



Tactile sensing method development for a mobile multi-legged robot in a cave environment

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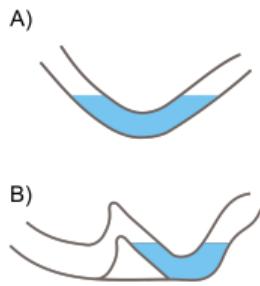
Supervisor: Alexander Maloletov



Motivation: why do we need to explore caves by robots



Salt



Siphon



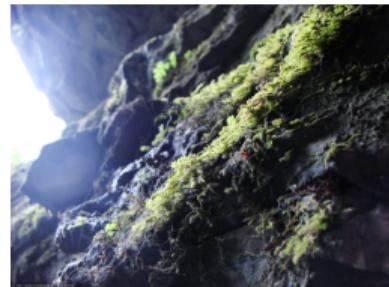
Glacier cave



Clay



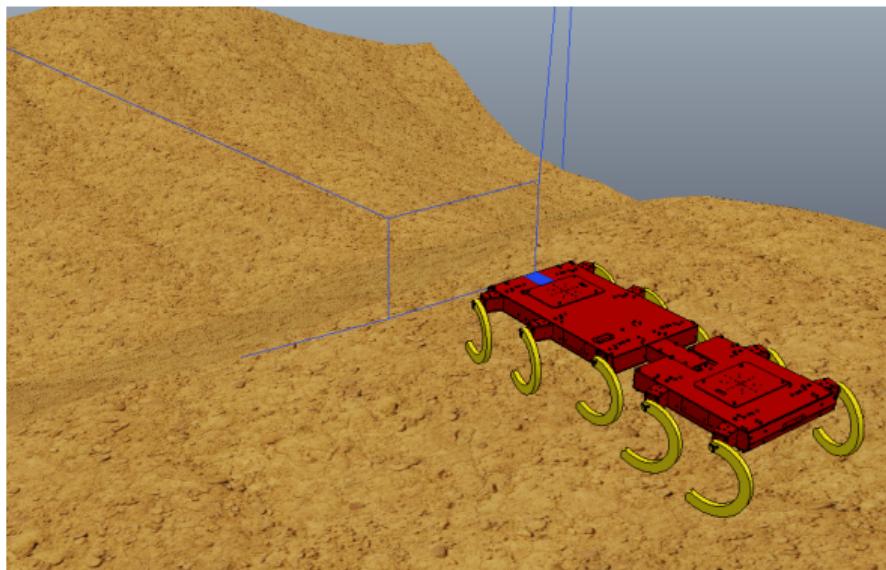
Splash



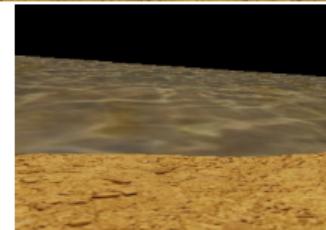
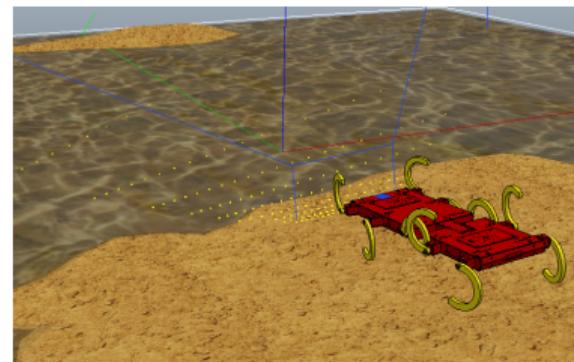
Moss

Motivation: unsolvable problem for cameras and lidars

Question: *how to make a terrain map when you have a splash above?*



Terrain without water



Camera view



Problem statement

Problem 1

How to obtain a useful information about terrain, **when we have a SLAM based on lidars, cameras?**



Problem statement

Problem 1

How to obtain a useful information about terrain, **when we have a SLAM based on lidars, cameras?**

Obtain map and type of terrain



Proposed solutions

Problem 1

Map can be built using tactile sensors on each leg of the robot and create a **dense point cloud** using sampling from generated mesh using **modified Delaunay triangulation**.

Terrain type can be obtained solving **terrain classification** problem using **machine learning**.



Literature review

I searched about:

- Cave environment: obstacles, dimensions.
- Robots for cave exploration. From zeppelins, to quadruped robots.
- Methods for map creation using classical way and haptic. Based on cameras, lidars, tactile sensors and etc.

Summary

I haven't found any paper, who tried to create a map using tactile sensors in a cave.



Robot design

Requirements

Problem – choose robot mover type. This robot should:

- should have *small dimensions* to sneak through holes;
- have enough *mobility* to pass a granular terrain;
- should *pass a small water obstacles*;
- can *climb on a big stones*;



Robot design

Requirements

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- can *climb on a big stones*;

1-DoF multilegged robot was chosen



Robot design

Structural synthesis problem

Question

What the optimal amount of legs should be in such robot?



Robot design

Structural synthesis problem

Question

What the optimal amount of legs should be in such robot?

Answer

Robot should have **10-12 legs** in total!

Robot design

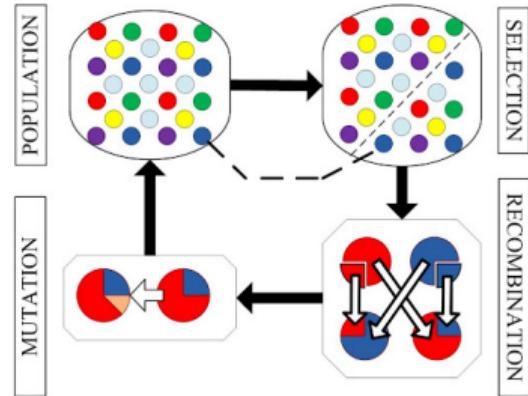
Technological stack



*Generating terrain
approach*



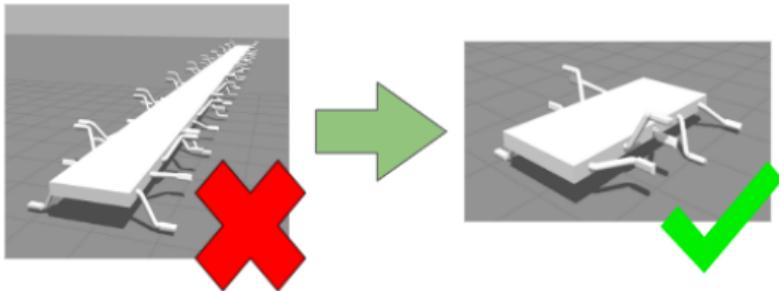
GAZEBO
Robot simulator



*Genetic algorithm
(DEAP Library)*

Robot design

Proposed solution



$$F = \beta \left(\omega_1 \cdot \underbrace{\delta}_{\text{Distance}} + \omega_2 \cdot \underbrace{\frac{1}{(\gamma - 1)\sin(x)}}_{\text{Body length}} \right) + \\ + (1 - \beta) \delta^{\omega_1} \left(\frac{1}{(\gamma - 1)\sin(x)} \right)^{\omega_2}$$

