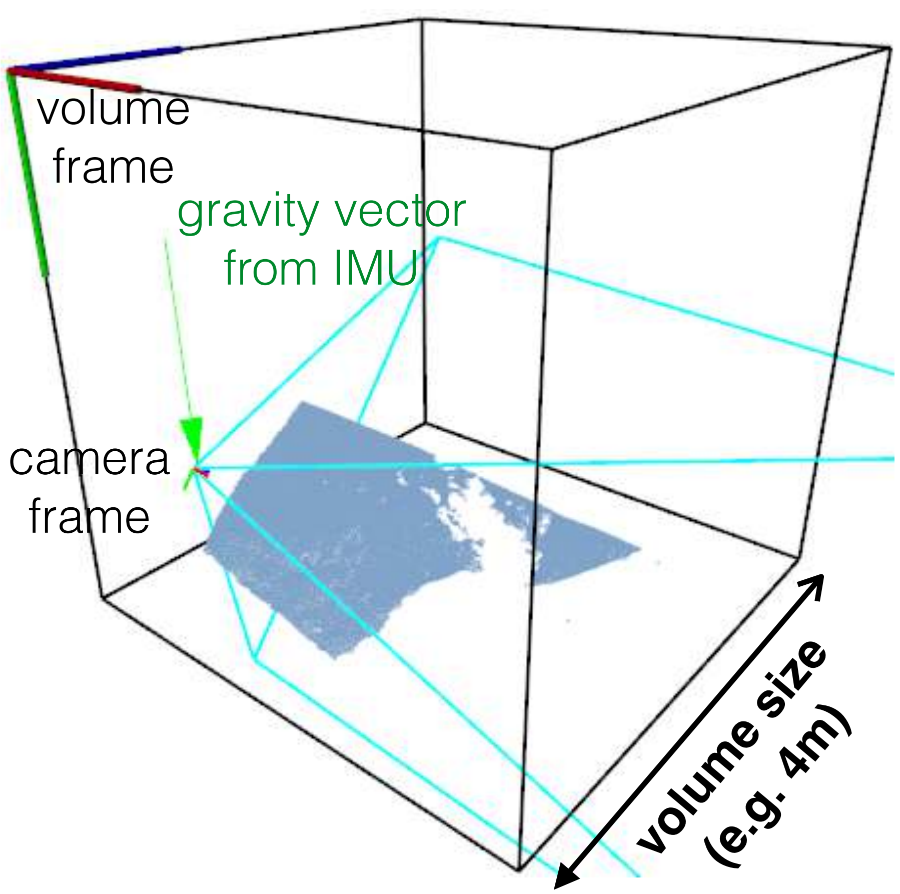
Stage I: Acquire Input Data

range sensing + IMU

- **PrimeSense Microsoft Kinect / Carmine 1.09**
- **CH Robotics UM6 9-DoF IMU**



Range Sensor: 640x480 pixels, i.e. 307,200 point cloud [~30Hz framerate]
IMU Sensor: gravity vector [~100Hz framerate]

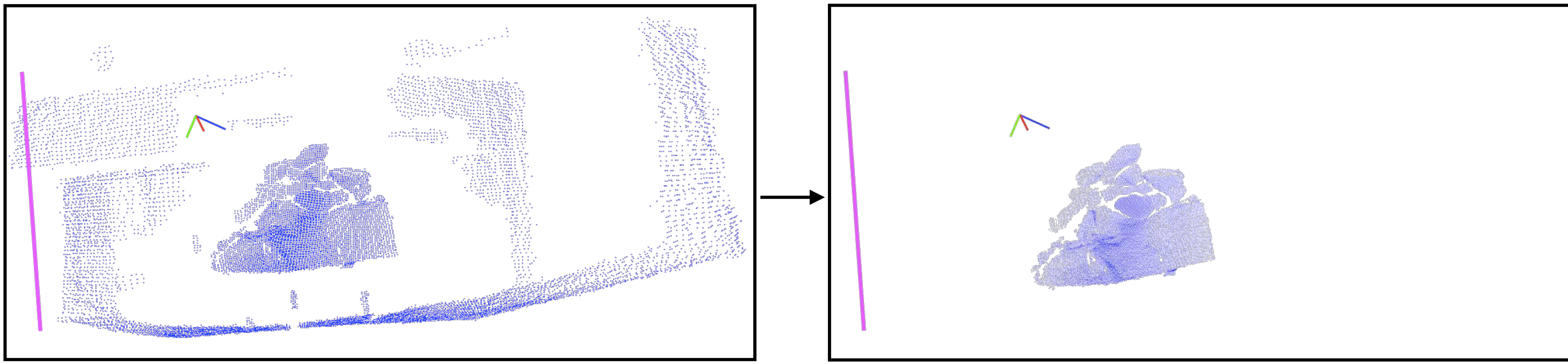


Local Volumetric Workspace

Moving policies:
1. fixed volume in the world
2. move volume with camera

Stage II: Preprocess the Input Point Cloud

1. **Remove"background"points (outliers):**
   - *either* using a passthrough filter for thresholding wrt points' depth
   - *or* by setting the volume size appropriately, keeping only the points in it



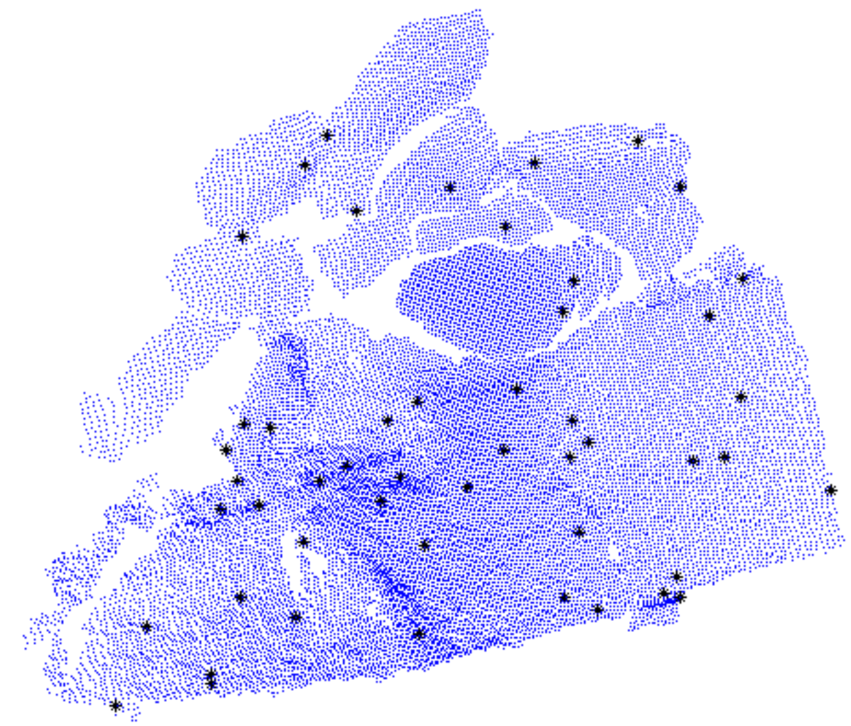
2. **Apply discontinuity preserving filters to reduce noise effects, e.g. median filter rejects outliers**

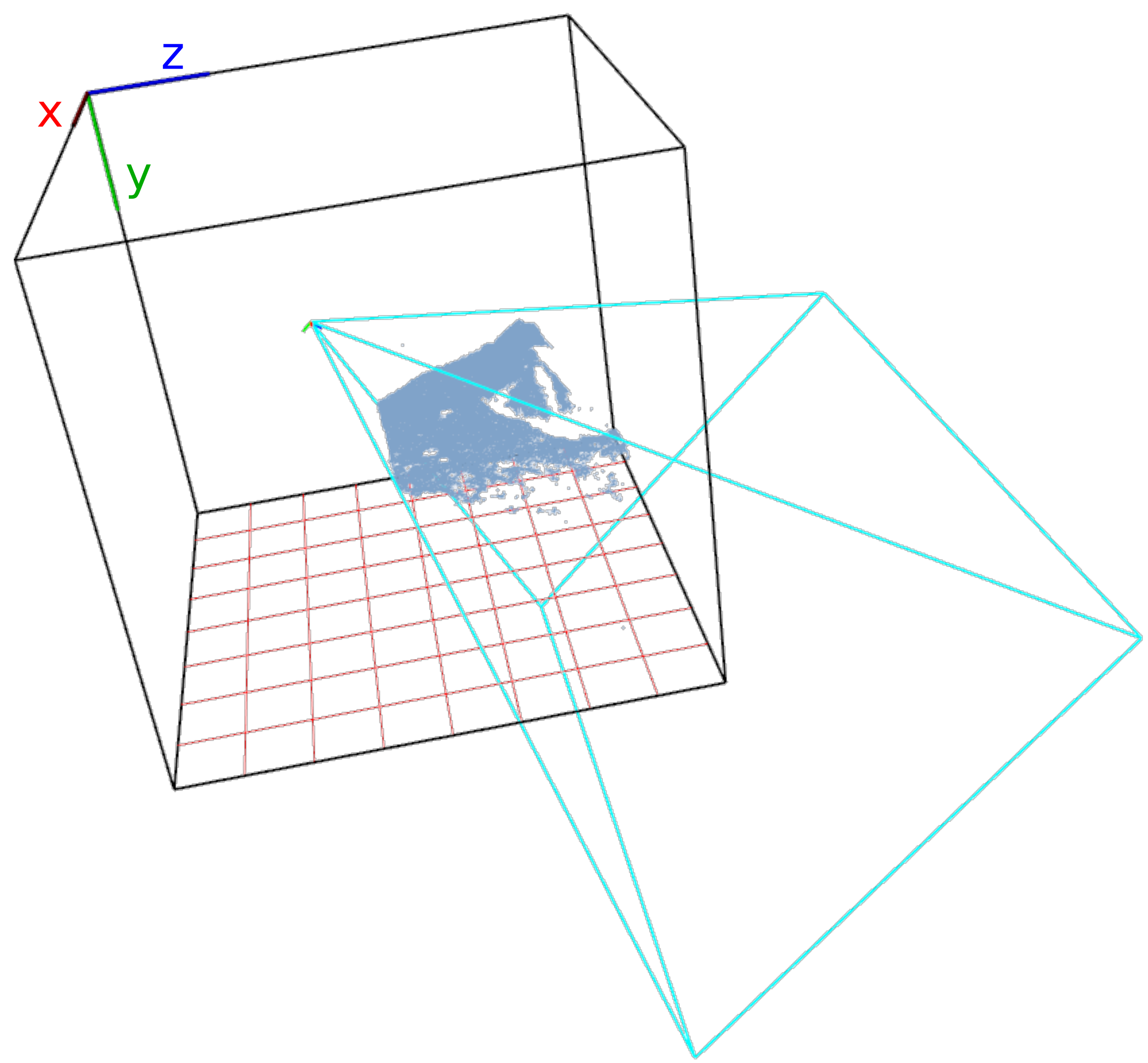
Stage III: Seed Selection

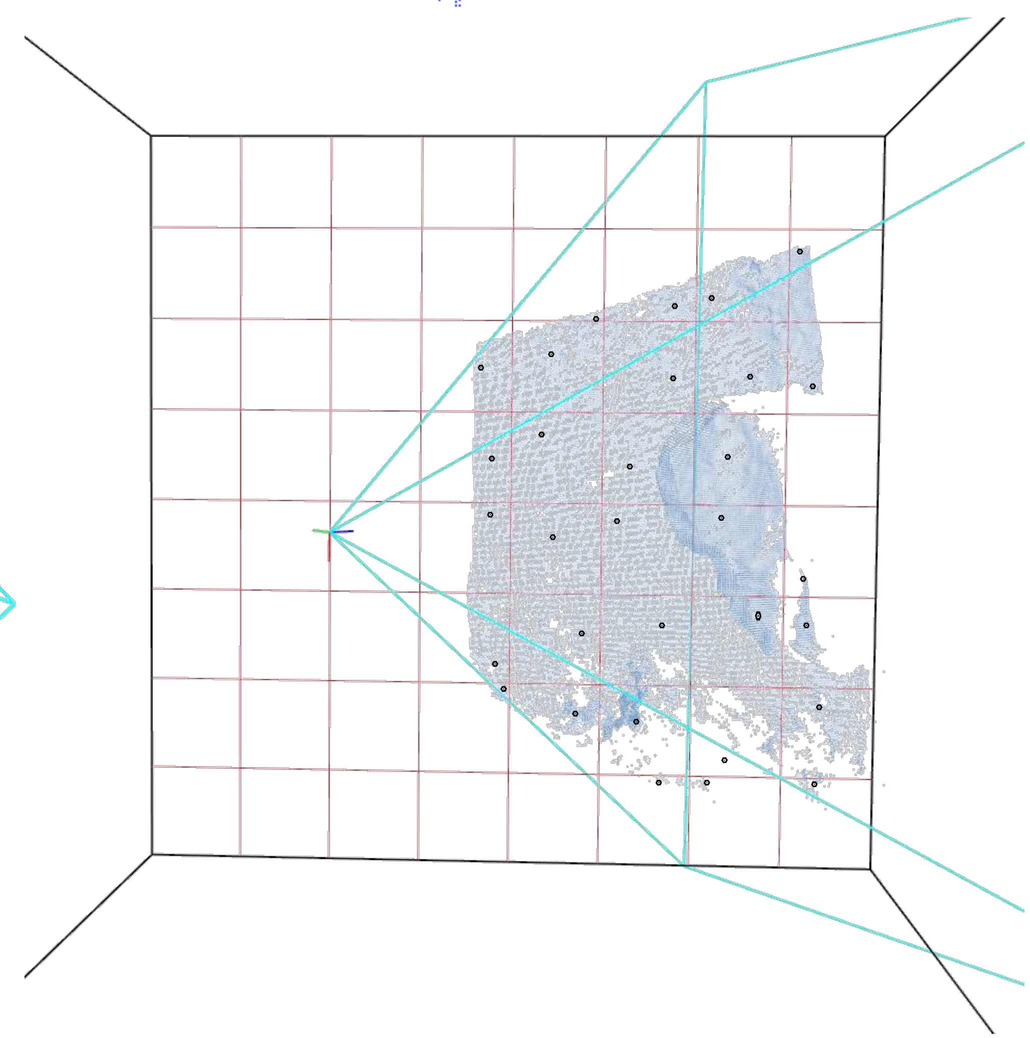
Uniformly random points

- fast baseline method
- general and task-independent
- **but** requires fast evaluation of the patch

