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

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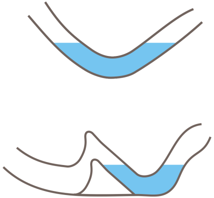
Supervisor: Alexander Maloletov

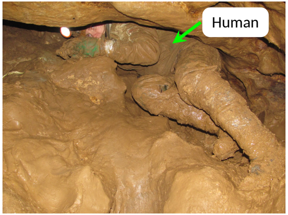
Motivation: why do we need to explore caves by robots

Salt

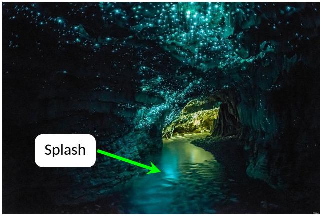


Siphon

Glacier cave



Clay

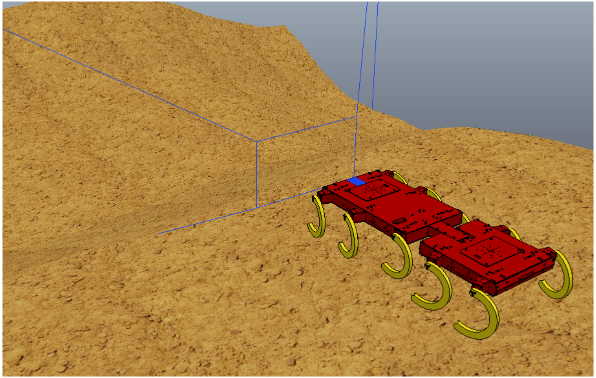


Splash

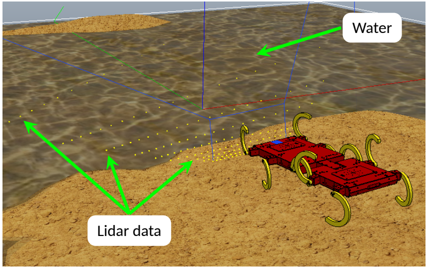
Moss

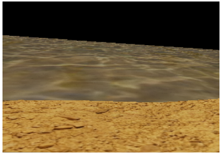
Motivation: unsolvable problem for cameras and lidars

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 on terrain, **when we have a SLAM based on lidars, cameras**?

Problem statement

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

Obtain map and terrain type

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 from **modified Delaunay triangulation**.

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

Literature review

Consider issues:

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

Existance problems

- Robotics systems for exploring loose caves
- Object mesh creation using tactile sensor installed on manipulator
- Map creation using lidars and cameras

Literature review

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Existance problems

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- Map creation using lidars and cameras

New problem was found

Robot design

Requirements

Problem – choose robot mover type. This robot should:

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

Robot design

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cycling robot with 1 DoF leg

Robot design

Structural synthesis problem

Question

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

Robot design

Structural synthesis problem

Question

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

Answer

Robot should have **8-14 legs** in total!

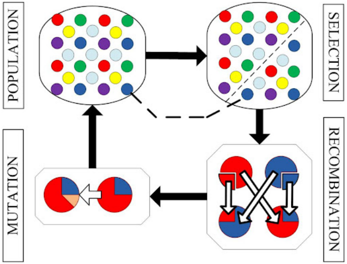
Robot design

Technological stack

*Generating terrain approach (Robot traverse an **artificial terrain** based on **generating parameters**)*

GAZEBO

Robot simulator



Genetic algorithm (DEAP Library)

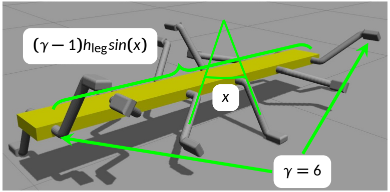
Robot design

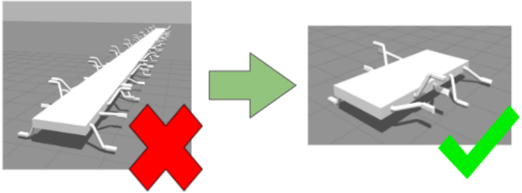
Assumptions

- Generated terrain family with the same constants has the same complexity.
  Parameters:
  - cell width and length
  - cell height range
  - distribution parameter