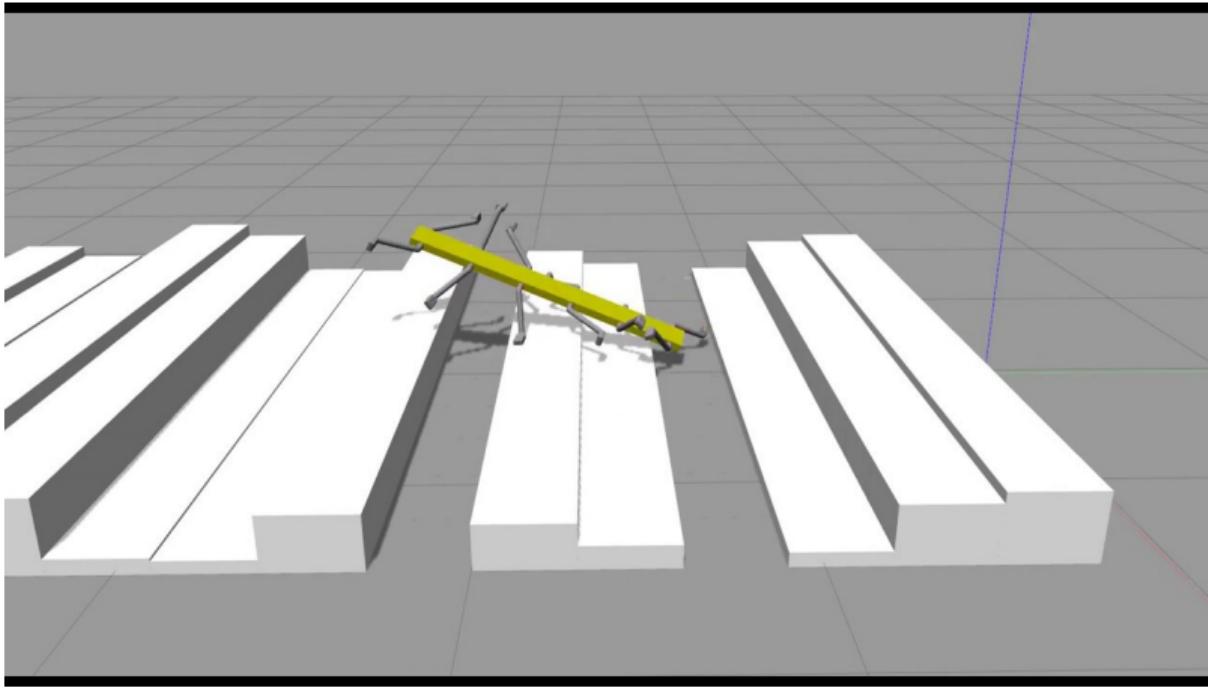
Idea: Minimize number of legs without losing cross-road passability

β is adaptive parameter, $\omega_{1,2}$ are the weight coefficients.



Robot design

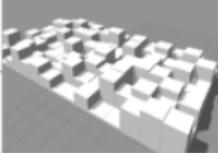
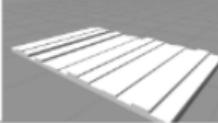
Video: the story of one generated robot





Robot design

Results

	Terrain types	Number of legs <u>per side</u>	Angle btw neighbor legs	Wave offset btw sides	Number of individuals
Phase1		6	73	163	200
Phase2		6	72	165	55
		5	68	177	
		6	77	167	

Summary: robot should have 10-12 legs in total



Robot design

Increasing maneuverability

Question

1. Long robot can stuck in a cave hole, while rotating. How to avoid it?
2. How to climb on big stones?



Robot design

Increasing maneuverability

Question

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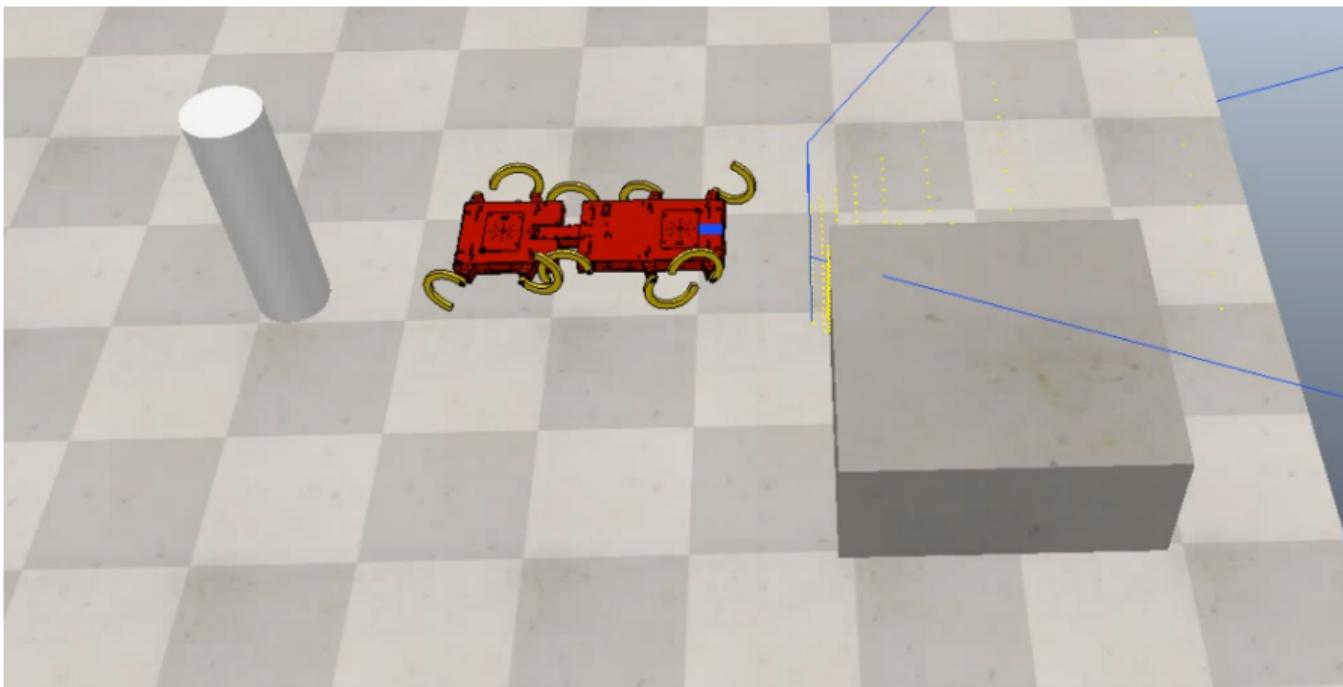
Answer

1. Add an ability to sidestep without changing orientation.
2. Make a segmented body.



Robot design

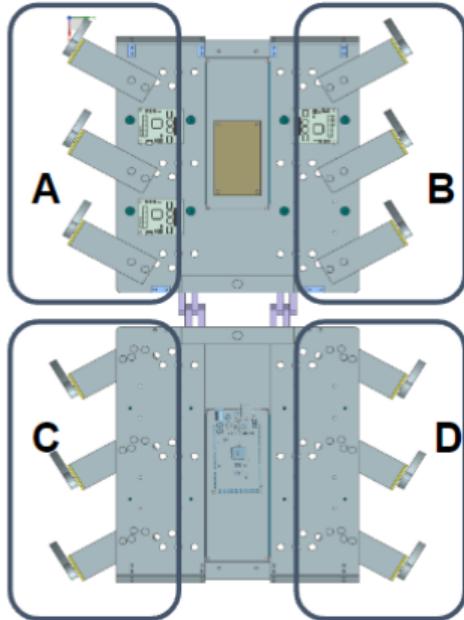
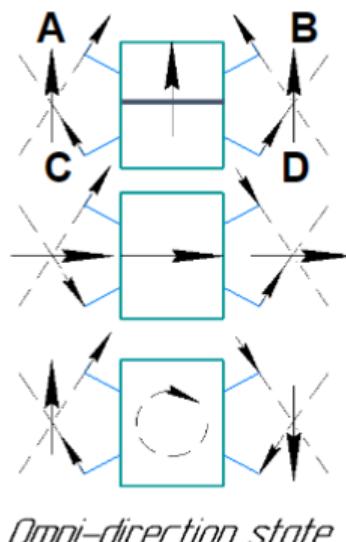
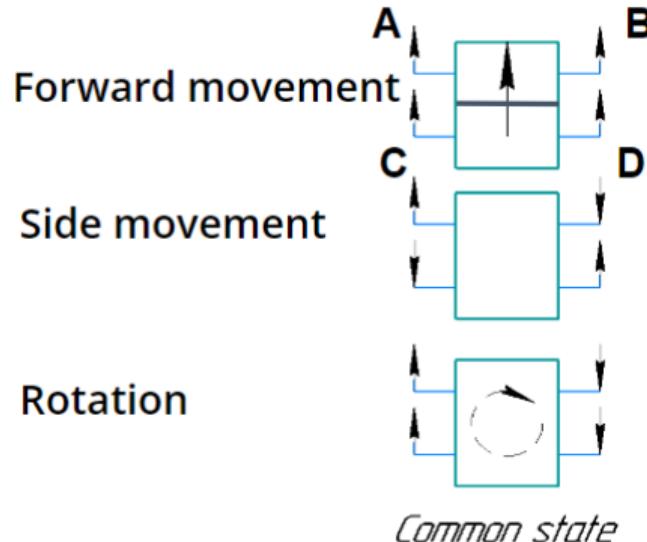
Video