Keep seeds ordered wrt the distance from the robot







Real-Time Bio-Inspired Salient Seed Selection

Task: bipedal hiking in rough rocky terrain
Intend to: find **salient** seed points to fit foot-scale curved surface patches

<u>Bio-Inspired method</u> Analyze human subjects footholds, while traversing rocky trails, with respect to their: ***1) location, 2) curvature, 3) orientation***

Kanoulas, Vona – ICRA 2014

Bio-Inspired Saliency

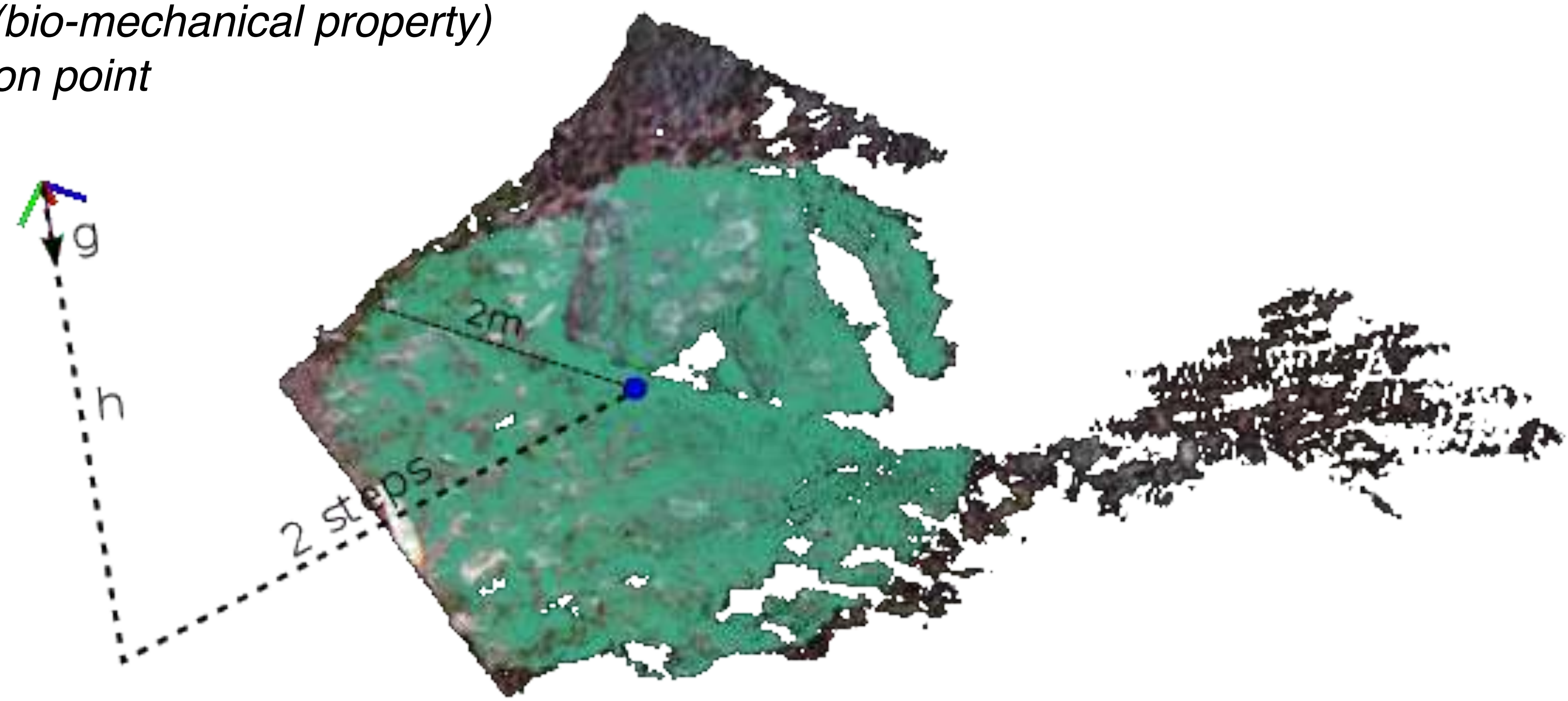
Four measures of saliency that relate to patches that humans commonly select for stepping:

1. Distance to Estimated Fixation Point (DtFP)

- humans tend to fixate about 2 steps ahead (bio-mechanical property)

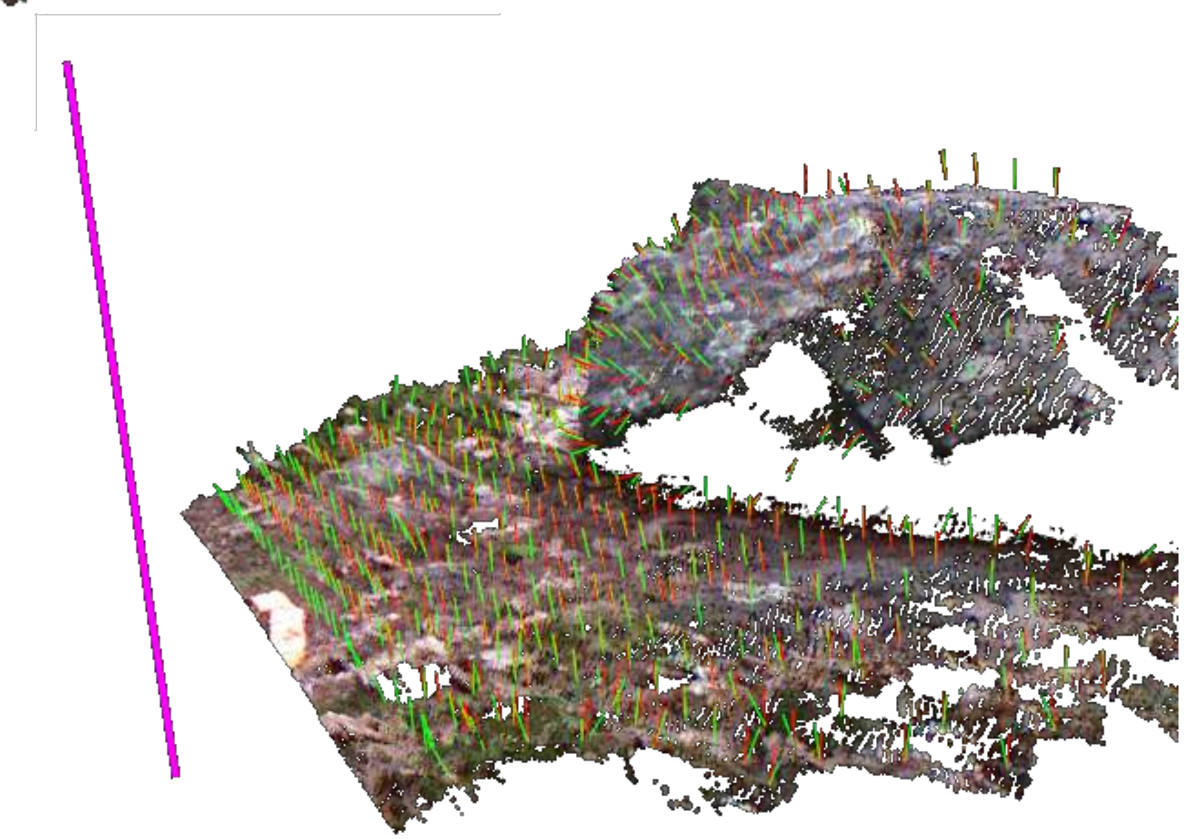
- ***salient points:*** *at most 2m away from fixation point*

[Marigold, Patla – Neuroscience 2007]



2. Difference of Normal-Gravity (DoNG)

- *use of fast Integral Images approach [Holzer et al – IROS 2012]*
- ***salient points:*** *small angle between normal and gravity vector*

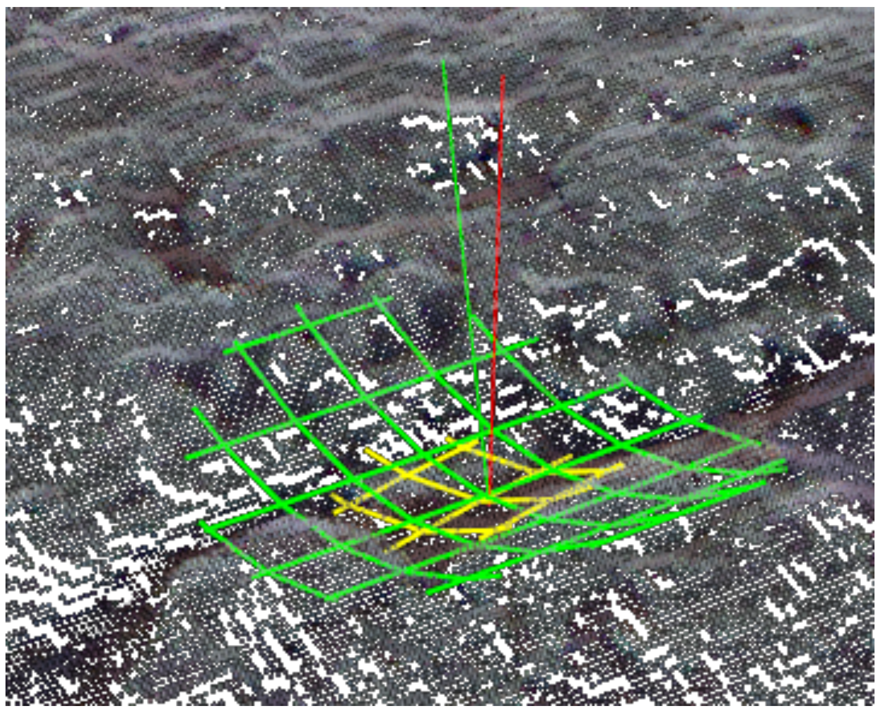


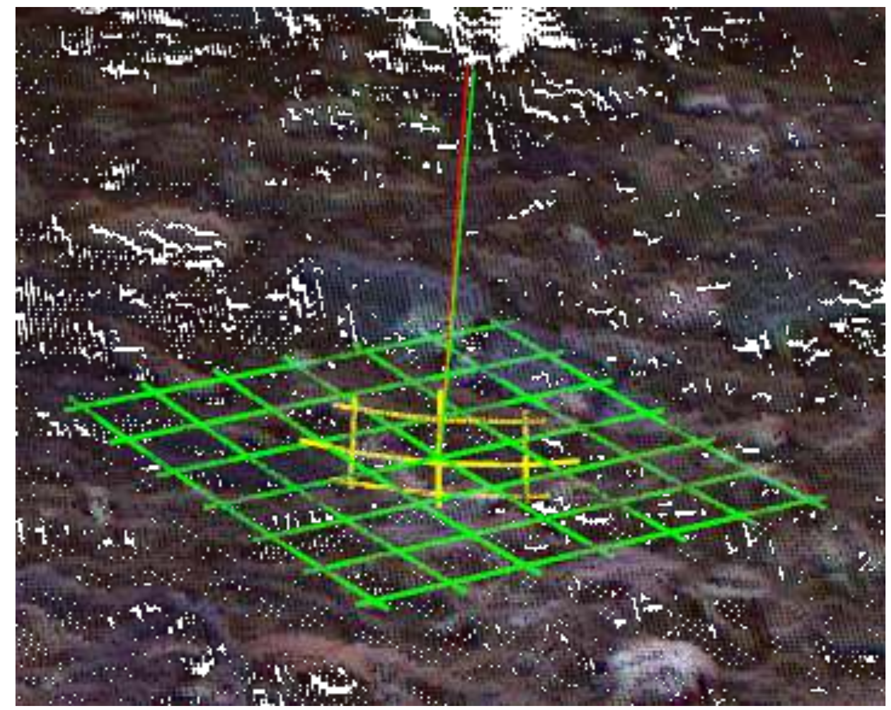
Bio-Inspired Saliency

Four measures of saliency that relate to patches that humans commonly select for stepping:

3. Difference of Multiscale Normals (DoN)

- the angle difference between normals for fine vs coarse scale neighborhoods of a point, relates to irregularity of the surface around the point [Lam, Greenspan – CRV, 2012]
- ***salient points**: low angle difference between normals*