Robot design

Proposed solution





$$F \rightarrow max = \beta\left(\omega_1 \cdot \overbrace{\delta}^{\text{Distance}} + \omega_2 \cdot \overbrace{\frac{1}{(\gamma-1)h_{\text{leg}}sin(x)}}^{\text{Simplified body length}}\right) + (1-\beta)\delta^{\omega_1}\left(\frac{1}{(\gamma-1)h_{\text{leg}}sin(x)}\right)^{\omega_2}$$

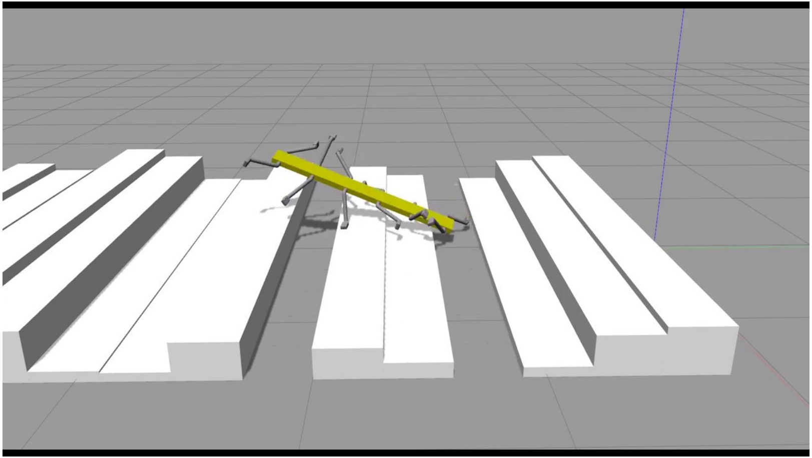
Idea: *Minimize number of legs without losing off-road passability*

β is adaptive parameter,

$\omega_{1,2} \in [0..1]$ are the weight coefficients.

Robot design

Video: the story of one generated robot



Roboti design

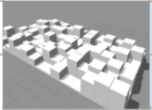
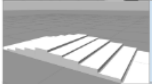
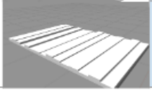
Result interpretation

Based on fitness function the number of legs range starts from 8. It can be explained by static stability criteria. In such case 4 legs will touch the ground.

TODO

Robot design

Results

	Terrain types	Number of legs per side	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**: created robot should have 10-12 legs in total*

Robot design

Increasing maneuverablity

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 maneuverablity

Question

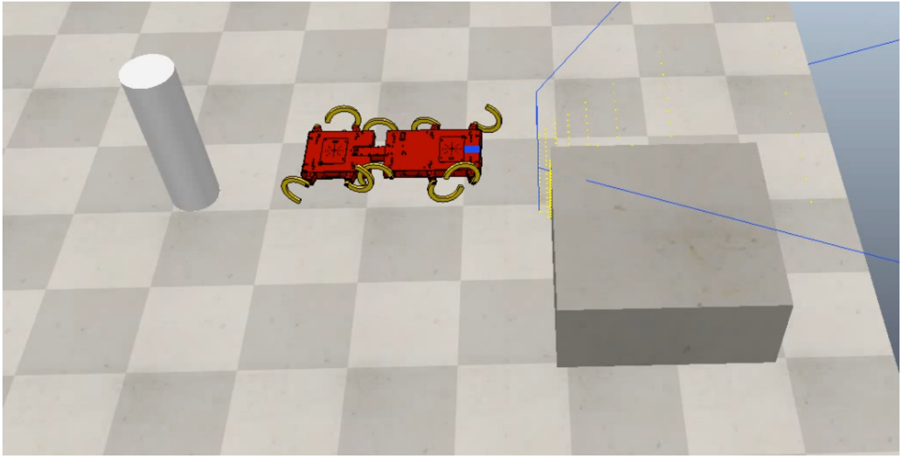
1. Long robot can stuck in a cave hole, while rotating. How to avoid it?
2. How to climb on big stones?