Robot design

Proposed solution

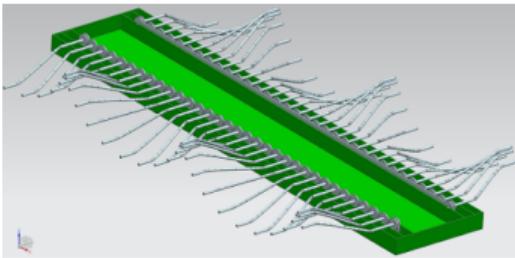


Vector representation of forces in the conventional and omni-direction states

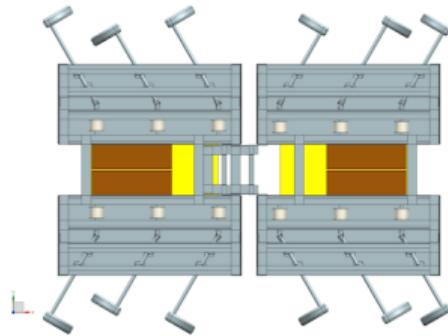


Robot design

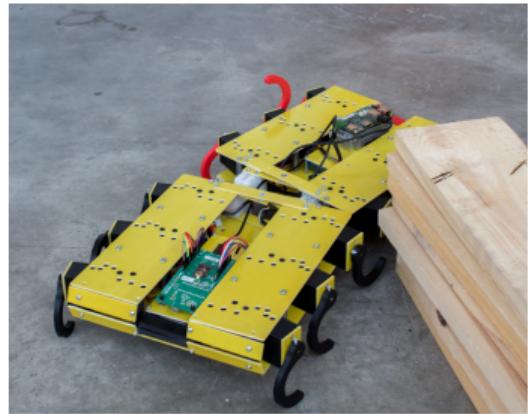
StriRus prototypes (1)



1st gen: 54 legs
1 segment



2nd gen: 12 legs
2 segments, 1 DoF
connection
*Continuous angle b/w
body, leg up to 45 deg*

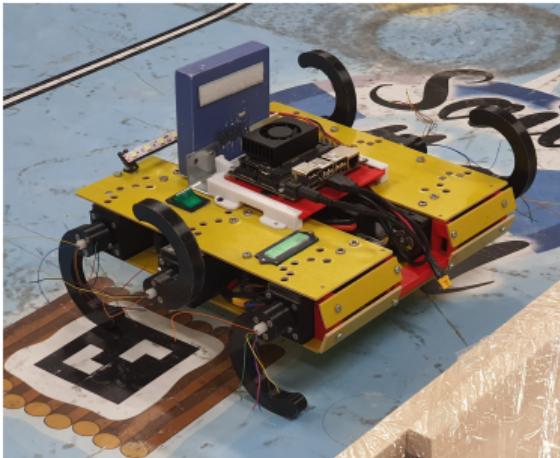


3rd gen: 12 legs
2 segments, 2 DoF
connection
*Discrete angle b/w body,
leg up to 45 deg*

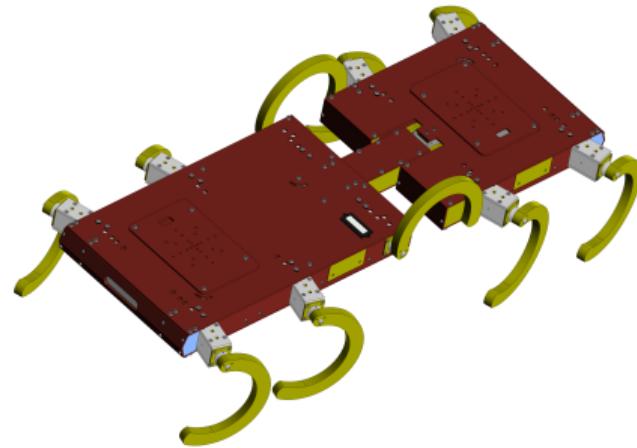


Robot design

StriRus prototypes (2)



3th+ gen: 6 big legs
1 segment



4th gen: 10 biggest legs
2 segments, 1 DoF connection
Discrete angle b/w body, leg up to 15 deg



Force transducer design

Question

How to receive a reaction force from the ground?



Force transducer design

Question

How to receive a reaction force from the ground?

Answer

Installing a force sensor on each leg



Force transducer design

Force sensor types

- **F/T sensors:** too big and expensive for small robots.
- **Optical:** too thick.
- **Magnetic:** too thick.
- **Capacitive:** expensive, but the best in terms of requirements.
- **Piezoresistive sensors based on conductive inks or polymers:** inexpensive and robust, but has problems with hysteresis
- **Stain gages:** challenge for wiring between continuously rotating legs and the robot body.

My choice is **Resistive sensor based on Velostat**

It's cheap and it can be made by hand.

Force transducer design

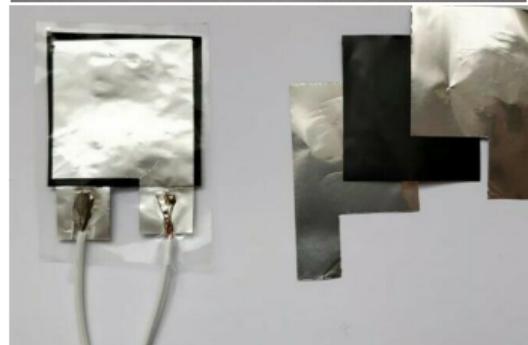
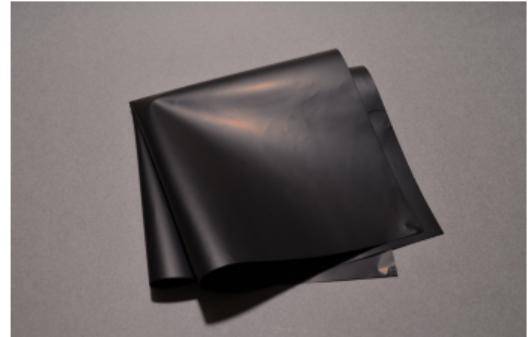
Velostat

Definition

The Velostat is a polymer material filled with carbon black.

Expected effects:

- Quantum tunnelling (Precipitation) – Diod is using such effect;
- Piezoresistive – electrical resistivity of semiconductor is changed by mechanical strain;
- Viscoelasticity – material can damp vibrations.



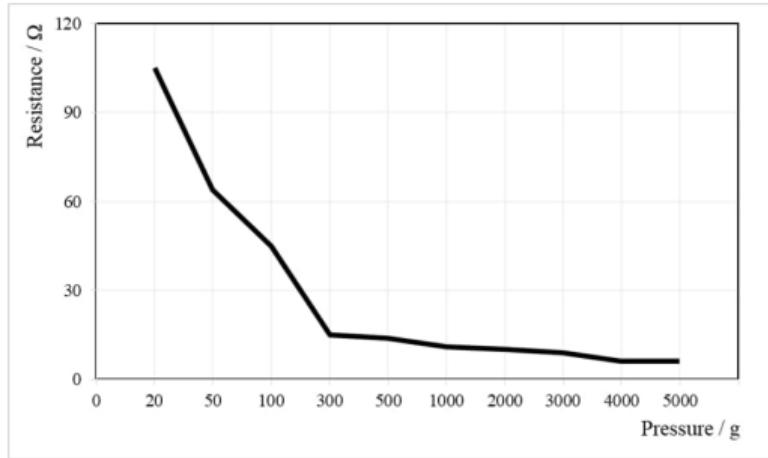
Simplest force transducer



Force transducer design

Velostat: Faced problems

- Hysteresis
- Nonlinearity
- Different values with the same pressure if the square of load is less than the sensor



Scientific Problem Statement

To characterize Velostat material for cases when point load is less than sensor size and propose solutions for avoiding such issues.



Force transducer design

Experimental setup requirements

- Force control.
- Position and force repeatability.
- To have an ability to apply force only on a part of a sensor.
- To change object of the experiment quickly.