4. Min and Max Principal Curvature

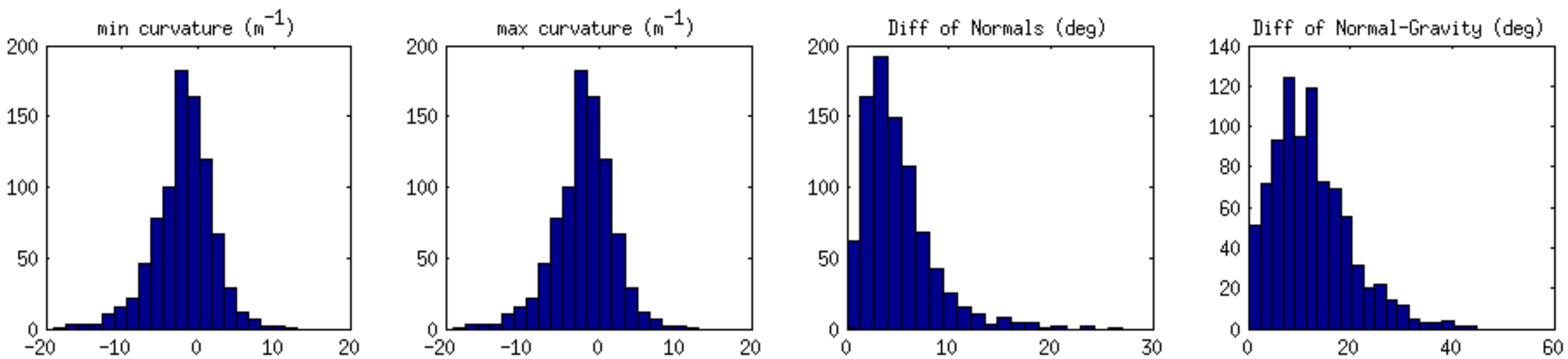
- *depends on the shape of the robot foot*
- ***salient points (for flat feet):** low curvature*

How do we set the thresholds: 1) min/max curvature, 2) slope, 3) diff of normals angle

Human Select Data (setting the saliency thresholds)

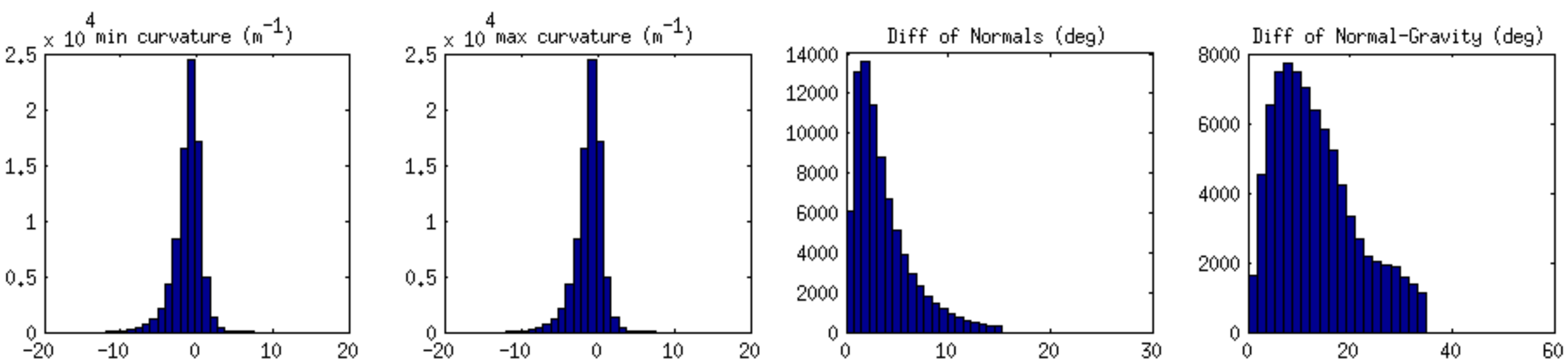
Thresholds:
- min/max curvature
- slope
- diff of normals angle

Data:
- 6 trails (~10m each)
- RGB-D + IMU data
- 5 humans
- 867 footsteps



Human Selected Patches
867 total patches
832 depth+IMU data frames

auto patch fit: set the thresholds to the corresponding averages+3σ

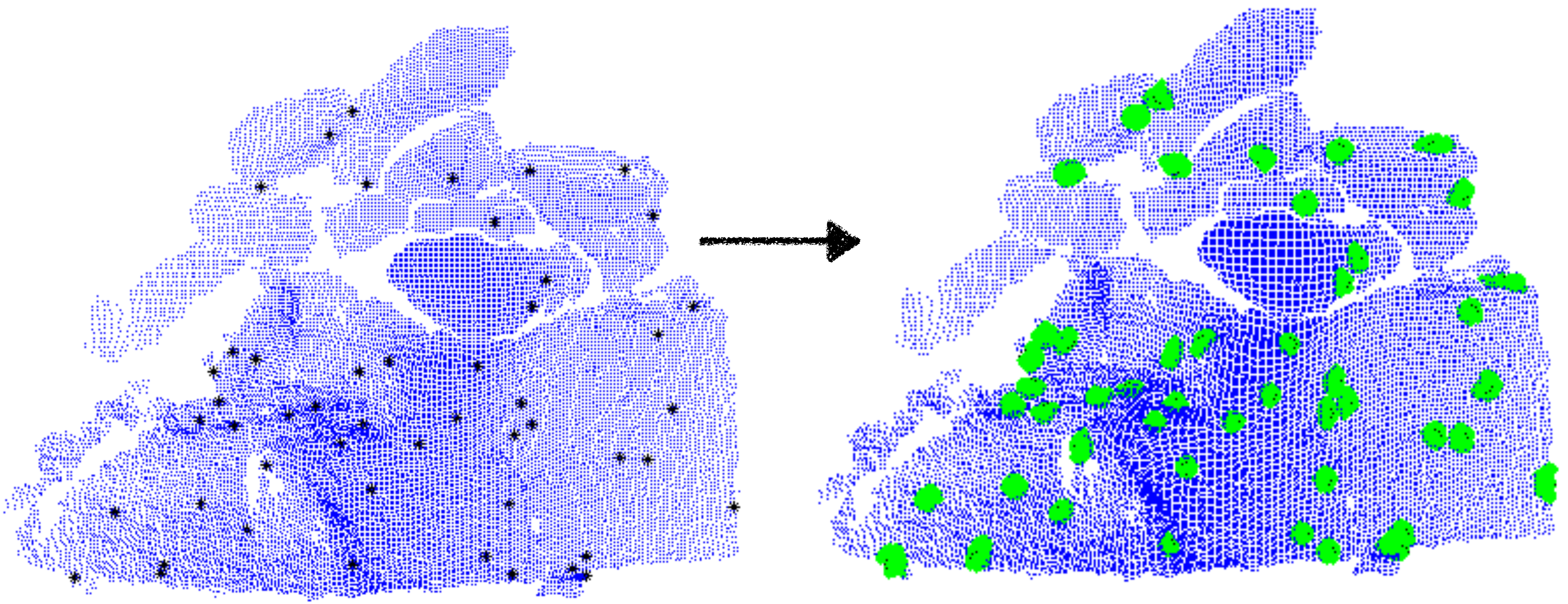


Automatically Fit Patches
82052 total patches
832 depth+IMU data frames
(same frames as above)

Stage IV: Neighborhood Searching

Given seed points, find the nearest neighbors in a sphere of **radius r** (i.e. patch size)

The method needs to be: **fast** & handle **jumps** and **occlusions**

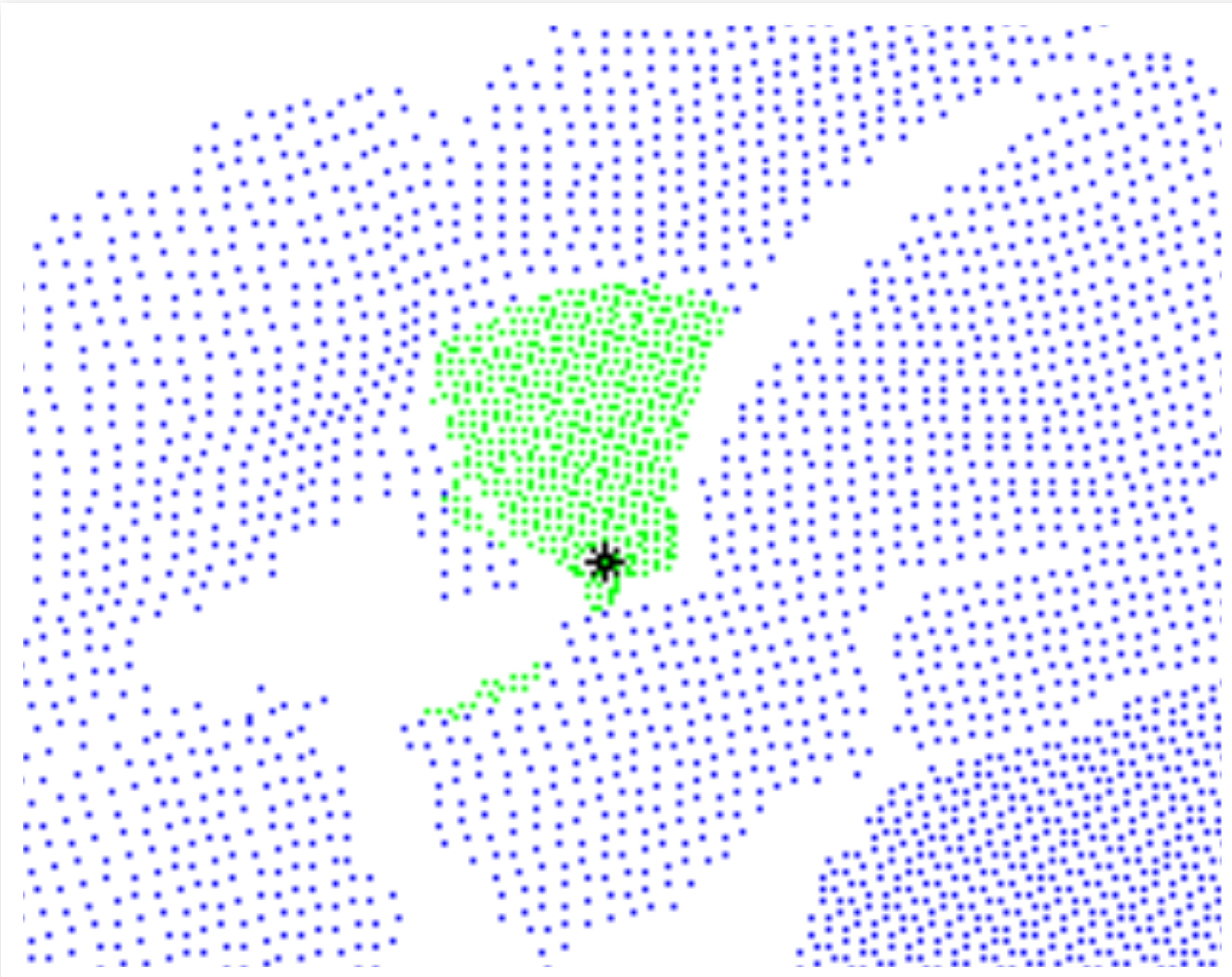


We tested three different methods:

- **kD trees**
- **mesh triangulation**
- **back-projection**

Stage IV: Neighborhood Searching

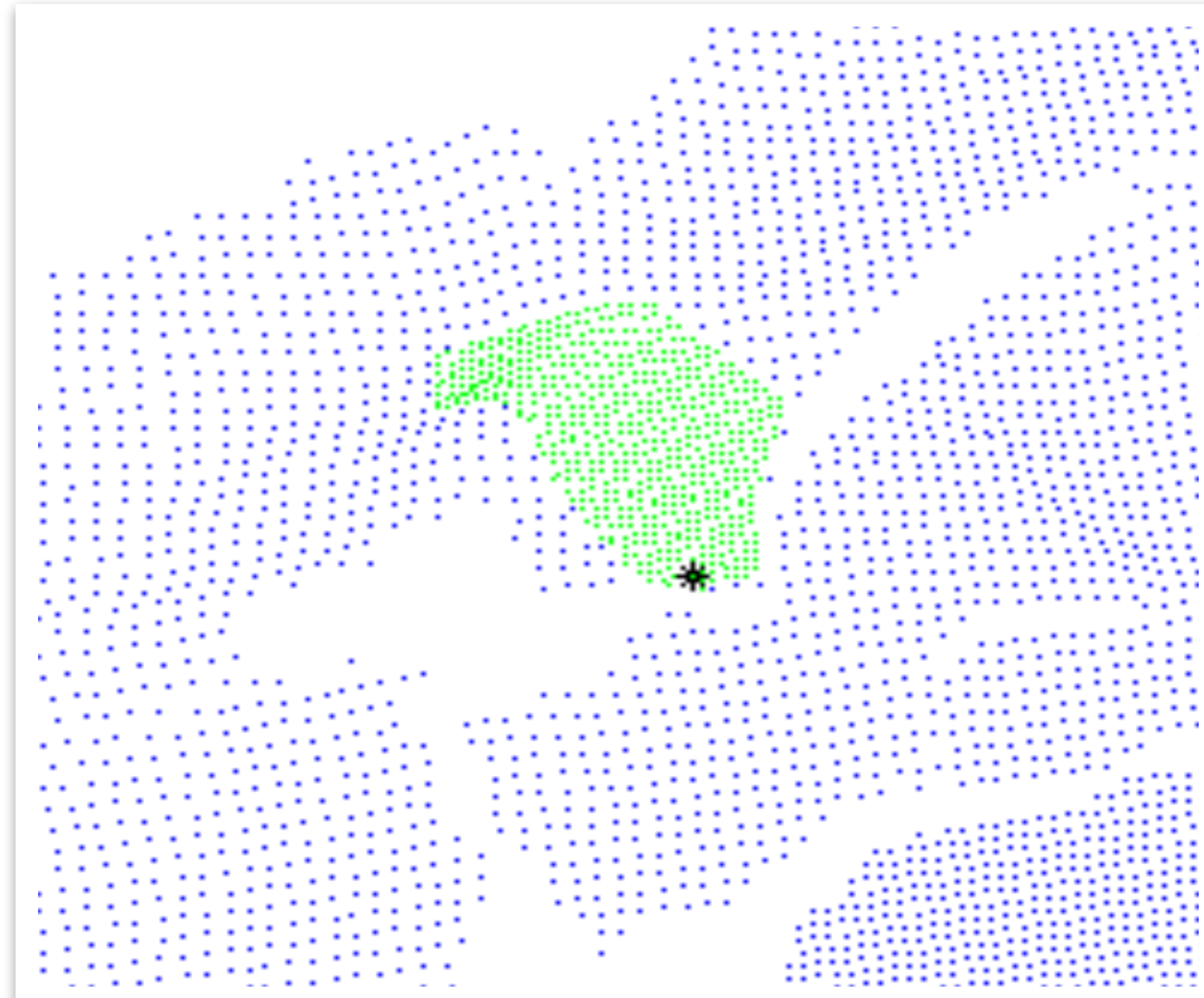
kD tree, back-projection



- ❖ **Time:**
  - kD tree building: *O(n logn)*
  - kD tree searching k neighbors: *O(k logn)*
  - back-projection searching in r-sphere: *$O(r^2)$*
- ❖ **Problem:** jumps and occlusions