Answer

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

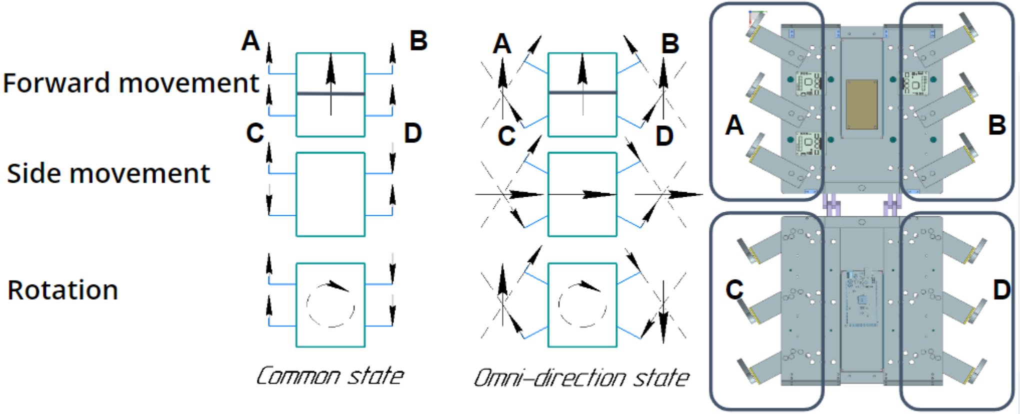
Robot design

Video



Robot design

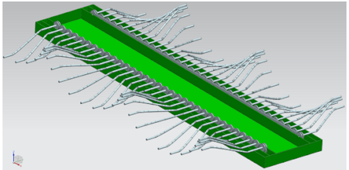
Proposed solution



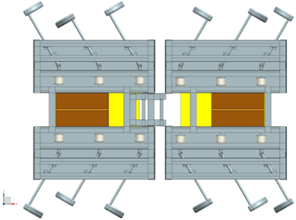
Vector representation of forces in the conventional and omni-direction states

Robot design

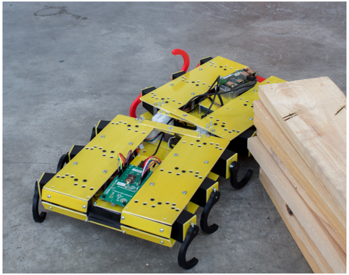
StriRus prototypes (1)



1st gen: *54 legs*
1 segment



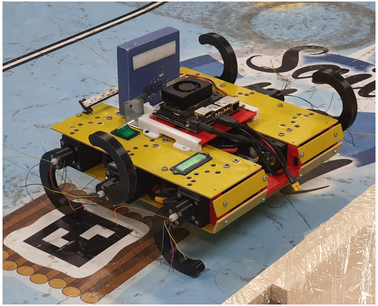
2nd gen: *12 legs*
2 segments, 1 DoF connection
Continuous angle b/w body, leg up to 45 deg



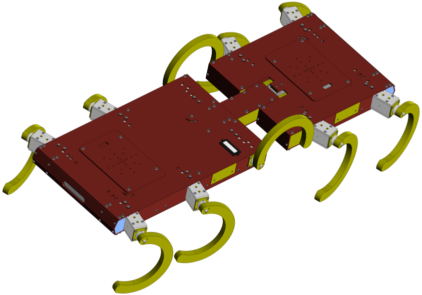
3rd gen: *12 legs*
2 segments, 2 DoF connection
Discrete angle b/w body, leg up to 45 deg

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

- Current/voltage measurements from motors
- Installing torque sensor on a shaft
- Installing a force sensor on each leg

Force transducer design

Force sensor types

- **F/T sensors**: too massive 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.

Force transducer design

Force sensor types

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

Force transducer design

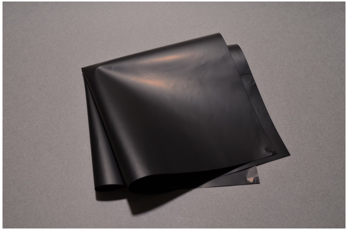
Velostat

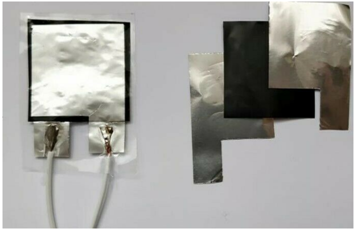
Definition

The Velostat is a polymer material filled with carbon black.

Expected effects:

- Quantum tunnelling (Precolation) – 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 then 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 particular part of a sensor.

Force transducer design

Experimental setup requirements

- Force control.

  Solved by Impedance Control

- Position and force repeatability.