Force transducer design

Experimental setup requirements

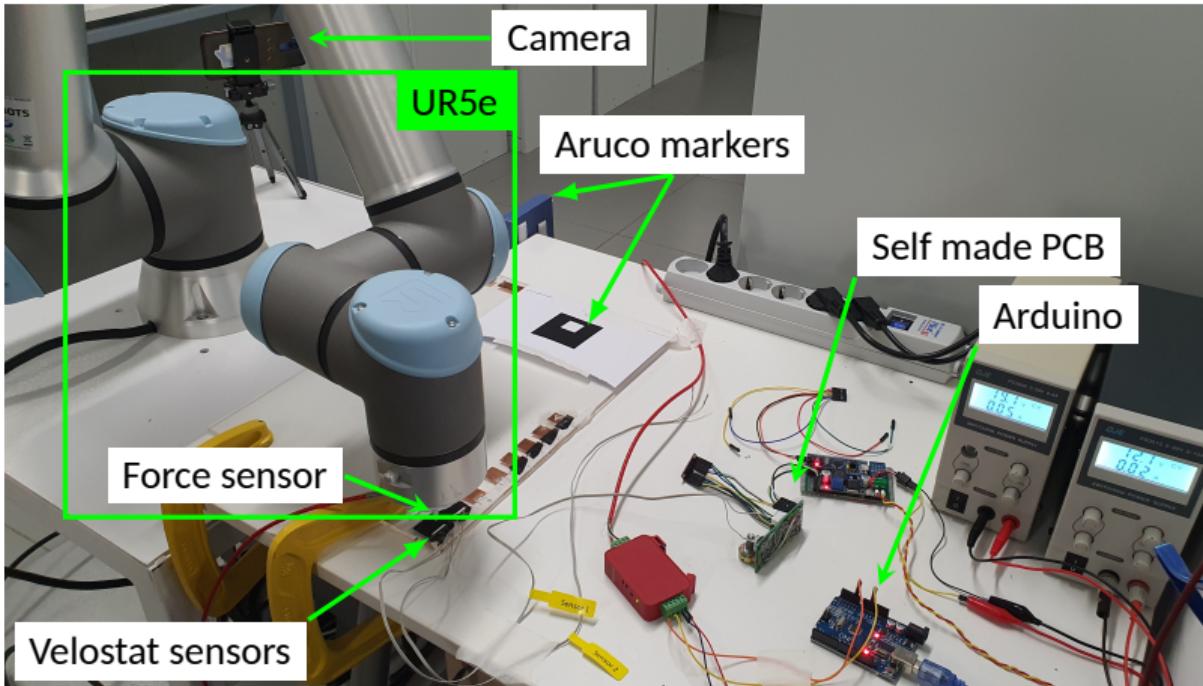
- Force control. **Solved by Impedance Control**
- Position and force repeatability. **Solved by adding manipulator and camera**
- To have an ability to apply force only on a part of a sensor. **Solved by adding several end-effectors**
- To change object of the experiment quickly. **Solved by experimental setup**

All requirements are fulfilled



Force transducer design

Experimental Setup: Hardware overall





Force transducer design

Experimental Setup: Hardware, aruco markers



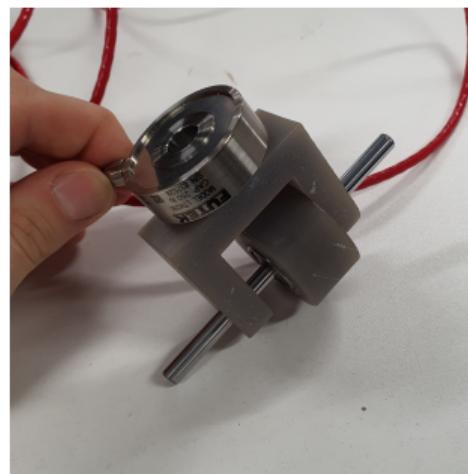


Force transducer design

Experimental Setup: Hardware, end-effector



*Point load: 2mm
diameter*



Rolling load

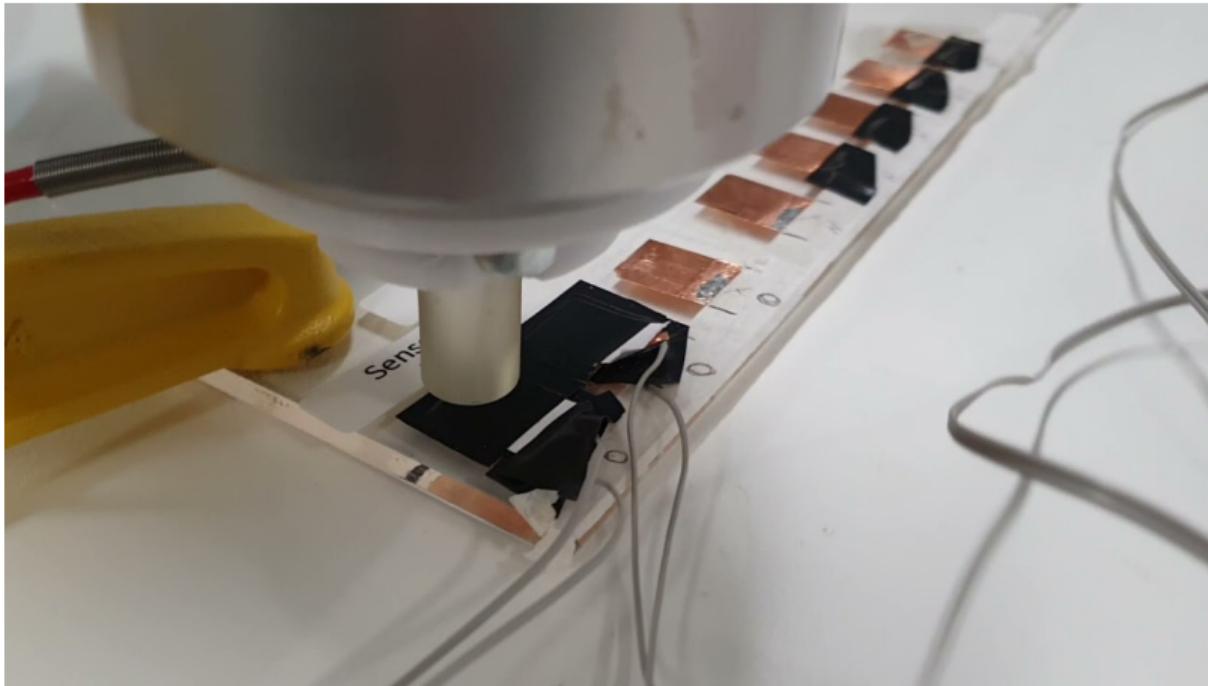


Futek LTH350



Experiment Design

Experimental Setup: Hardware, video

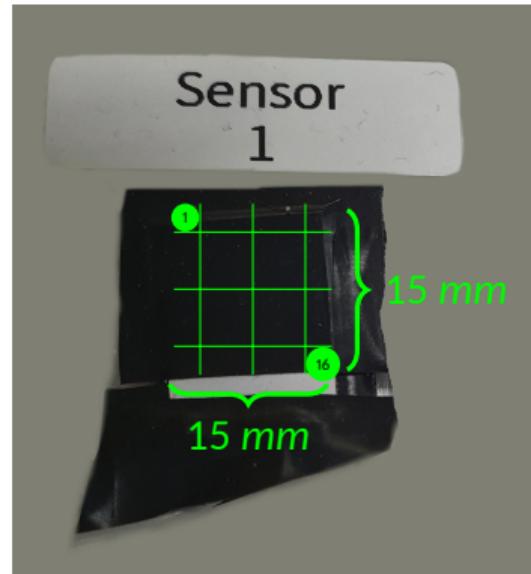


Force transducer design

Experiments

1. **Static experiment.** The goal is to identify the coefficients for the transducer model.
2. **Dynamic experiment.**

- We are representing a transducer as a 4×4 matrix. We touch with the same pressure using five different end-effectors (area starting from 2mm till 15mm).
- We are using 1st and last end-effector. We touch with different forces (5, 10, 20, 30, 40 H).