[Bentley – CACM'75]

mesh triangulation

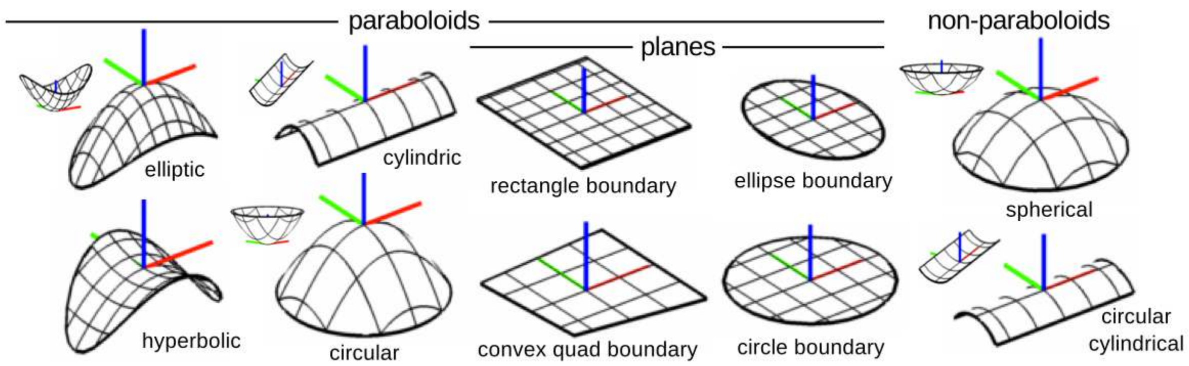


- ❖ **Time:**
  - mesh building: *O(n)*
  - *mesh searching k neighbors (BFS): O(k)*
- ❖ Suppress triangles that go along discontinuities to avoid jumps.

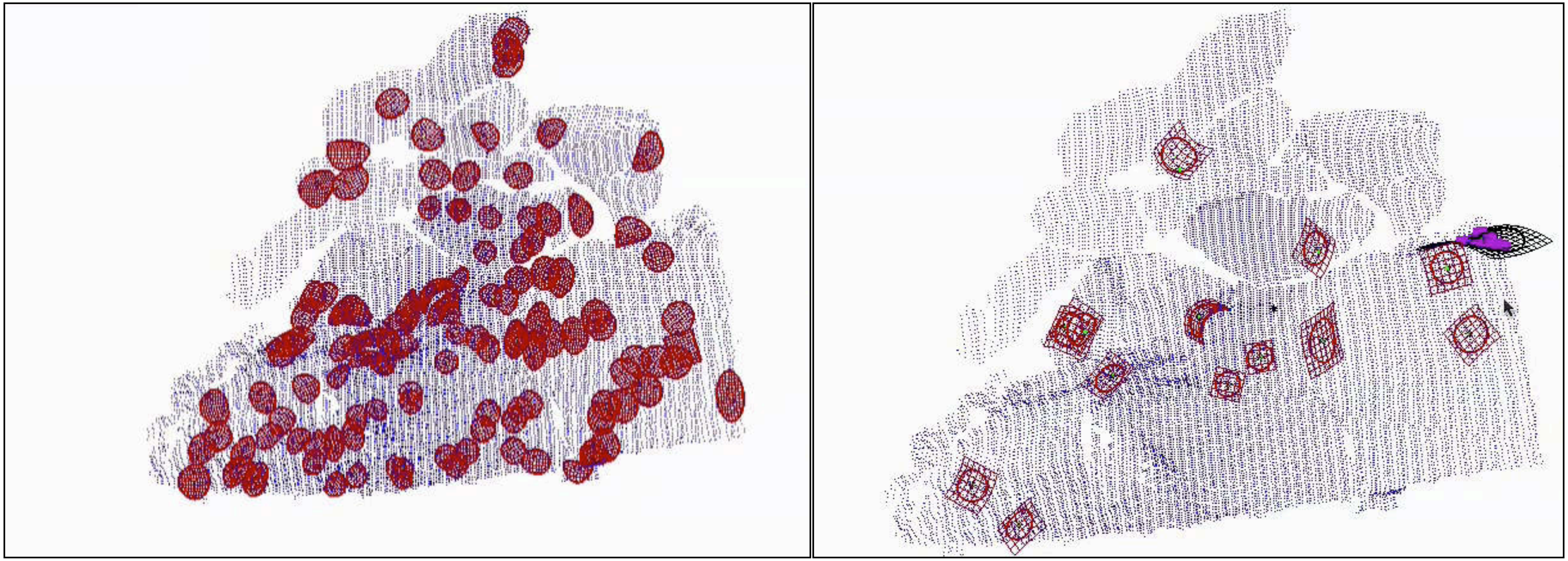
[Wolfart, et al – CVS'99]

Stage V & VI: Patch Fitting & Validation

Fit paraboloid patches with pre-selected size wrt the robot's patch size, e.g. 10cm



Validation with respect to: 1) geometric residual, 2) coverage, and 3) curvature



fitting *validation*

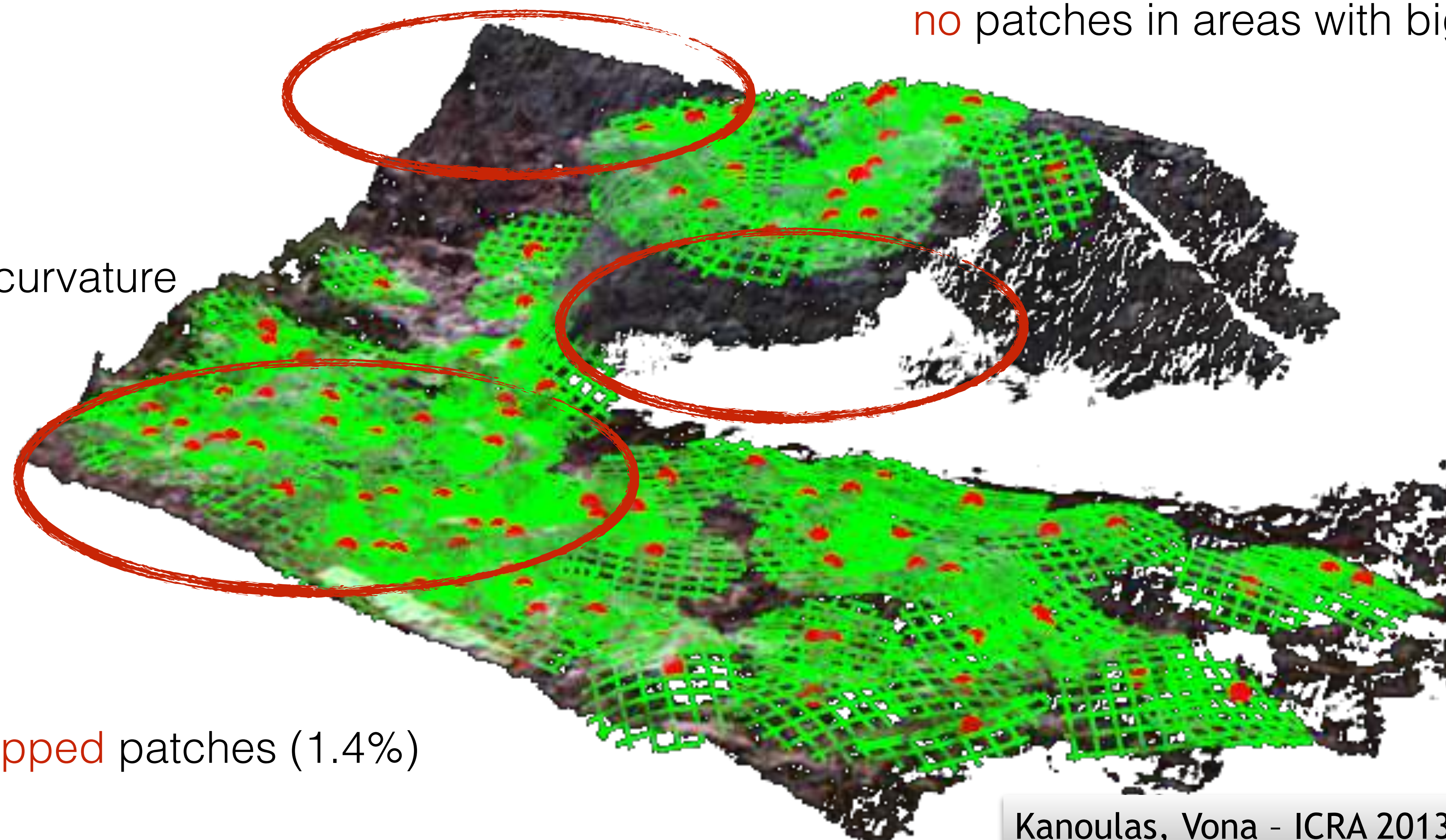
Patch Map in the Local Volumetric Workspace

100 patches are fit to a random sub-sampling of salient seeds and are validated

no patches fitted further than 2m from the Fixation Point

no patches in areas with big slope

no patches with big curvature



low number of dropped patches (1.4%)

Kanoulas, Vona - ICRA 2013

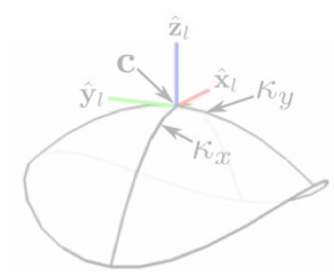
Performance: *700 salient patches/sec*
Goal: *reasonably sample upcoming terrain with quality patches in real time*

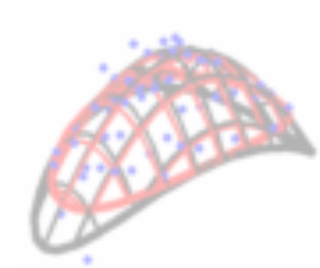
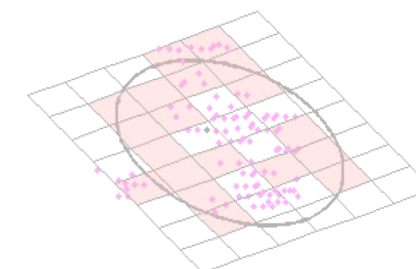
640x480 Point Cloud (0.4MB) -> 100 Patches (3kB)

Outline

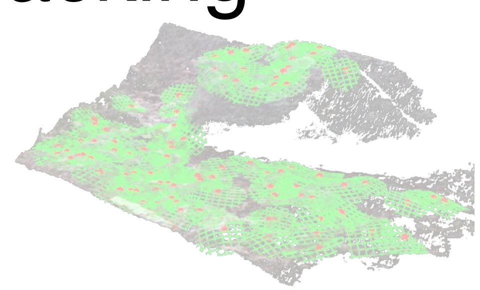
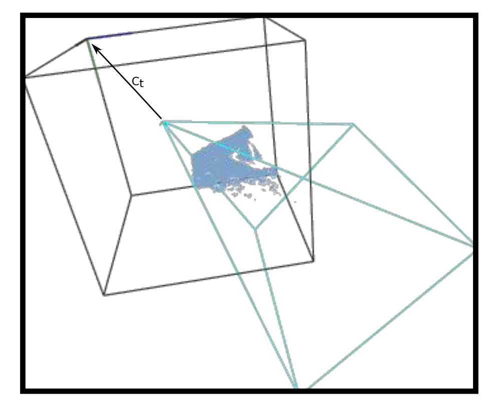
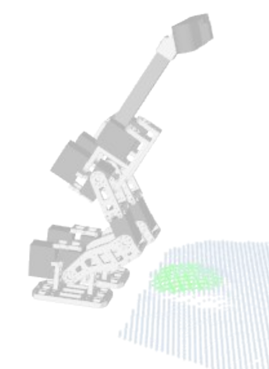
- Related Work

- Sparse Surface Modeling with Curved Patches
  - Patch Modeling
  - Patch Fitting
  - Patch Validation



- Curved Patch Mapping and Tracking
  - Patch Mapping
  - Patch Tracking
  - Application to Biped Locomotion

- Conclusions and Future Work

Patch Tracking

or "where is the patch in next frame?"