  Solved by adding a manipulator and a camera

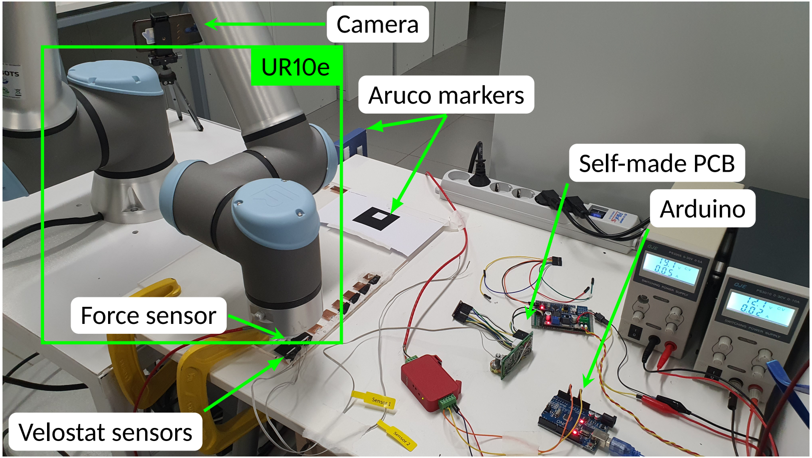
- To have an ability to apply force only on a particular part of a sensor.

  Solved by adding several end-effectors

All setup requirements are fulfilled

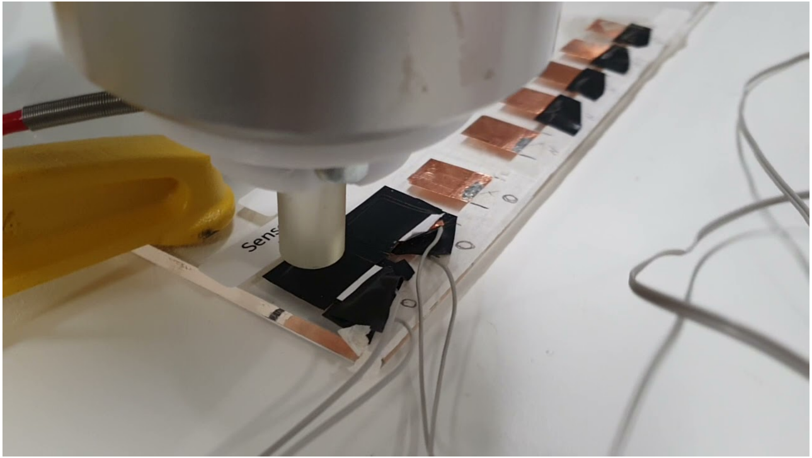
Force transducer design

Experimental Setup: Hardware overall



Experiment Design

Experimental Setup: Hardware, video

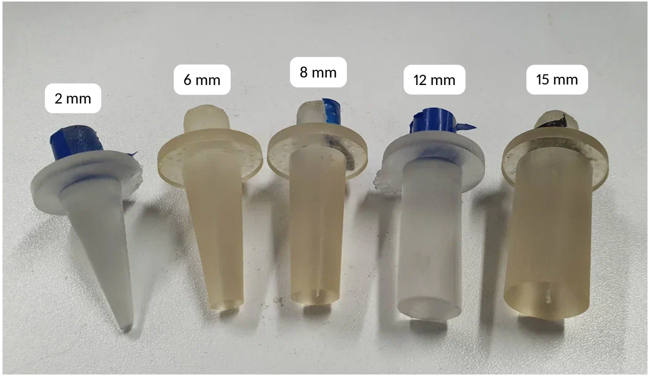


Force transducer design

Experimental Setup: Hardware, aruco markers

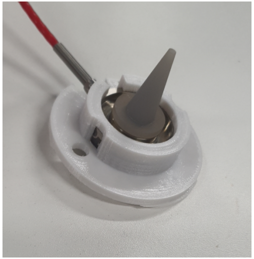
Force transducer design

Experimental Setup: Hardware, end-effector



All end-effectors

Ground Truth Force sensor

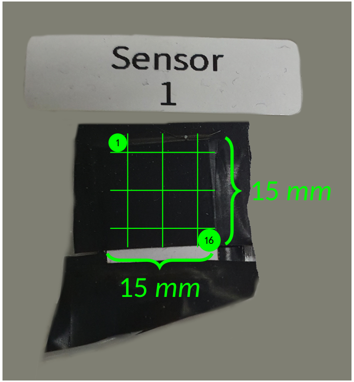


End-effector in assembly

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 grid. We touch with the same pressure using five different end-effectors (area starting from 2mm till 15mm).
   - We are using 2 mm and 15 mm end-effectors. We touch with different forces (5, 10, 20, 30, 40 H).