*Sensor representation
as 4x4 grid*



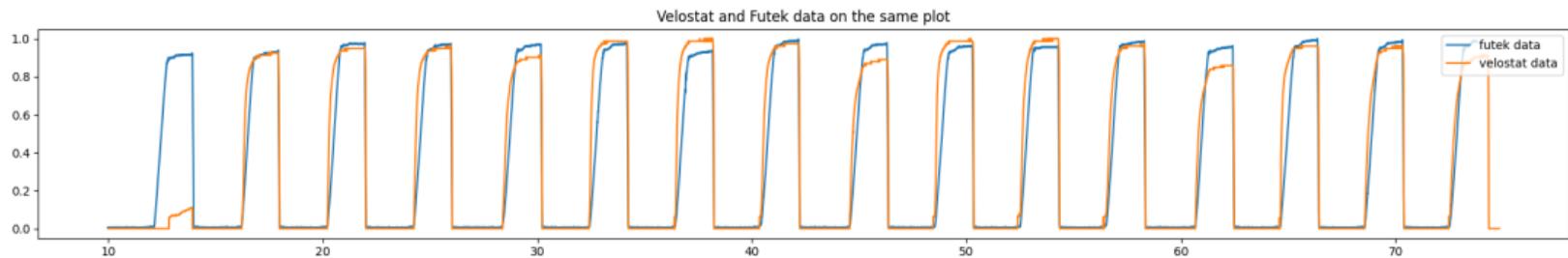
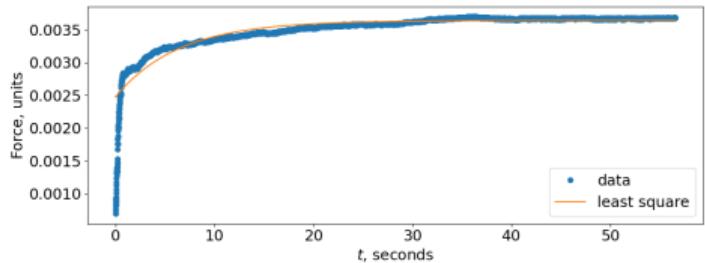
Force transducer design

Result: static experiment

$$V_{out} = V_0 + p[k_p + k_e(1 - e^{\frac{-(t-t_0)}{\tau_{res}}})](1 - e^{-\frac{A}{p}})$$

$$k_p = A_1 e^{-A_2 p}; \tau_{res} = B_0 + B_1 e^{-\frac{p}{B_2}}$$

Where V_0 - initial voltage, p , A_i , B_i , τ_{res} , k_i are constants, t - current time, t_0 - the time when the pressure appeared.

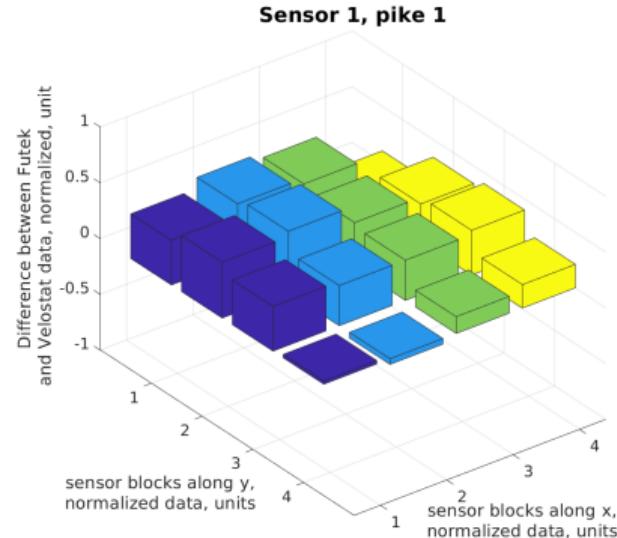


Normalized force data from sensor and transducer

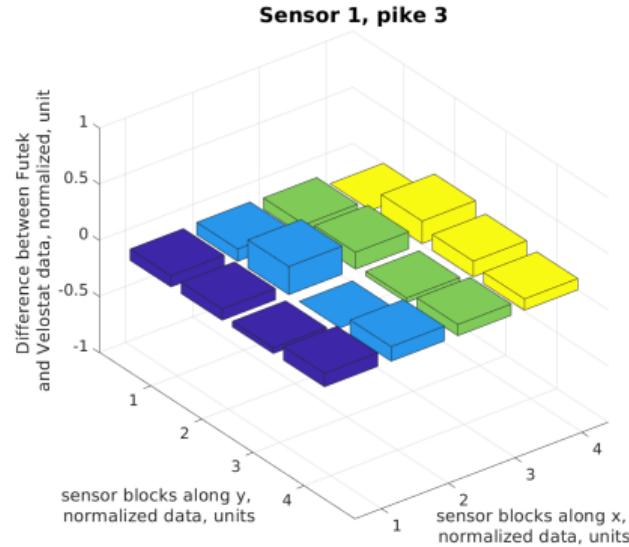


Force transducer design

Result: dynamic experiment



2mm end-effector diam



8mm end-effector diam



Force transducer design

Summary

1. Static experiment: transducers coefficients were identified.
2. Dynamic experiment: a transducer can be represented as one body, when pressure area is higher than 50% of the sensor area.



Terrain classification

Question

How to define the terrain type during the movement on such terrain?



Terrain classification

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How to define the terrain type during the movement on such terrain?

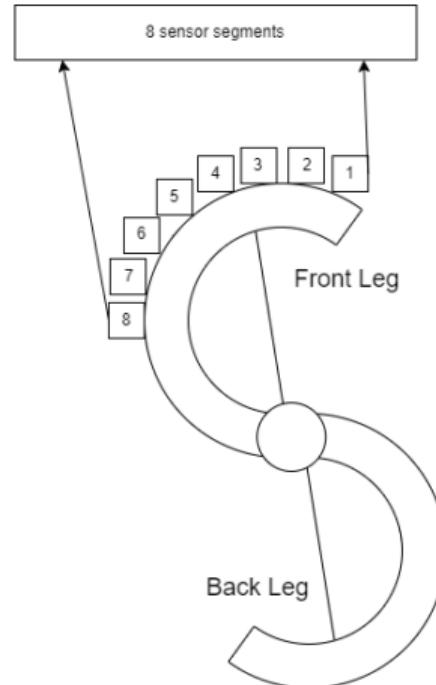
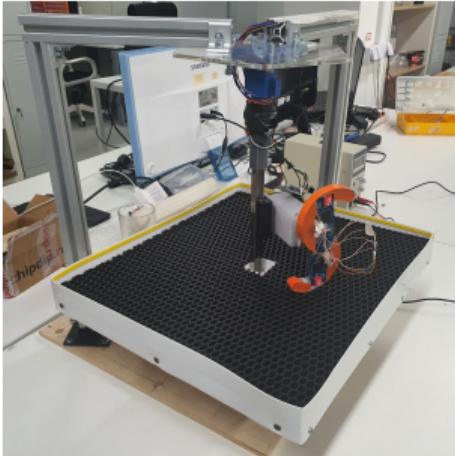
Answer

Solving terrain classification problem using Machine learning

Terrain classification

Experimental Setup

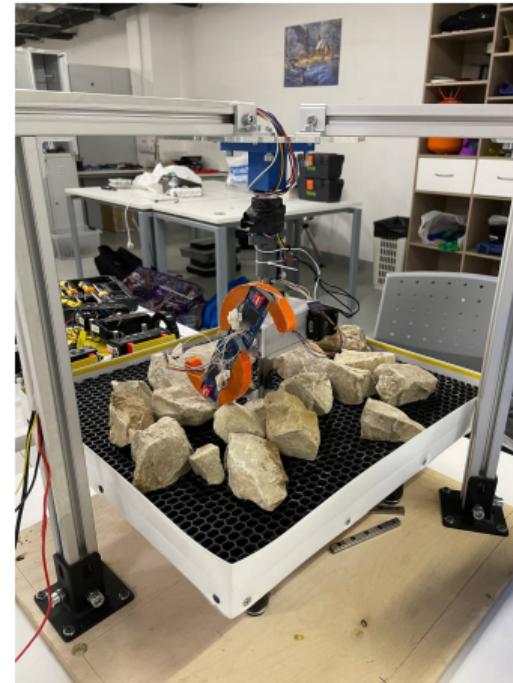
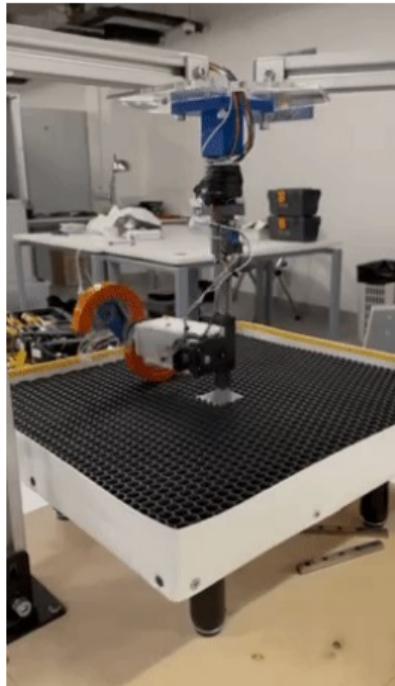
1. Dynamixel MX28 - 47 rev/min
2. Velostat transducer - 25 HZ freq.
3. Experiment duration - 120 sec