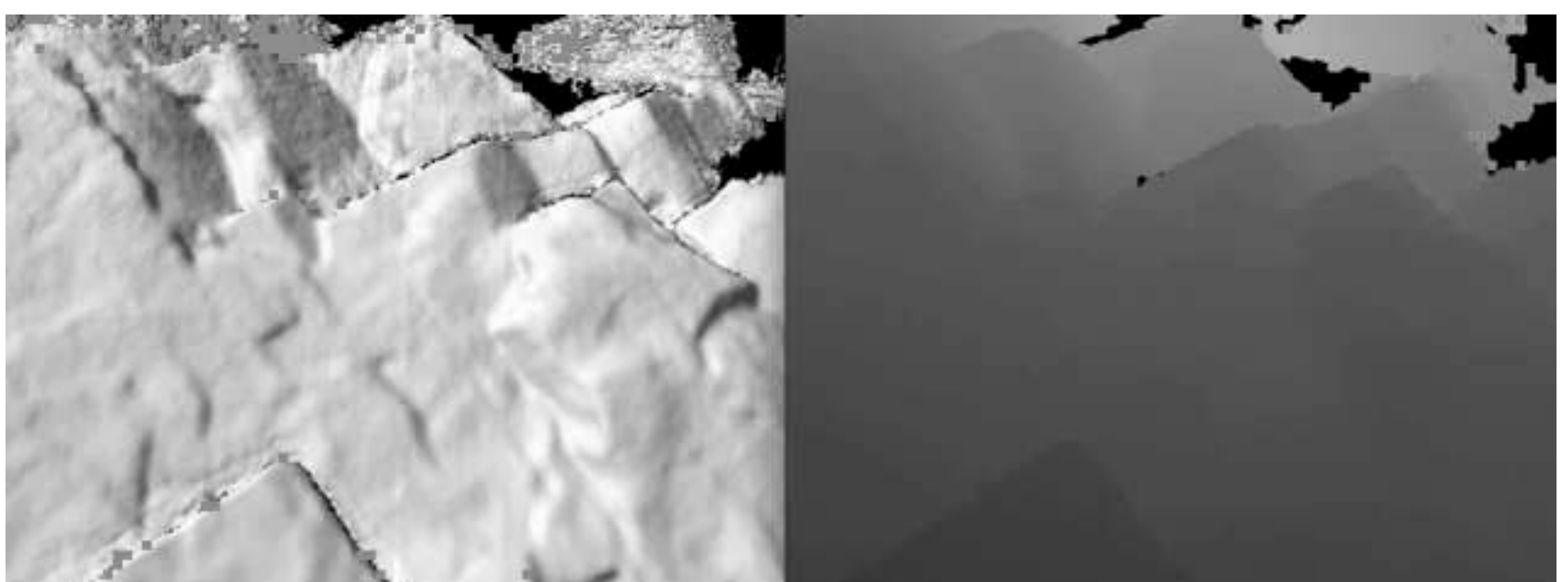
While moving from frame-to-frame, track the camera movement.

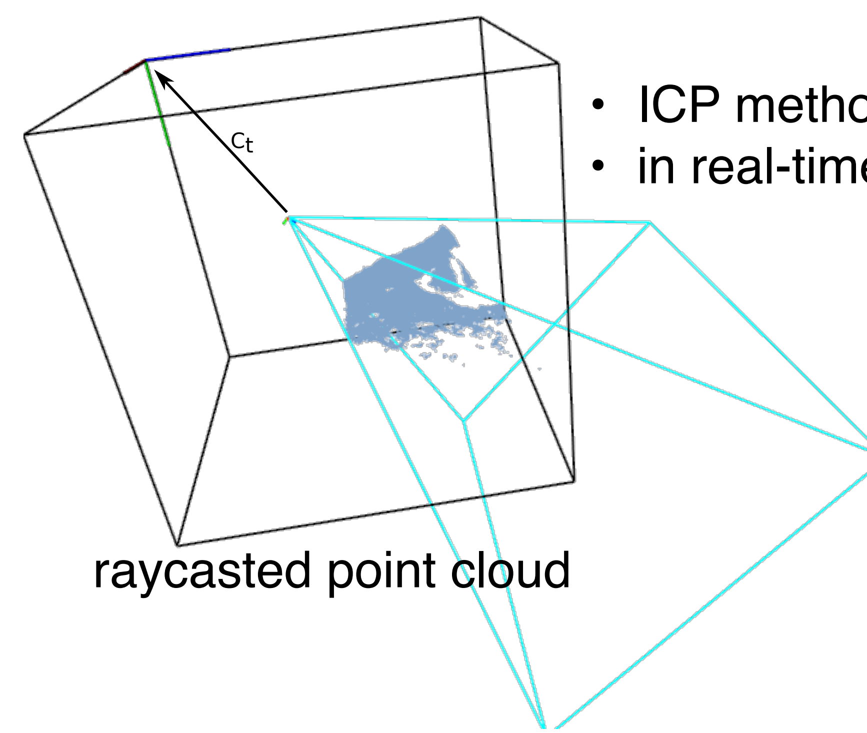
<u>Well studied:</u> in the context of Simultaneous Localization and Mapping (SLAM)
<u>Challenges:</u> shaking or jerky camera motion during walking

Solution: (**Moving Volume** [Roth, Vona – BMVC'12])
Kinect Fusion [Newcomb et al – ISMAR'11]

original
integrates depth maps into a truncated signed distance formula (TSDF) representation for <u>fixed space</u>

moving volume
translates and rotates the TSDF volume along with the camera

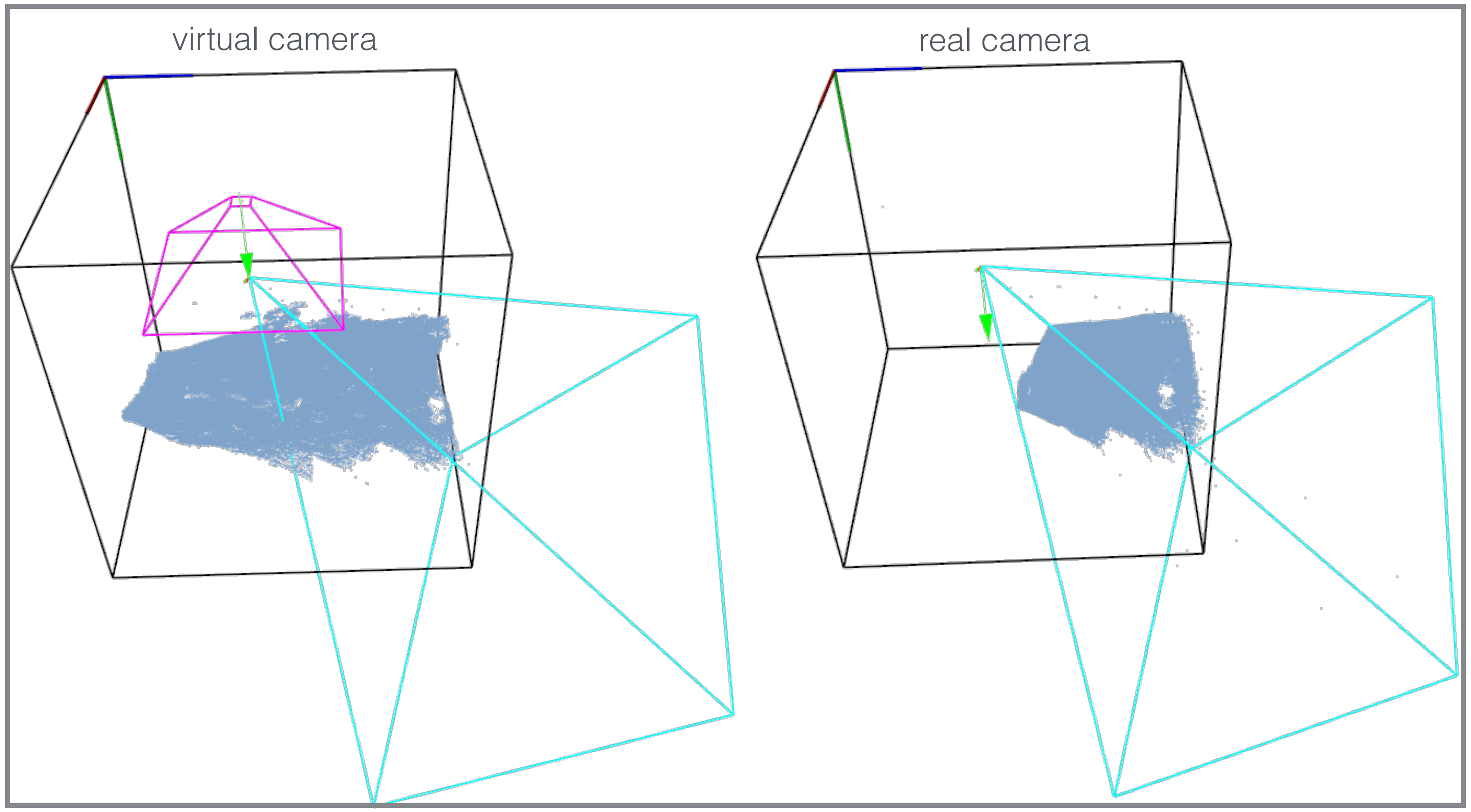


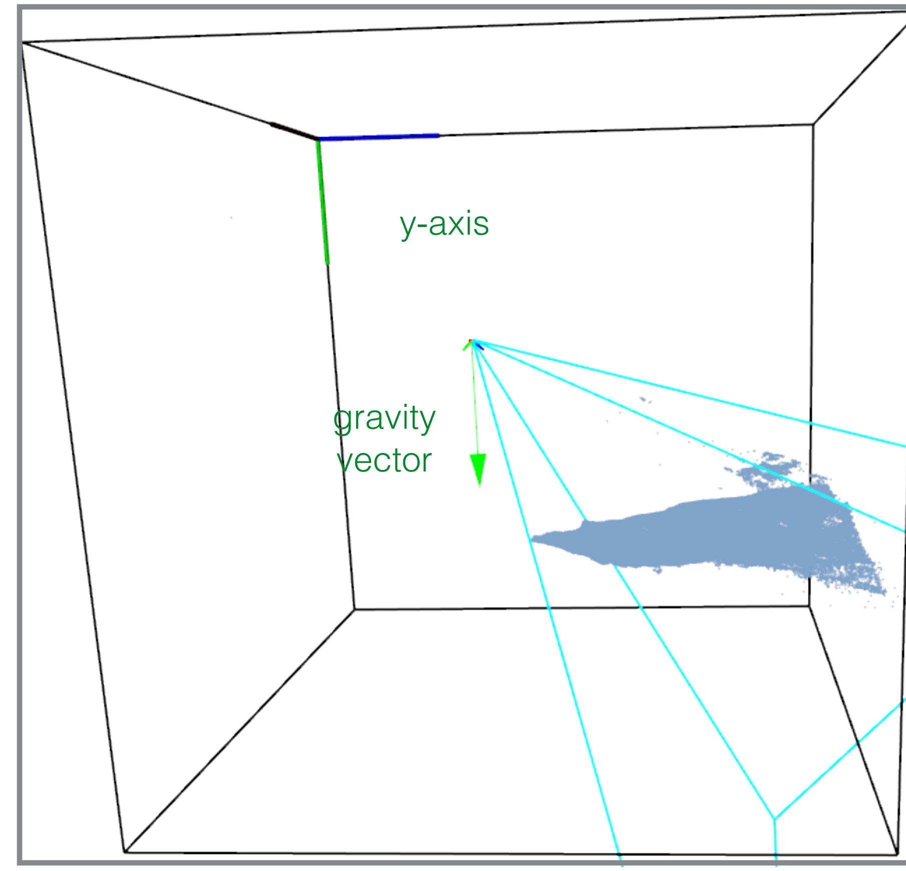


- ICP method
- in real-time (GPU)

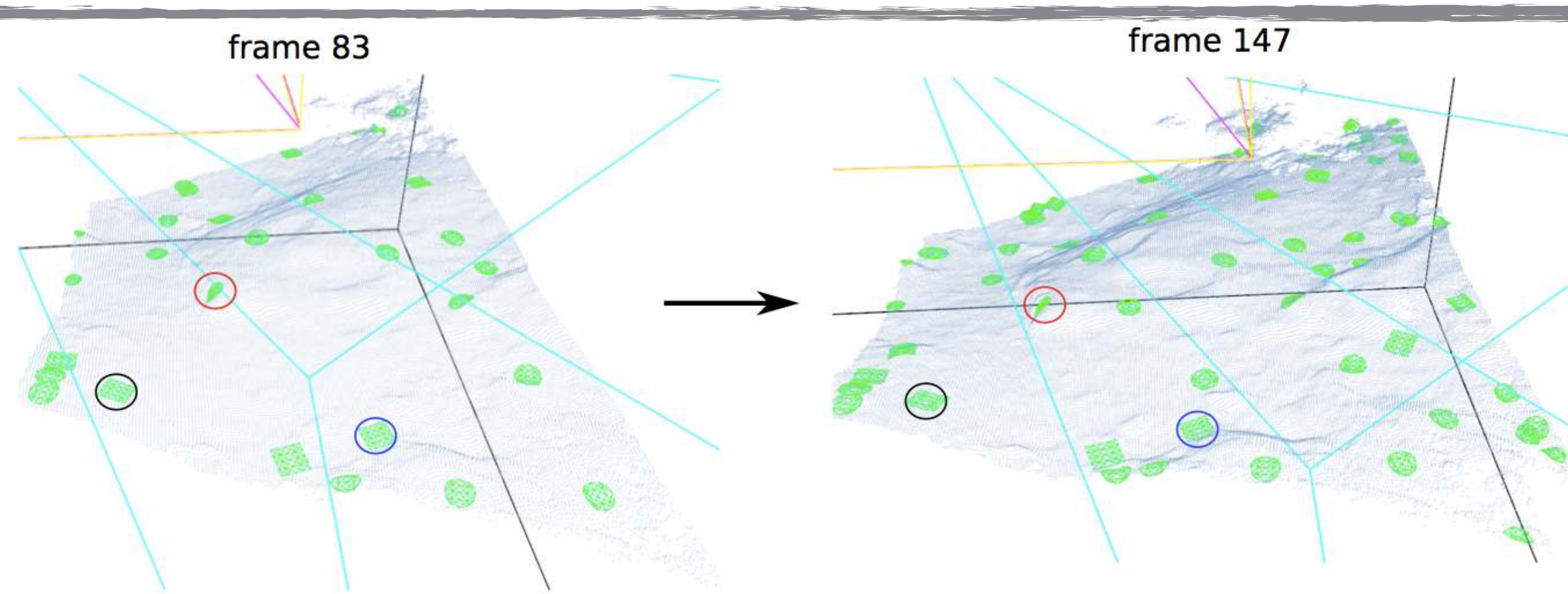
Adaptations to Moving Volume Kinect Fusion