Sensor representation as 4 × 4 grid

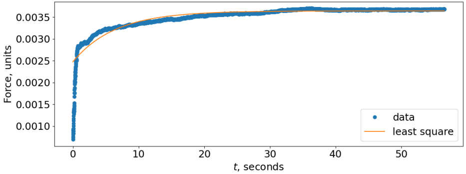
Force transducer design

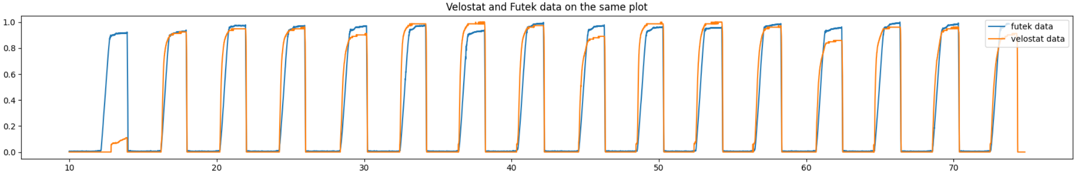
Result: static experiment

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

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

Where V_0 – initial voltage, $p,\ A_i,\ B_i,\ \tau_{res},\ k_i$ are constants, t – current time, t_0 – the time when the pressure appeared.

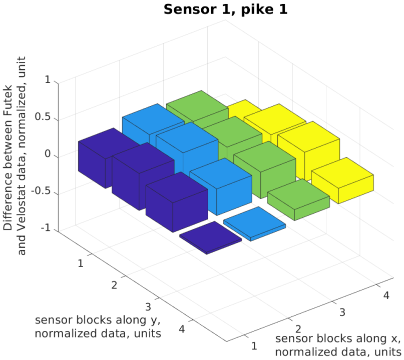




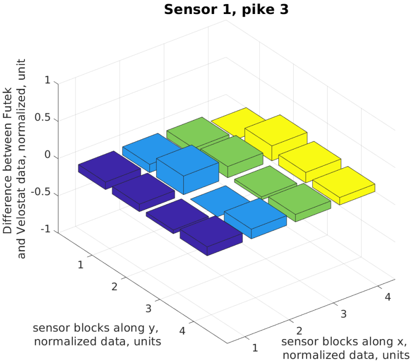
Normalized force data from sensor and transducer

Force transducer design

Result: dynamic experiment



2mm end-effector diam



8mm end-effector diam

Force transducer design

Summary

1. Static experiment: transducers coefficients $p,\ A_i,\ B_i,\ \tau_{res},\ k_i$ 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

Question

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

Answer

Solving terrain classification problem using Machine learning

Terrain classification

Experimental setup requirements

- To have a possibility to install new surfaces and change it quickly.
- Infinite movement.
- Movement part should be the same as on the StriRus

Terrain classification

Experimental setup requirements

- To have a possibility to install new surfaces and change it quickly.

  Solved by quick detachable table

- Infinite movement.

  Solved by creating the 2 DoF mechanism and a S-shape leg

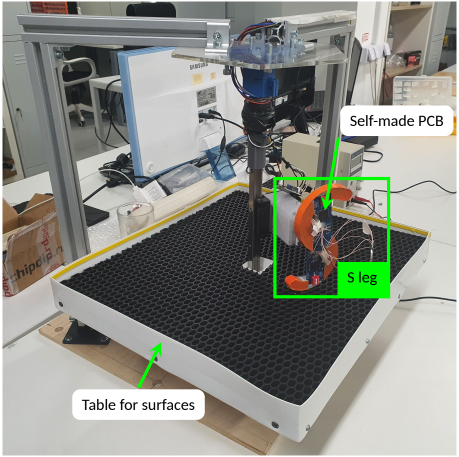
- Movement part should be the same as on the StriRus

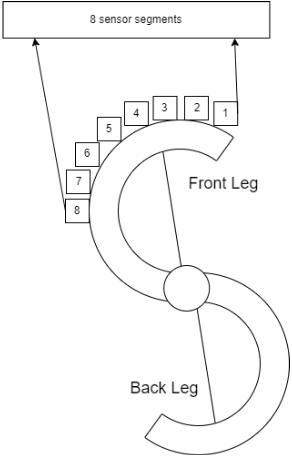
  Solved by creating a mount for a leg assembly