Terrain classification

Experimental setup: terrain types, video





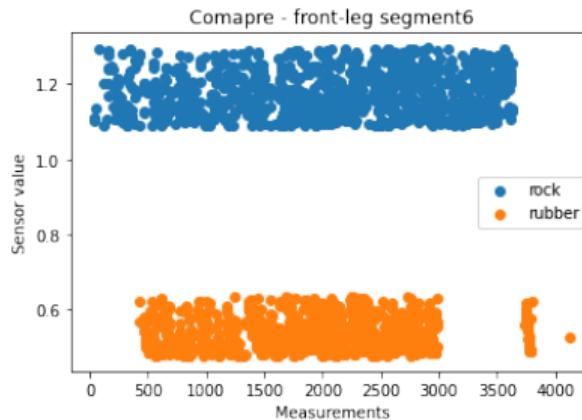
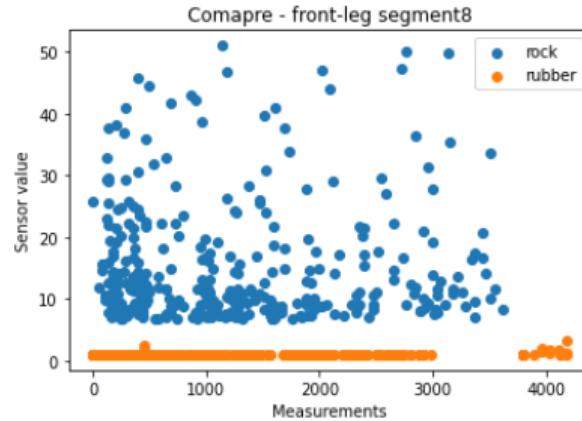
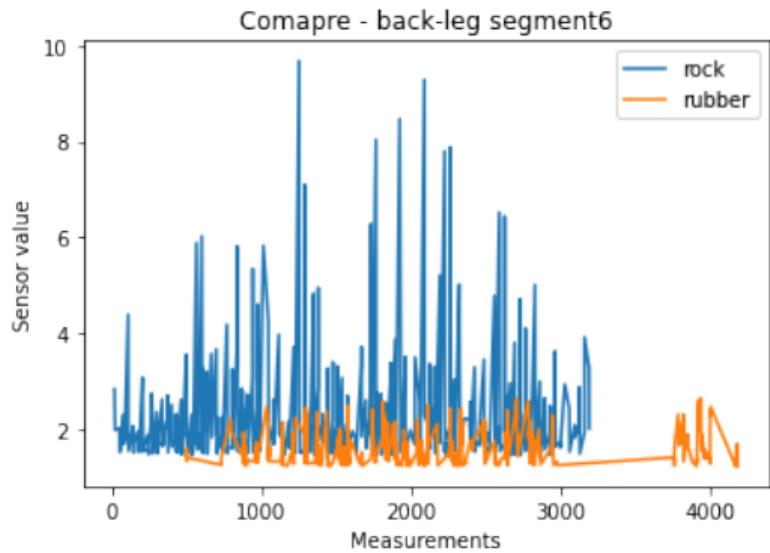
Terrain classification

Velostat transducer properties

- 'cause of high hysteresis and difficulties with calibration, we have to work with relative data.

Terrain classification

Obtained data from one experiment





Terrain classification

Summary

- Can distinct rubber and rock terrains
- Choose terrain classification parameters
 - RPM
 - Motor Torque
 - Acceleration from IMU
 - Force data which are represented as Sensor valuesegment, Peak amplitude, Average amplitude
- Prove that force transducer is working



Map creation based on tactile data

Question

How to create a dense point cloud, using sparse data from legs?



Map creation based on tactile data

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How to create a dense point cloud, using sparse data from legs?

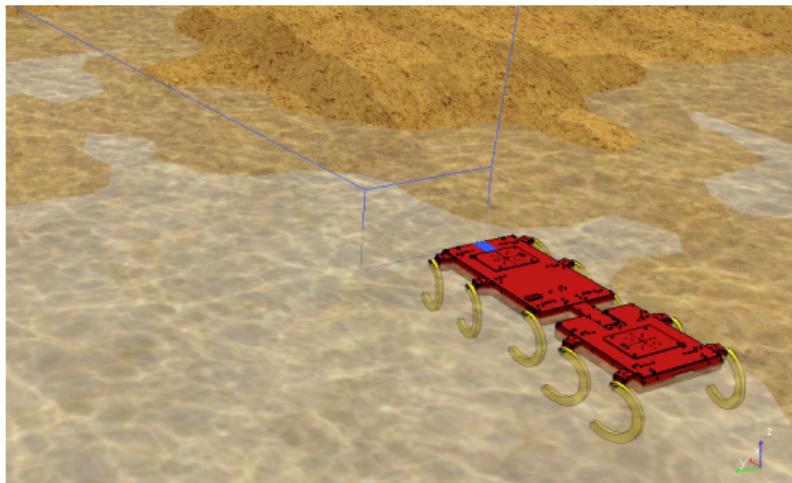
Answer

Take this data, create a mesh using concave hull Delaunay triangulation, sampling it and return to the main algorithm

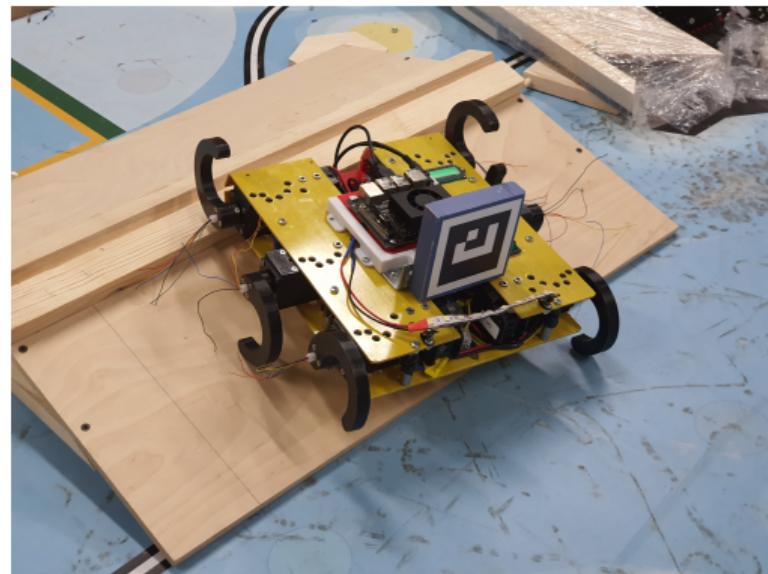


Map creation based on tactile data

Experimental setup



CoppeliaSim simulator, 4th gen StriRus



URL, 3th+ gen StriRus



Map creation based on tactile data

Assumptions

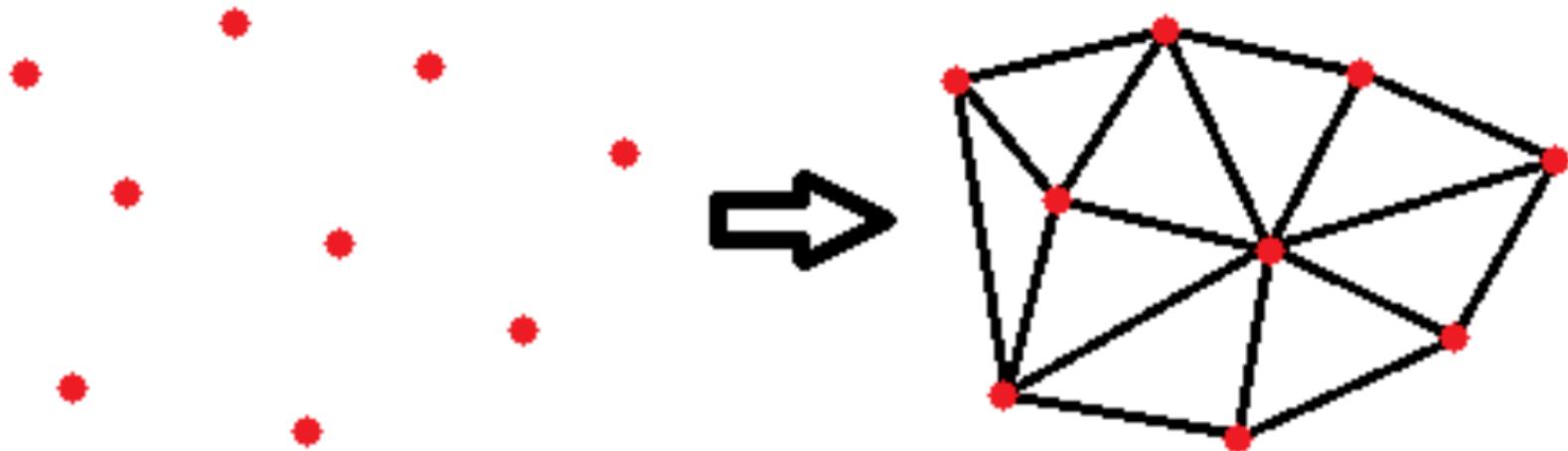
Current solution considering such assumptions:

- Our terrain can be represented $z = f(x, y)$. We can use 2D Delaunay triangulation (projected points on a plane)
- All simulation data are preprocessed by white noise



Map creation based on tactile data

Delaunay triangulation

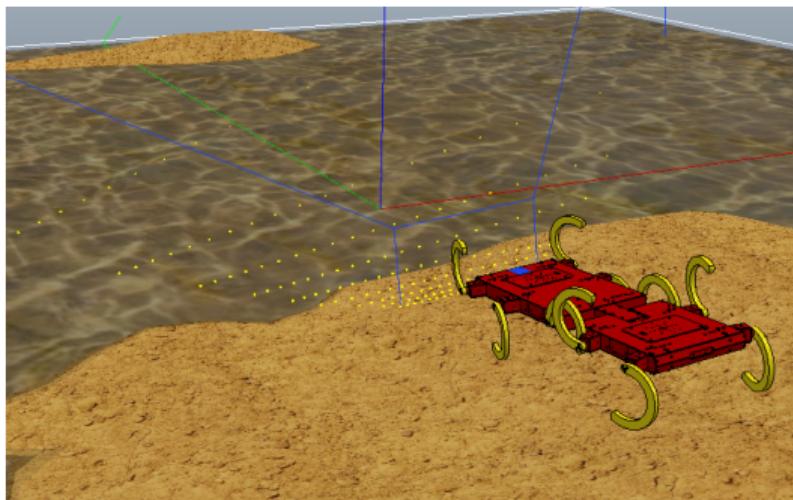


Common 2D Delaunay triangulation (Convex Hull)