1. Raycast point cloud from a virtual birds-eye view camera
2. Keep the volume y-axis aligned to the gravity vector





Patch mapping and tracking on rocky trails



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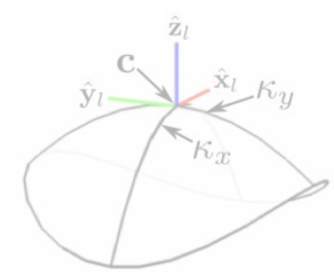

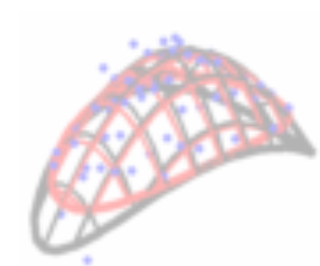

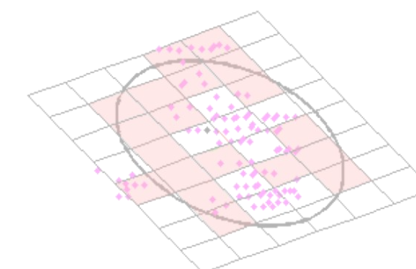

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  - Patch Mapping
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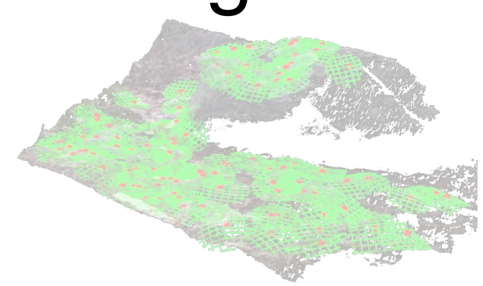
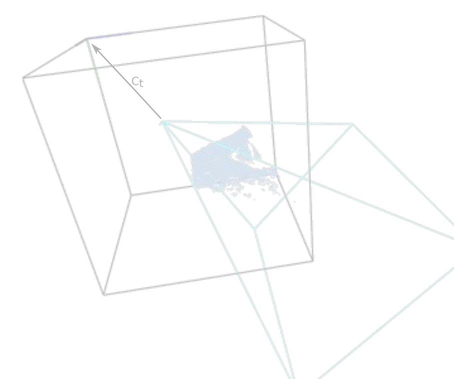
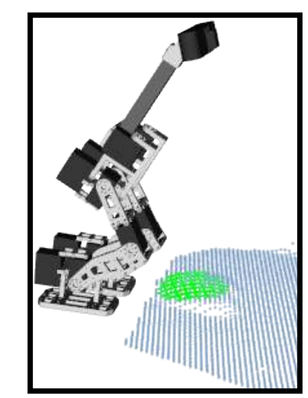
  - Application to Biped Locomotion

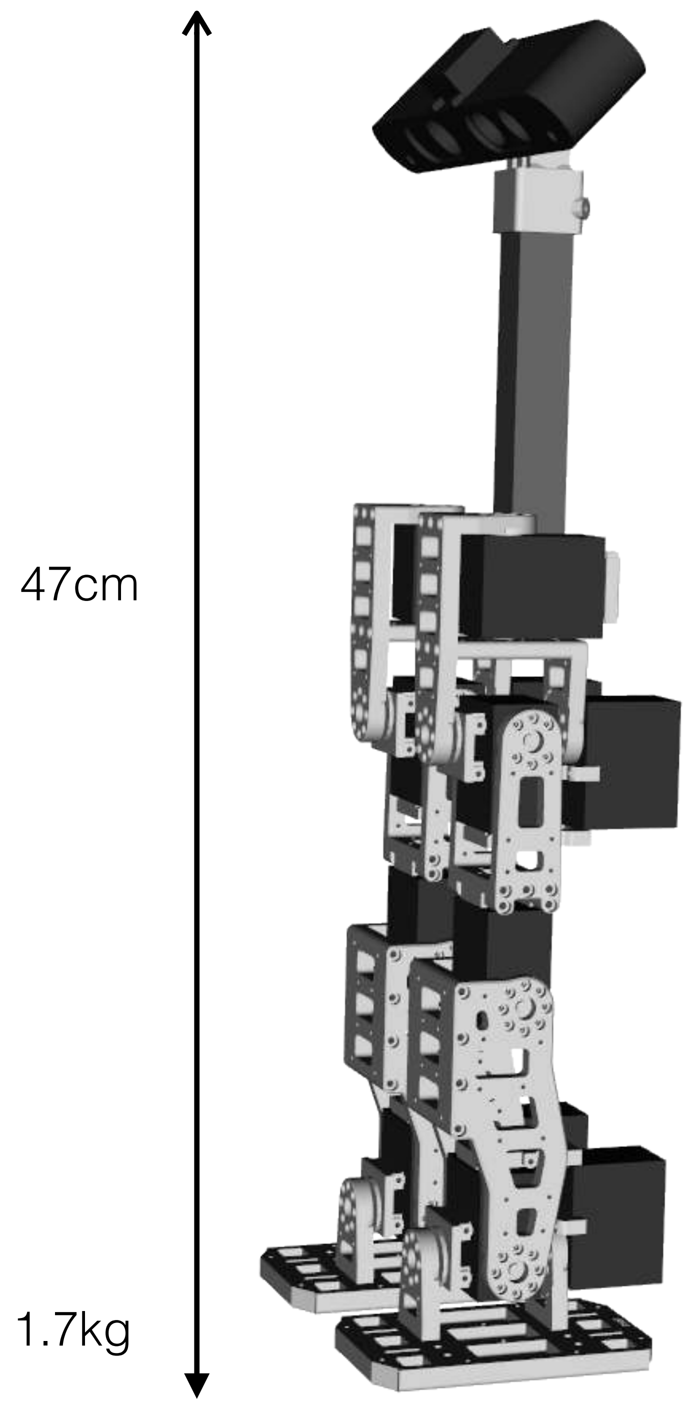




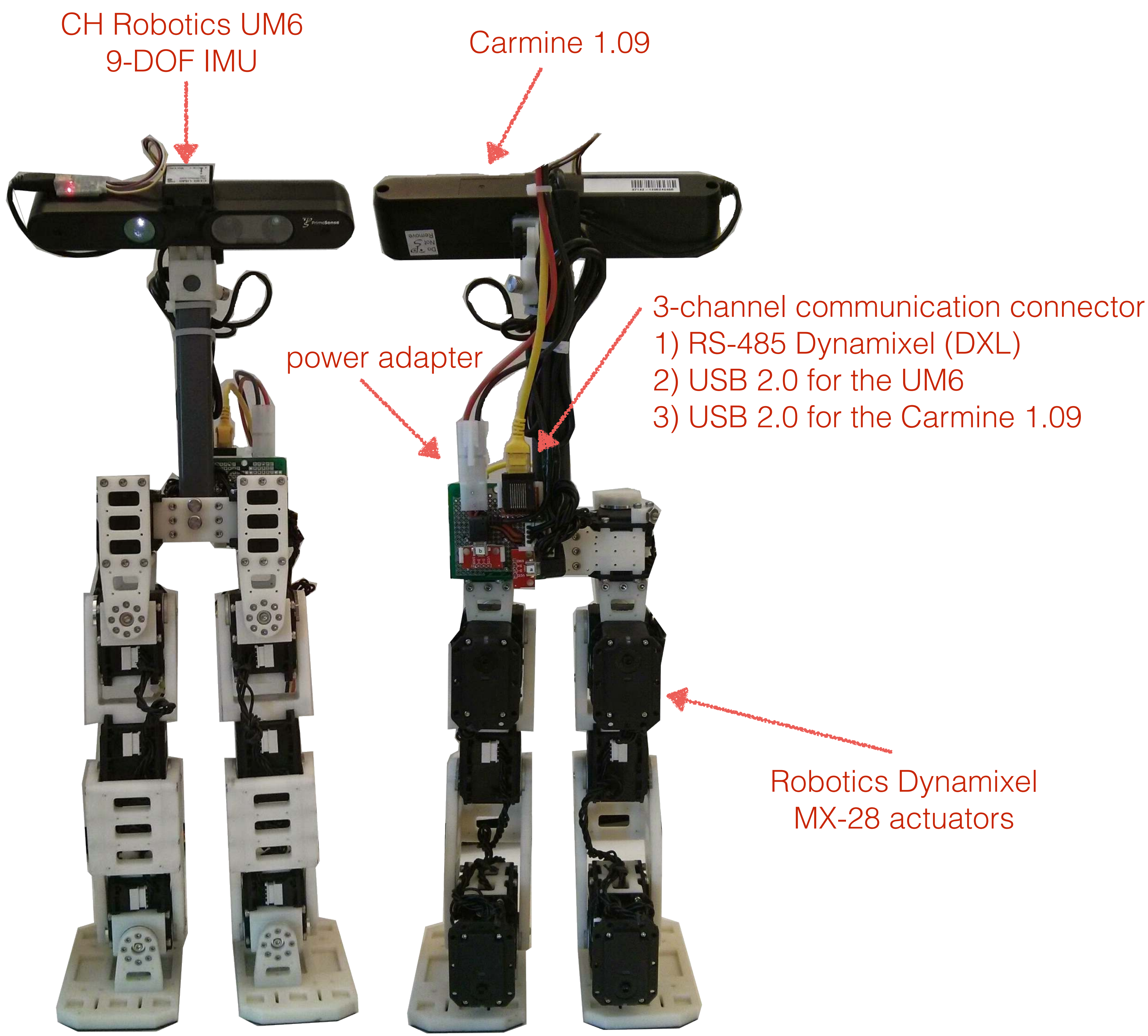


- Conclusions and Future Work

12-DoF Rapid Prototype Biped (RPBP)