All setup requirements are fulfilled

Terrain classification

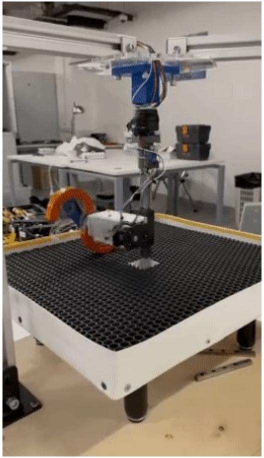
Experimental Setup

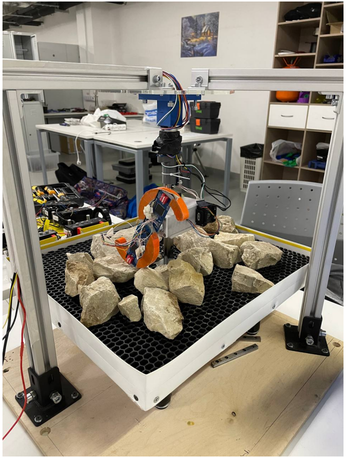




Terrain classification

Experimental setup: surface types, video





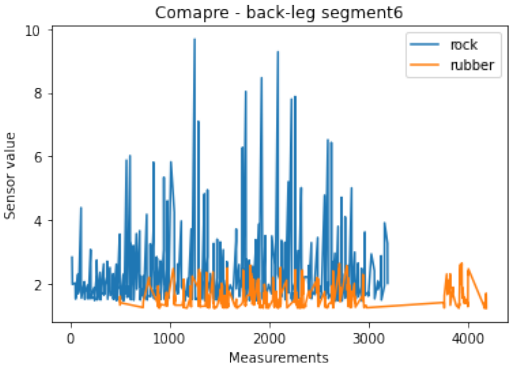
Terrain classification

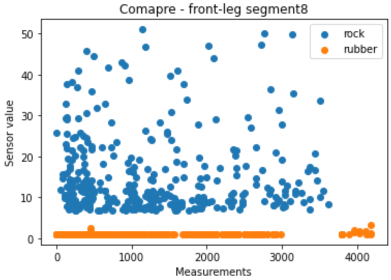
Velostat transducer properties

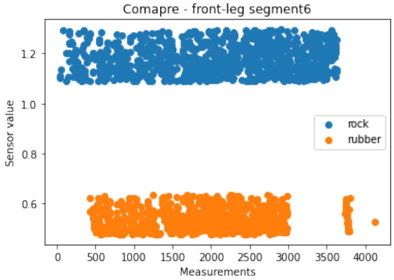
- Because of high hysteresis and difficulties with calibration, we have to work with relative data.

Terrain classification

Obtained data from one experiment







Terrain classification

Summary

- We can distinct rubber and rock surfaces
- Terrain classification parameters was chosen:
  - RPM
  - Motor Torque
  - Acceleration from IMU
  - Force data which are represented as Sensor valuesegment, Peak amplitude, Average amplitude
- The force transducer has been proven to work

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

Question

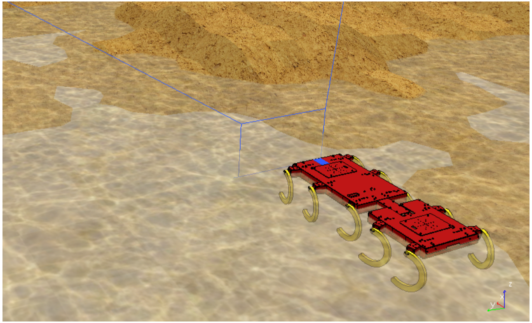
How to create a dense point cloud, using sparse data from legs?

Answer

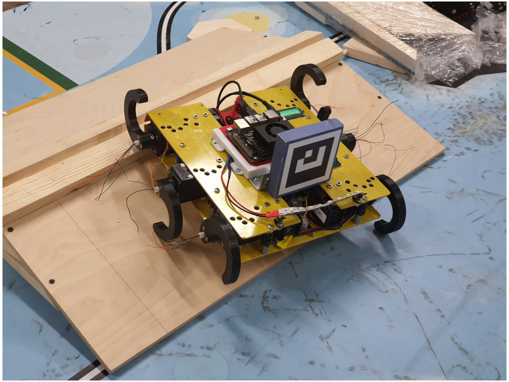
Create a mesh, using concave hull Delaunay triangulation using sparse data, *sampling it* and return to navigation