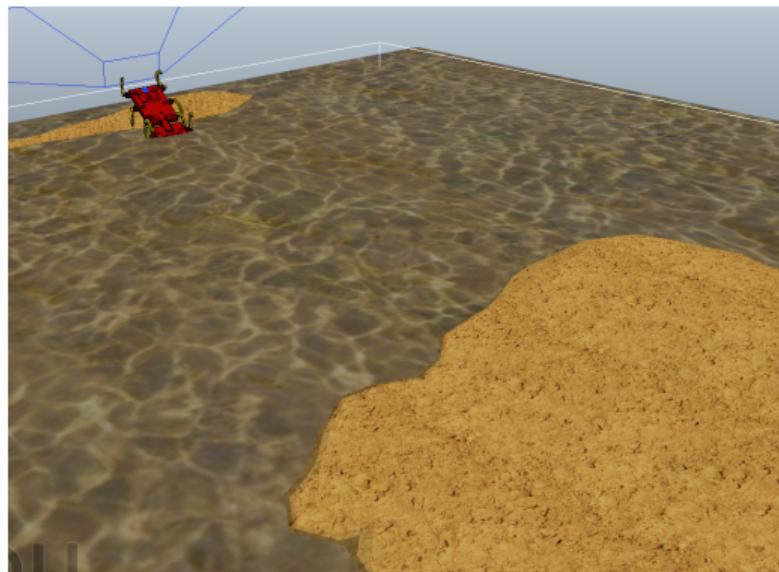


Map creation based on tactile data

Result: simulator



Start point

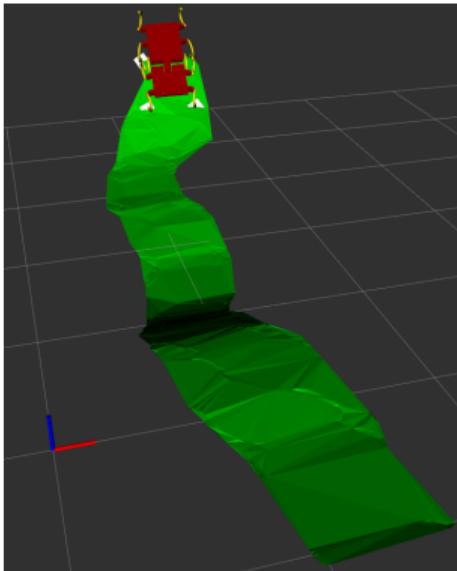


End point

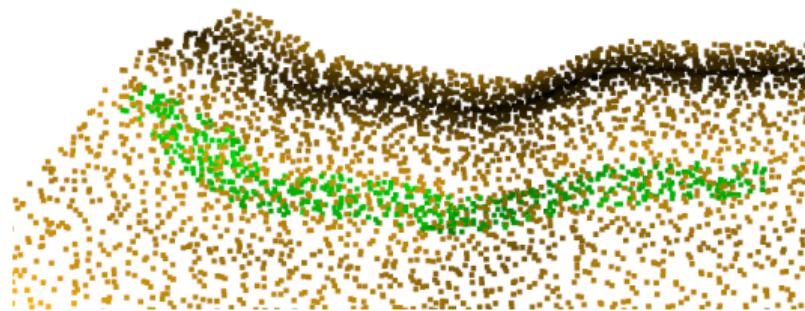


Map creation based on tactile data

Result: Mesh



*Mesh created using concave hull 2D
Delaunay triangulation*

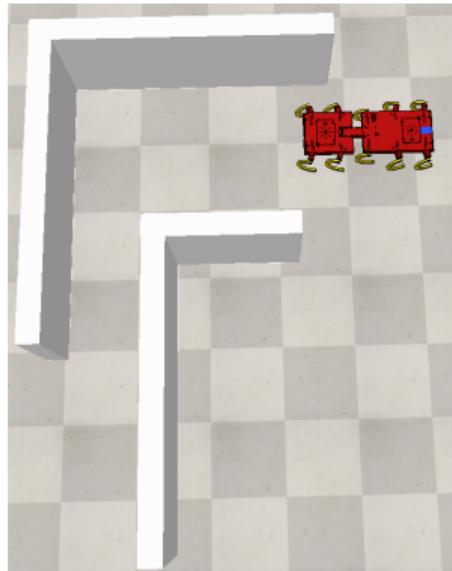


Sampled point cloud

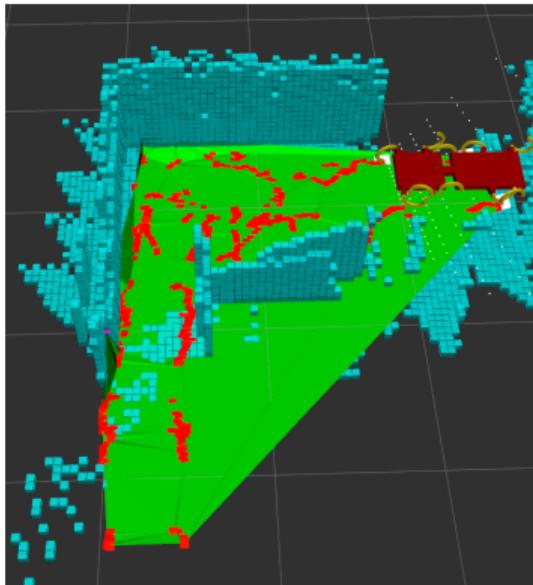


Map creation based on tactile data

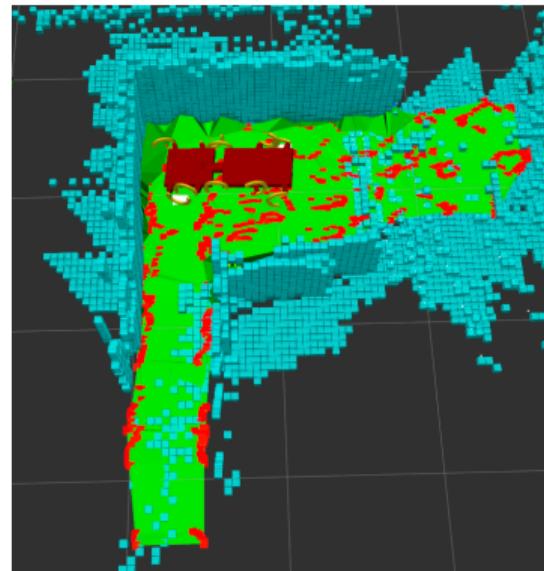
Why do we need concave hull



Case study



Convex Hull

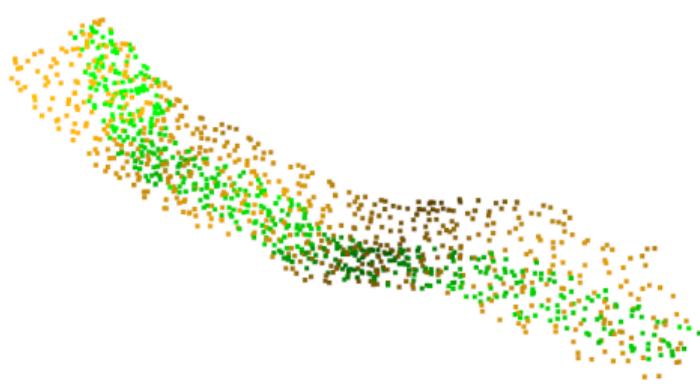


Concave Hull

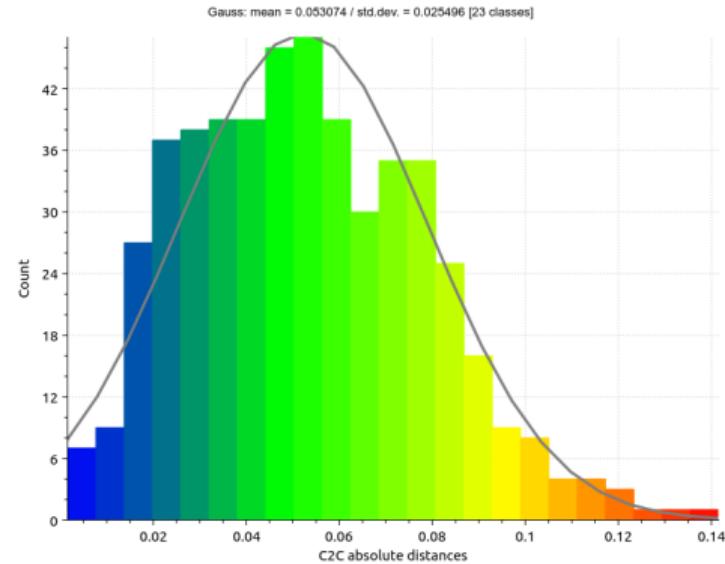


Map creation based on tactile data

Metric: point cloud comparison with ground truth



Overlaid point clouds

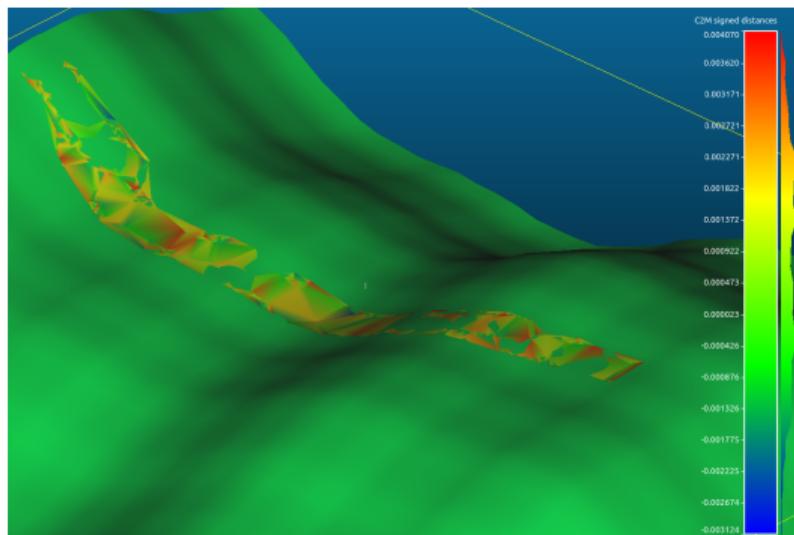


Error histogram (distance from point to closest ground truth point)

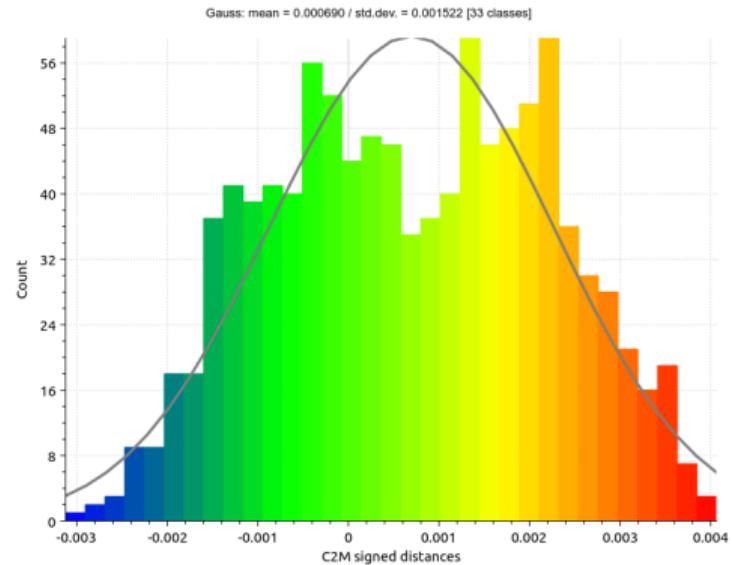


Map creation based on tactile data

Metric: mesh comparison with ground truth



Overlaid meshes

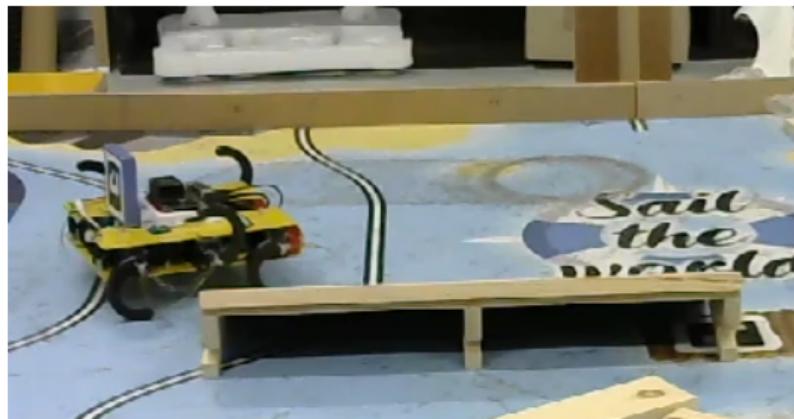


Error histogram (distance from point to closest ground truth point)



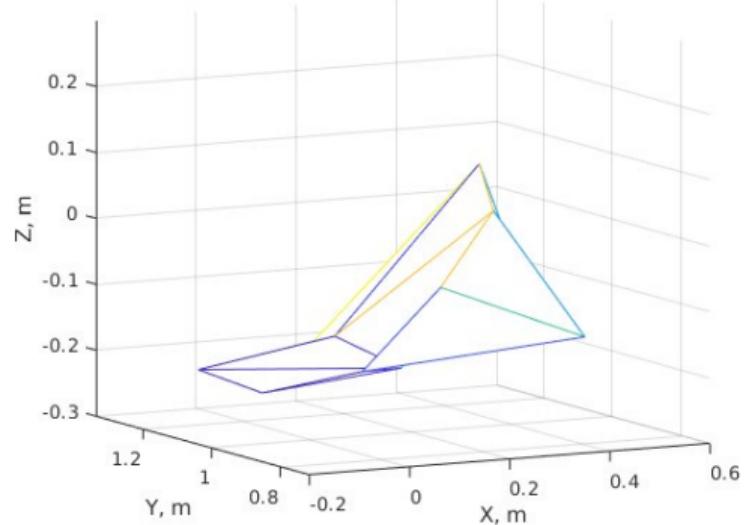
Map creation based on tactile data

Result: real world experiment, video



Robot is passing the obstacle

3D Delaunay triangulation based on 2D connectivity



Mesh, obtained from legs



Map creation based on tactile data

Summary

- Map can be built using concave hull 2D Delaunay triangulation.
A Sparse point cloud obtained from force sensors, installed on legs.
- *Simulator:*
 - Avg. Point cloud comparison RMSE is about 5 cm.
 - Avg. Mesh comparison RMSE is about 1 cm.
- *Real world experiment:*
 - Avg. Point cloud comparison RMSE is about 8 cm.



Summary

- Robot was created
- Force transducer based on Velostat was created and was investigated
- Robot can distinct rubber and rock terrains
- Robot can build a map using tactile sensors