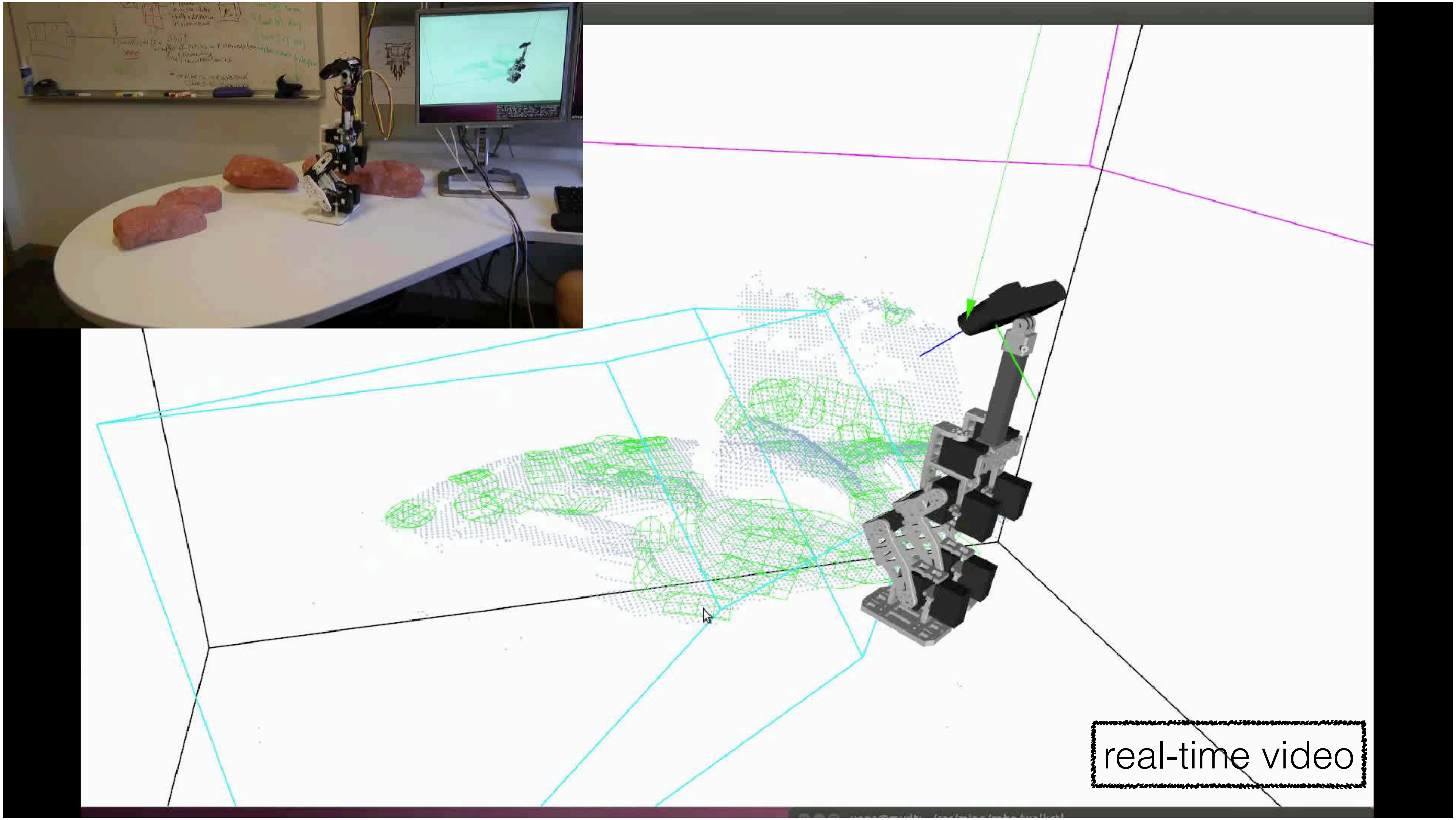


Model



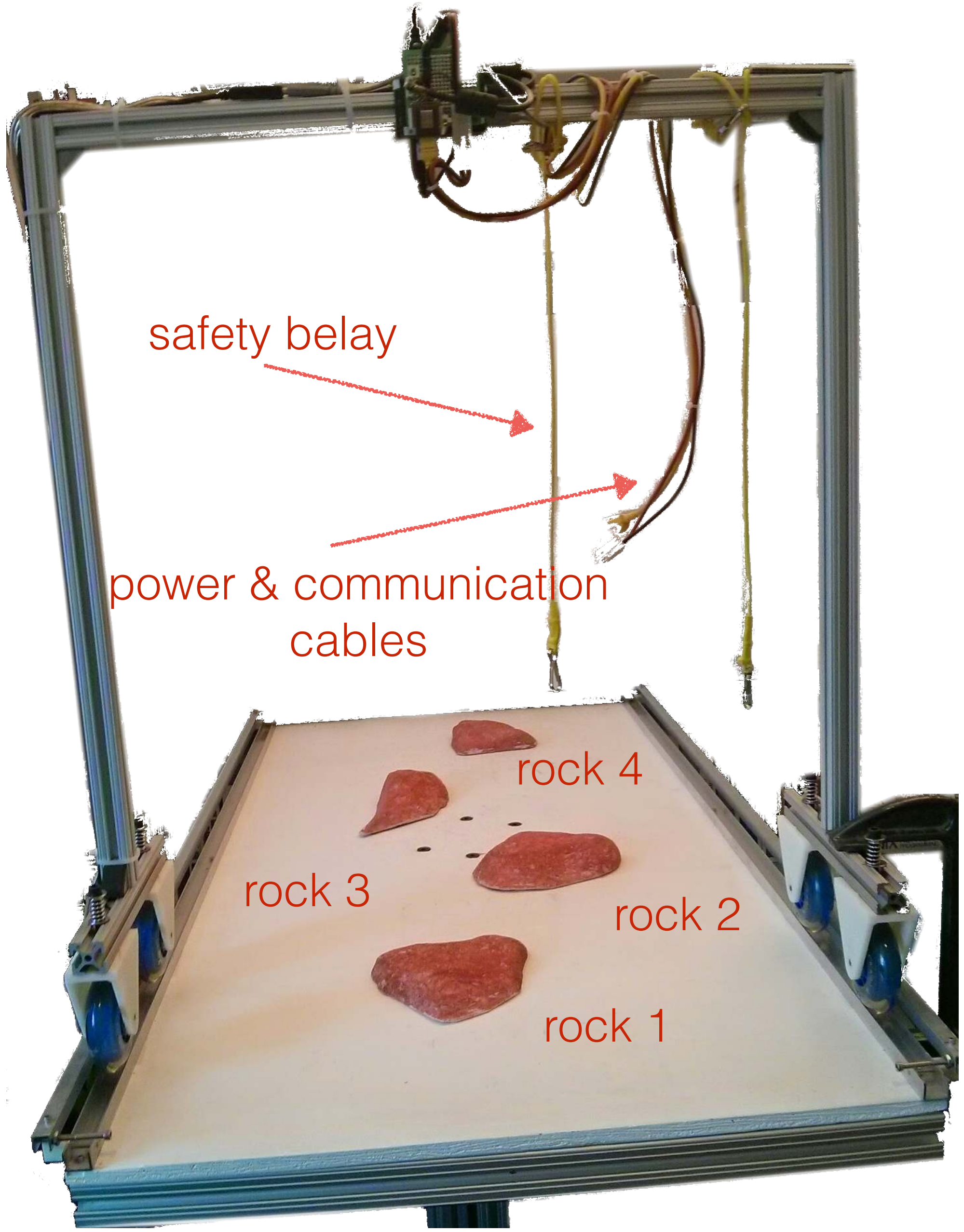
Physical Hardware

RPBP Experiment 1: Rock Patch Mapping and Tracking

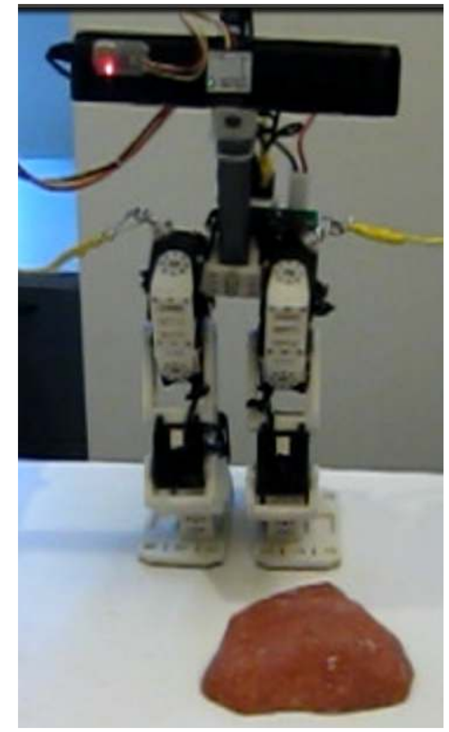


- ✳ We test the patch mapping and tracking on the robot independently of its control.
- ✳ We make sure that shaking and vibration do not hinder the tracking process.
- ✳ We remove patches that are behind the robot.

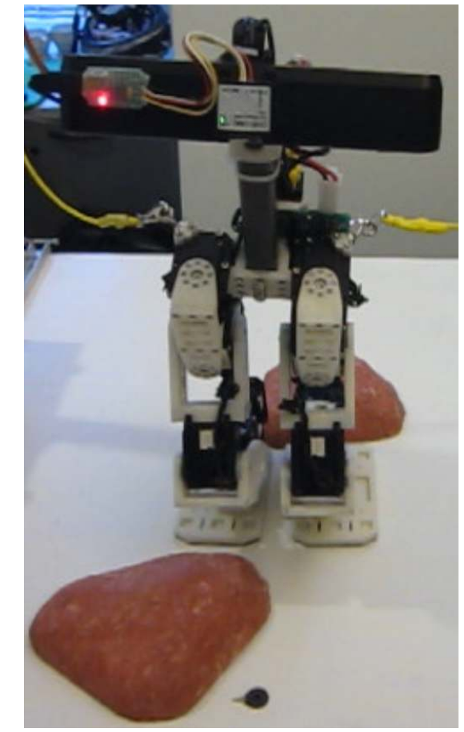
RPBP Experiment 2: Foot Placement on Rock Patches



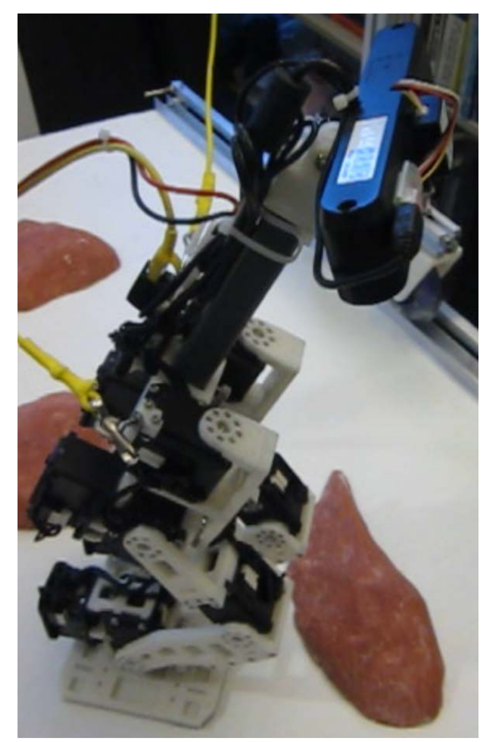
rock 1



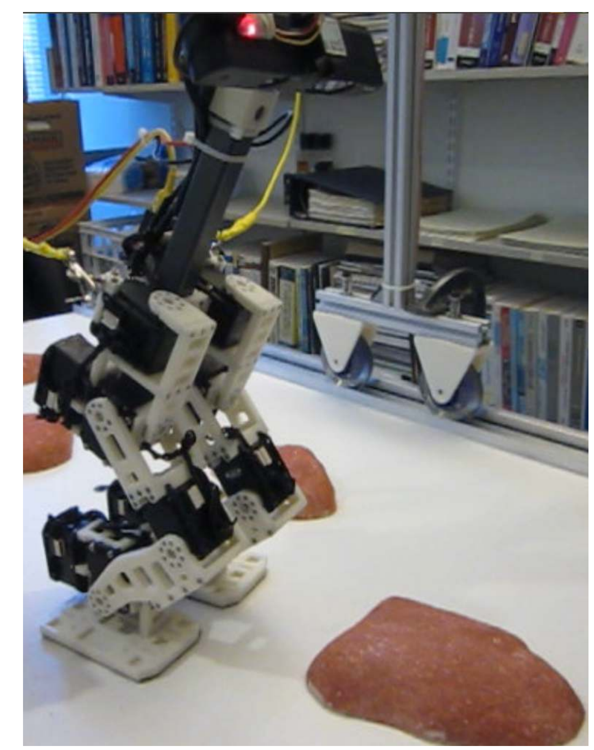
rock 2



rock 3

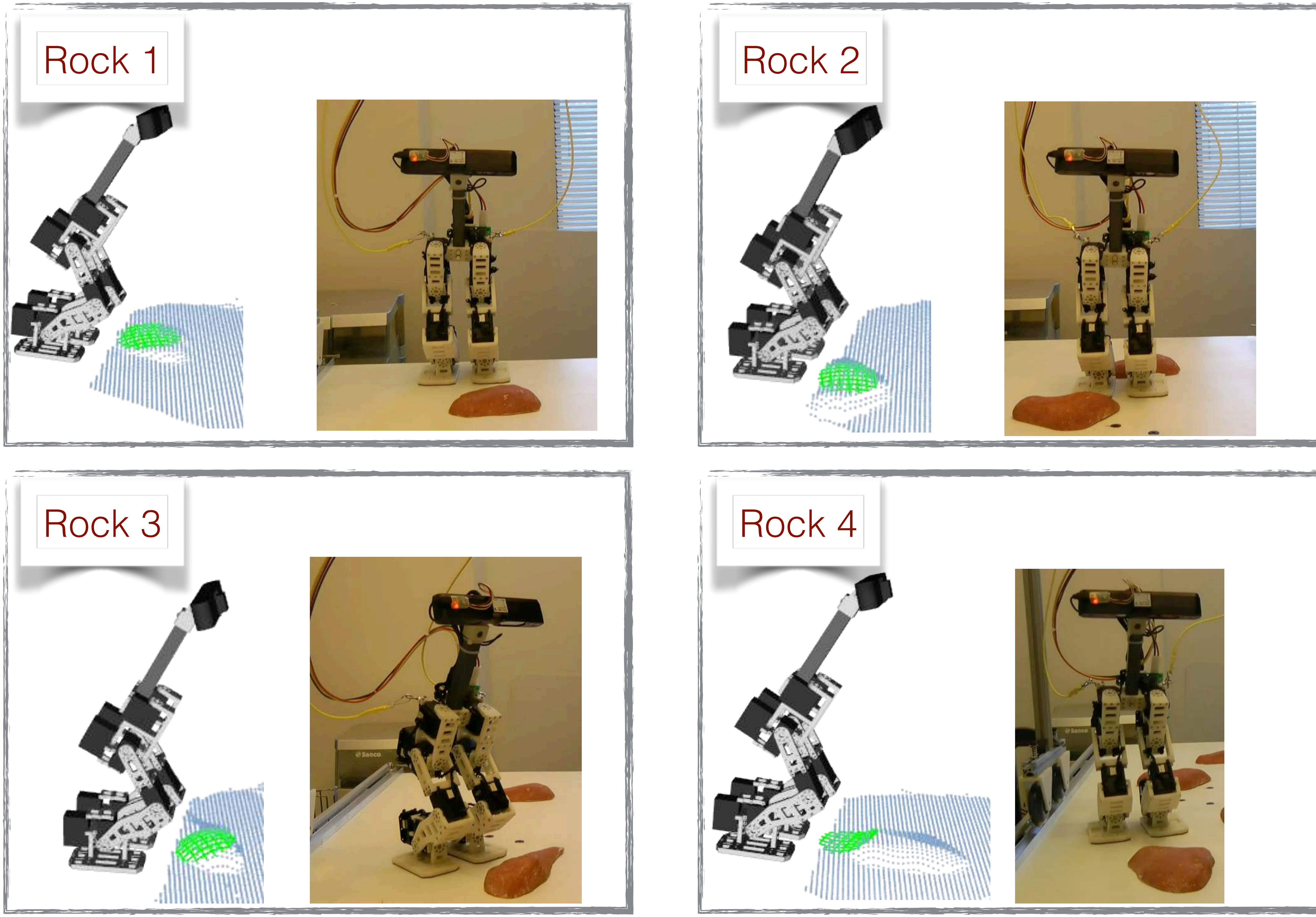


rock 4



Use the real-time patch mapping system integrated in a **foot placement application**