Map creation based on tactile data

Experimental setup



*CoppeliaSim simulator, **4th gen** StriRus*



*IRL, **3th+ gen** StriRus*

Map creation based on tactile data

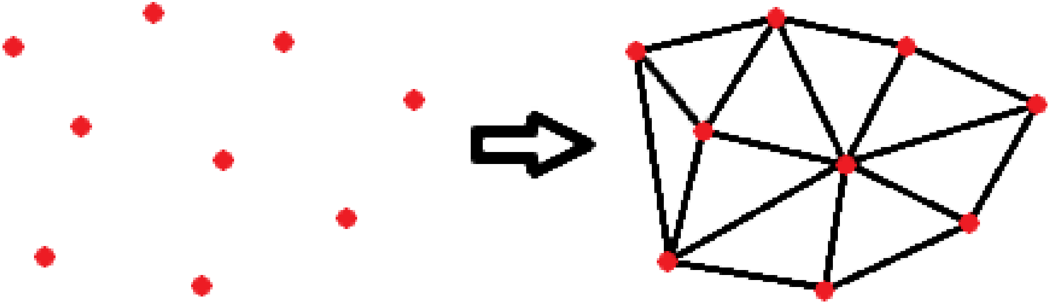
Assumptions

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

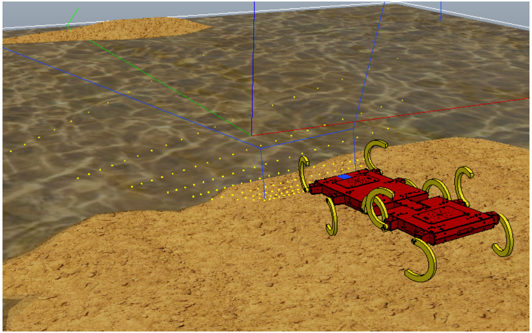


Common 2D Delaunay triangulation (Convex Hull)

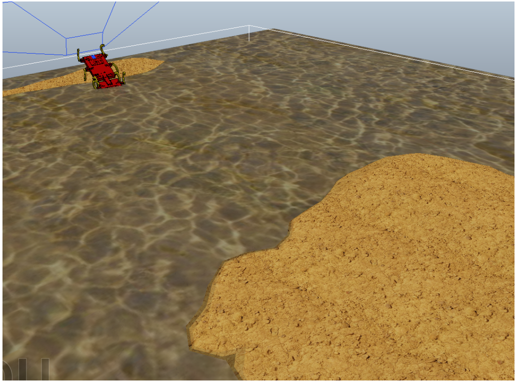
From point cloud to mesh

Map creation based on tactile data

Result: simulator



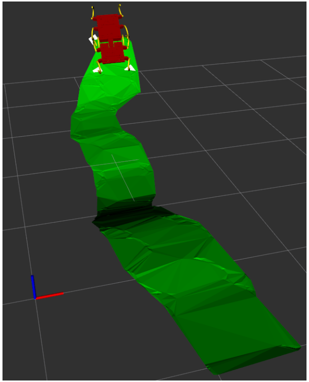
Start point



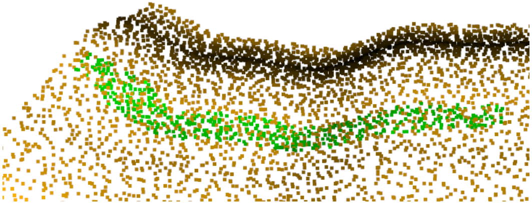
End point

Map creation based on tactile data

Result: Mesh



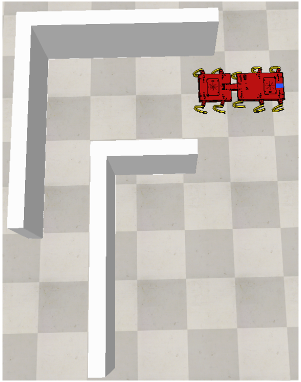
Mesh created using concave hull 2D Delaunay triangulation