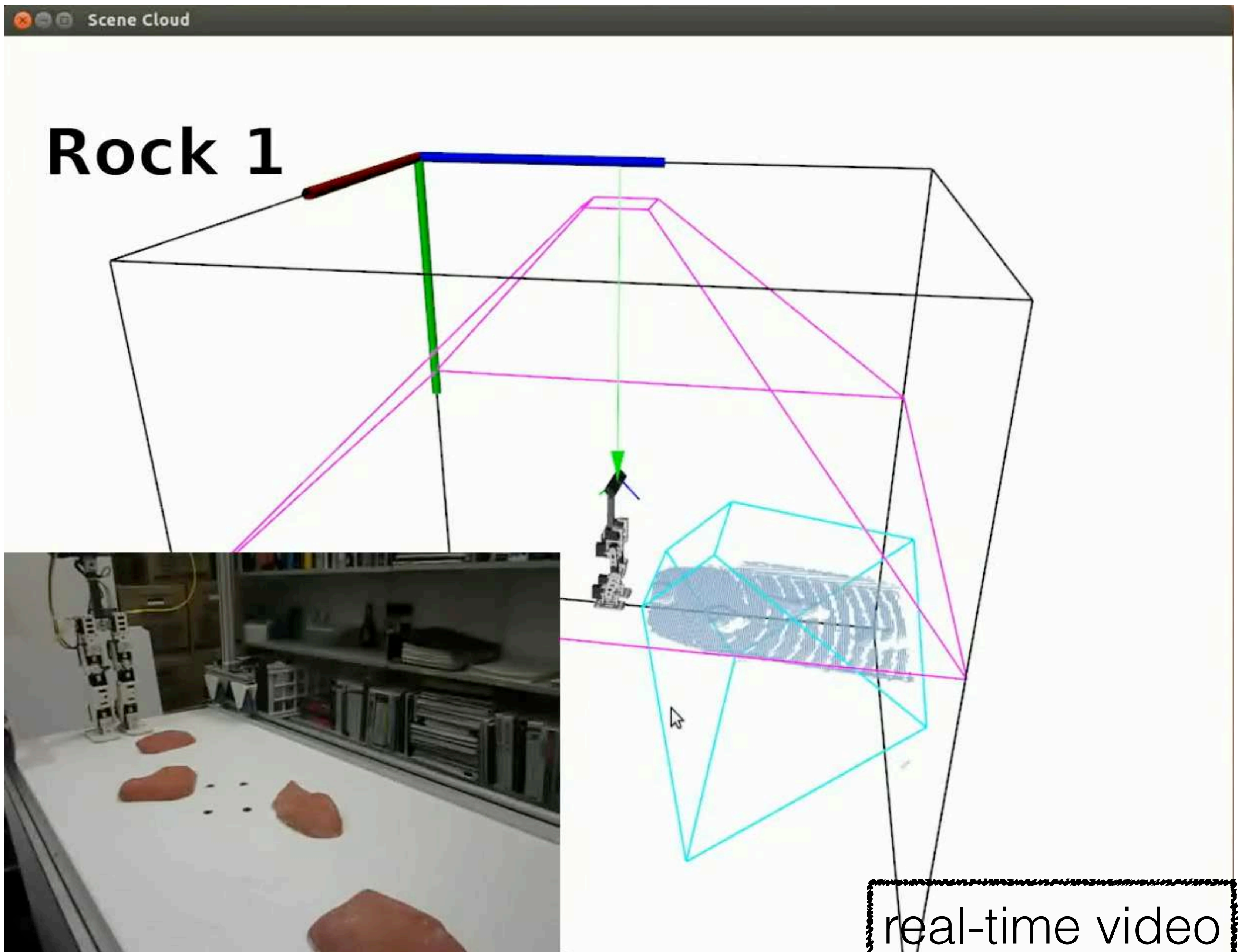
RPBP Experiment 2: Foot Placement Training



Use of predefined motions related to the rock patches

RPBP Experiment 2: Foot Placement Testing

1. Place the robot in front of a rock; robot looks down to the rock.
2. Build and maintain a dynamic patch map:
   seeds are all points within 5cm from the center of each trained patch
3. If a patch is similar to a trained one proceed with the predefined motion.



We ran the experiments 20 times per rock without failure

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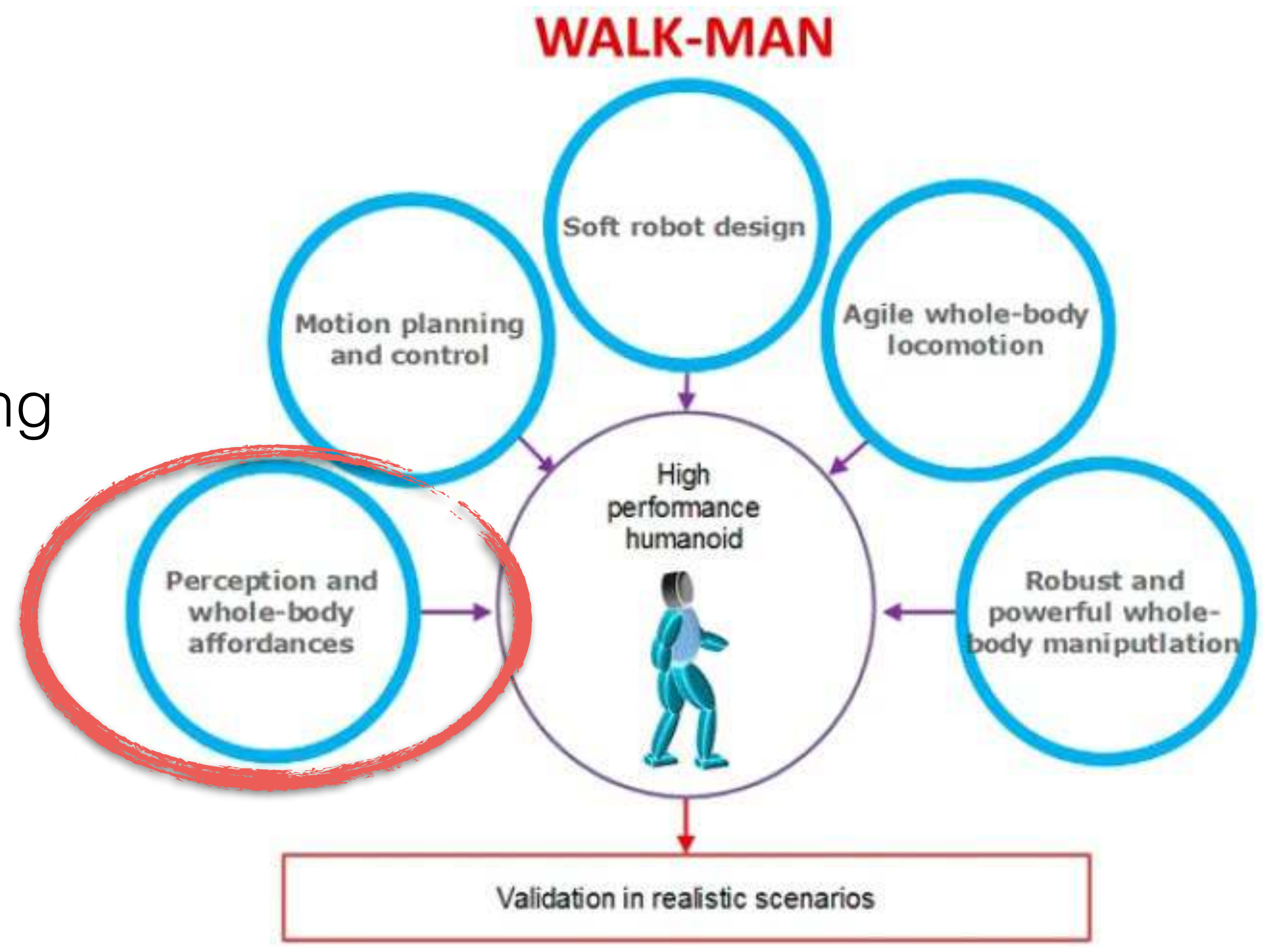
- Conclusions and Future Work

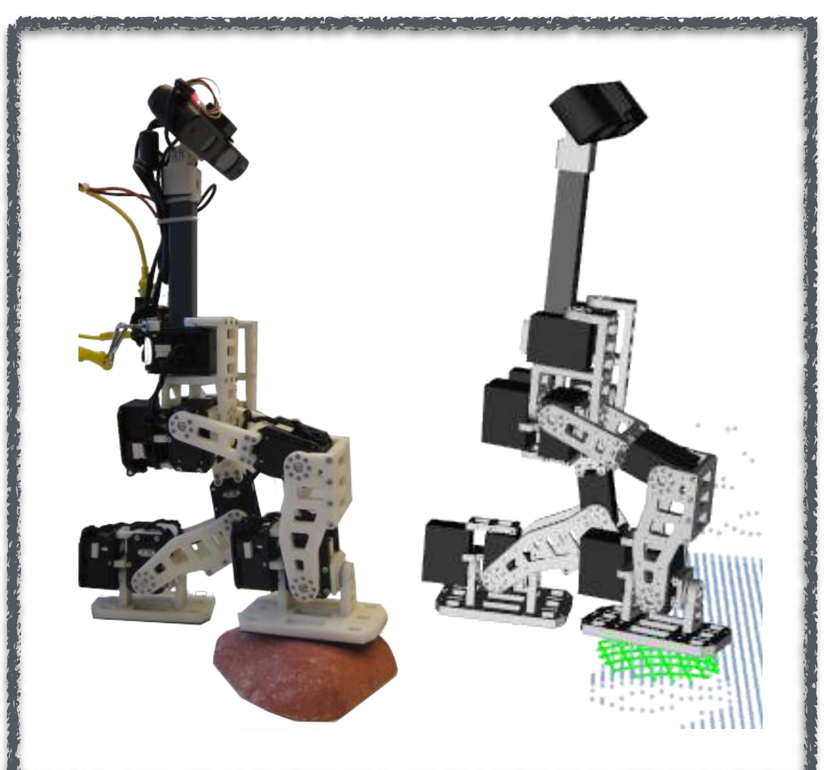
Future Work

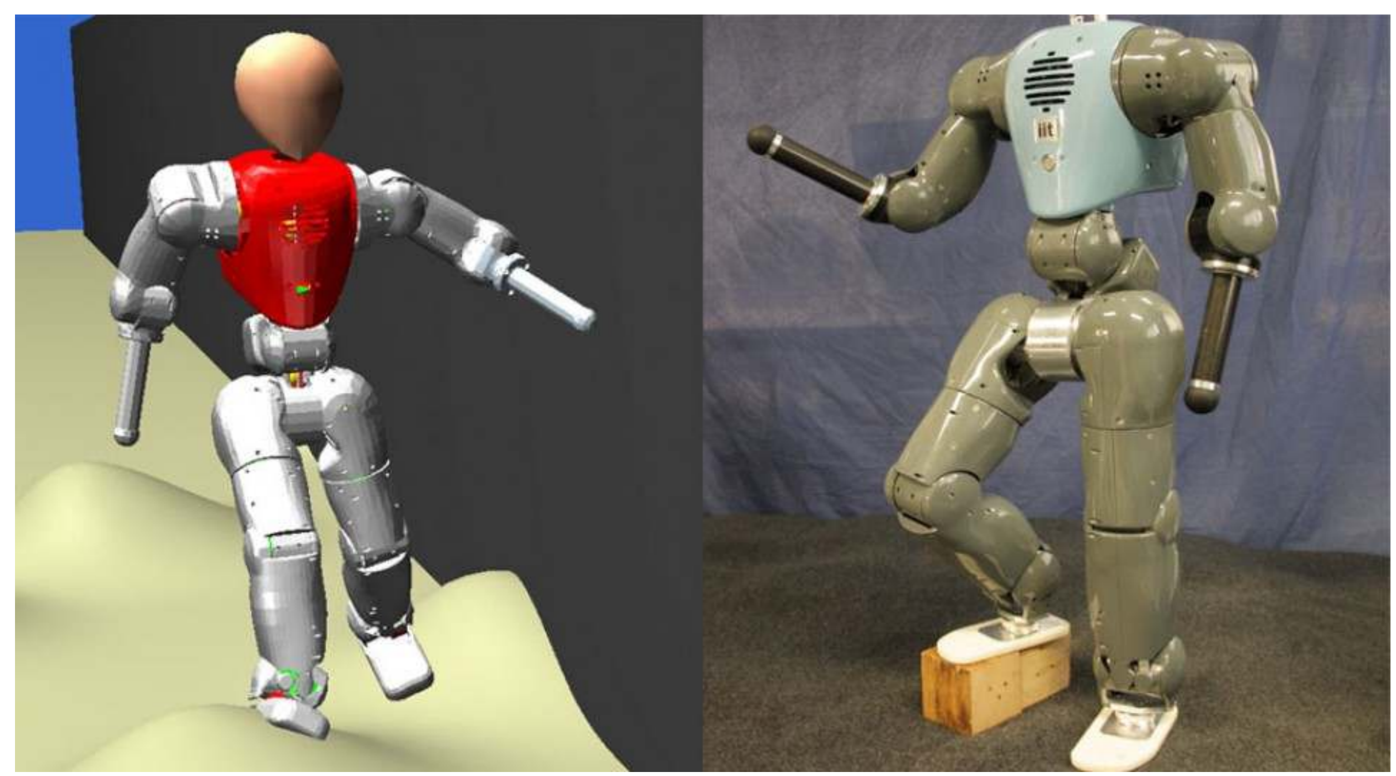
ISTITUTO ITALIANO DI TECNOLOGIA
ADVANCED ROBOTICS

Bigger walking system:

➡ more advanced control and path planning
➡ patch tracking without GPU
➡ use of uncertainty for motor compliance and fusion







Our 3D Perception System for Bipedal Locomotion