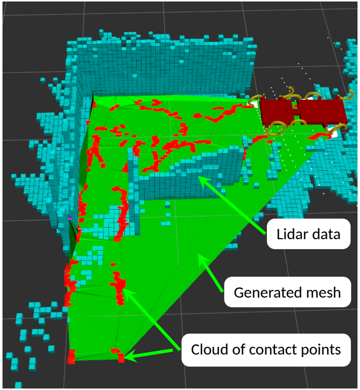
Sampled point cloud

Map creation based on tactile data

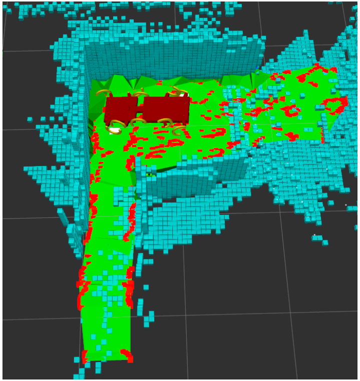
Why do we need a concave hull solution



Case study



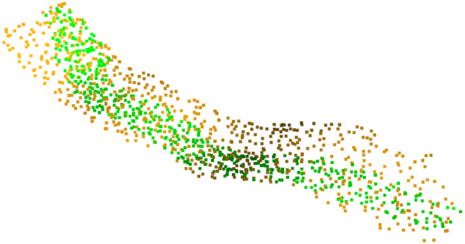
Convex Hull



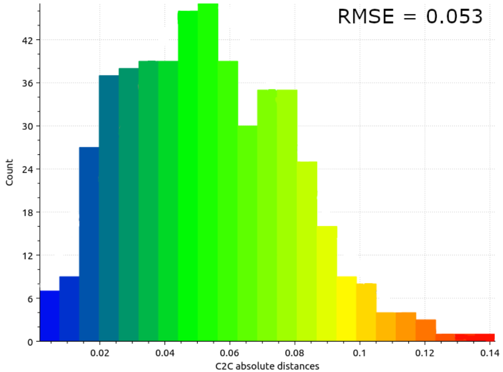
Concave Hull

Map creation based on tactile data

Metric: point cloud comparison with ground truth



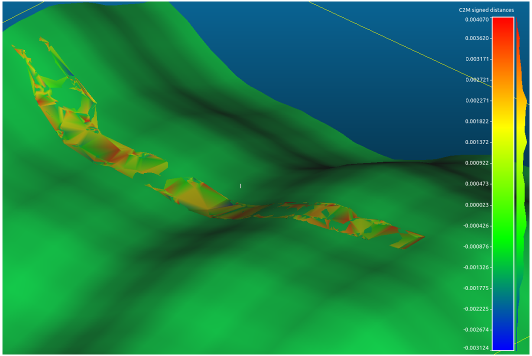
Overlaid point clouds



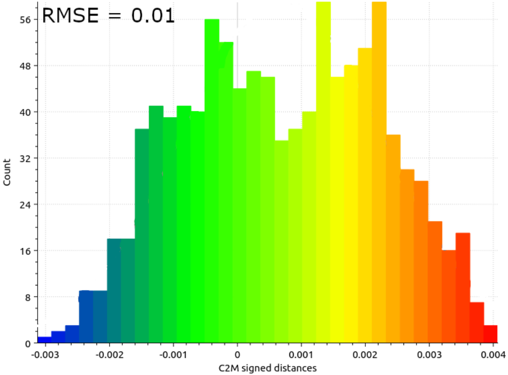
Error histogram (distance from a point to closest ground truth point)

Map creation based on tactile data

Metric: mesh comparison with ground truth



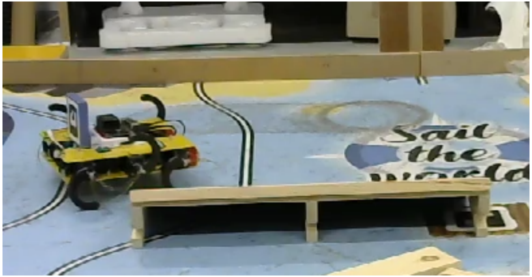
Overlaid meshes



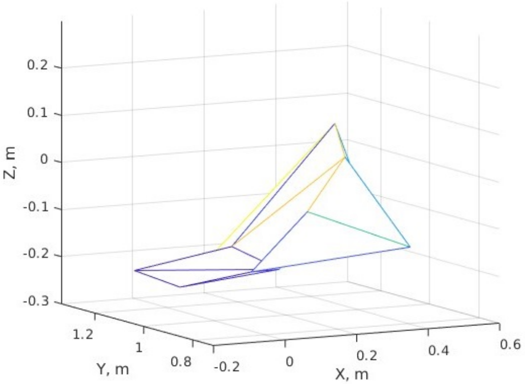
Error histogram (distance from a point to closest ground truth point)

Map creation based on tactile data

Result: real world experiment, video



Robot is passing the obstacle



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.

It is appropriate accuracy for such task.

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