# Intelligent Robot Design and Implementation

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A robotic software package specifically designed for robot dogs

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# Objectives

# Objectives

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- Inverse Kinematics

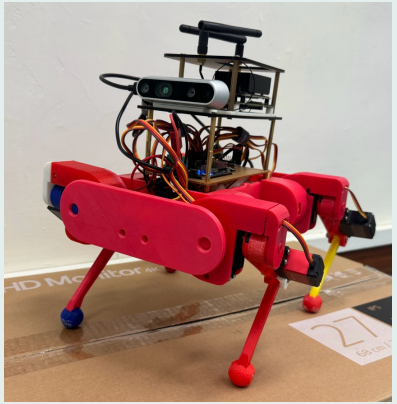
## 02 Intelligent behaviors

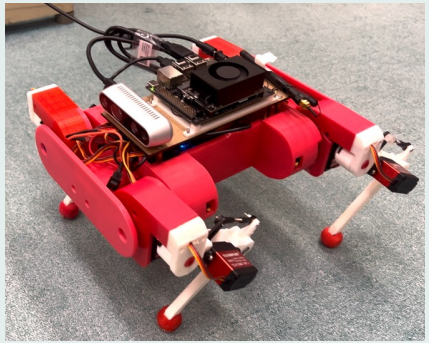
- Focus: sensing the environment
- Frontier exploration
- Object tracking

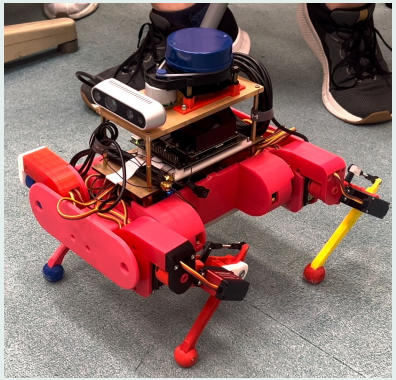
## 03 Interactive dashboard

- High-level remote control
- Real-time visualizations

# Quadruped Robot

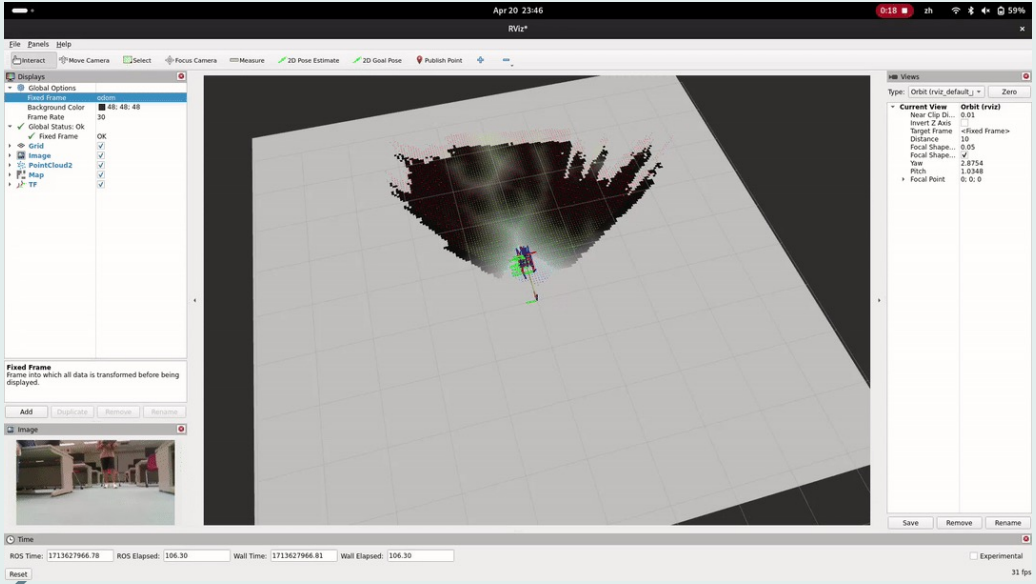






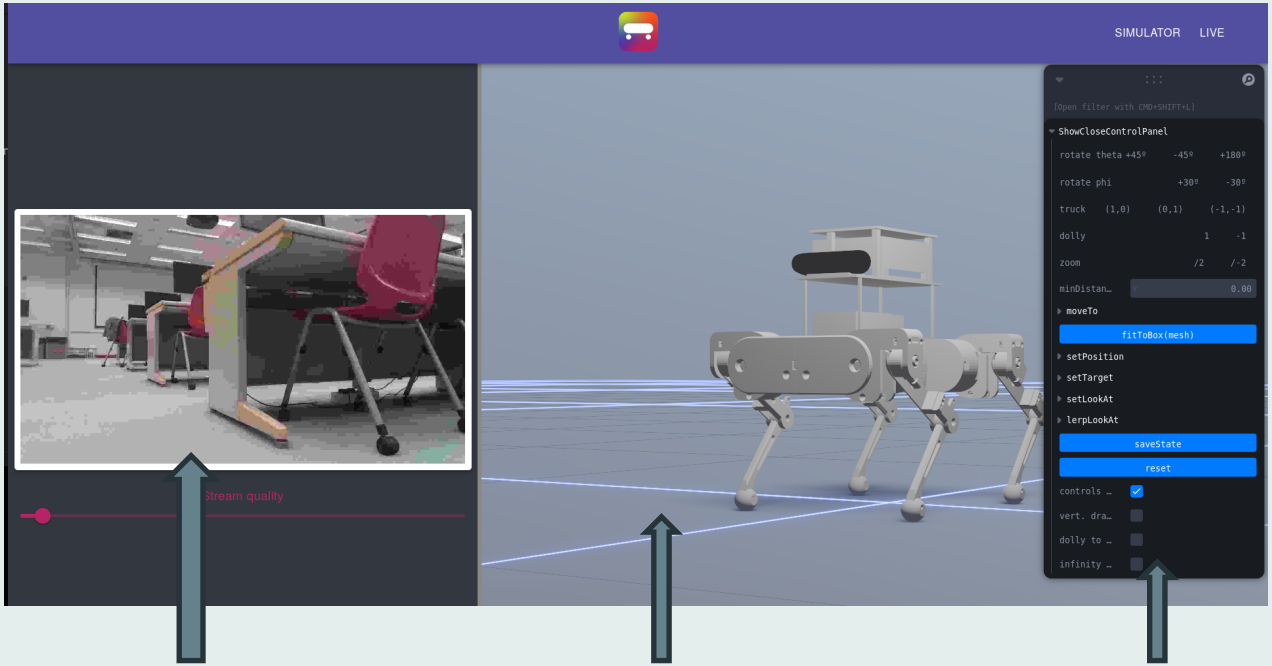
- **Goal**: Use off-the-shelf components to implement
- **Wheeled vehicles**: Cannot travel on very steep slopes
- **State-of-the-art robots**: Running on rough terrain, jumping, balancing...

# Intelligent behaviors




- **Auto navigation**: Finding shortest path, mapping, reaching navigation goals...
- **Frontier exploration:** Explore the map using SLAM
- **Dynamic object following:** Detecting an object of interest and use its world coordinate as navigation goal
- **Applications:** Patrolling, rescuing, logistics...

# Interactive Dashboard




Live feed from camera

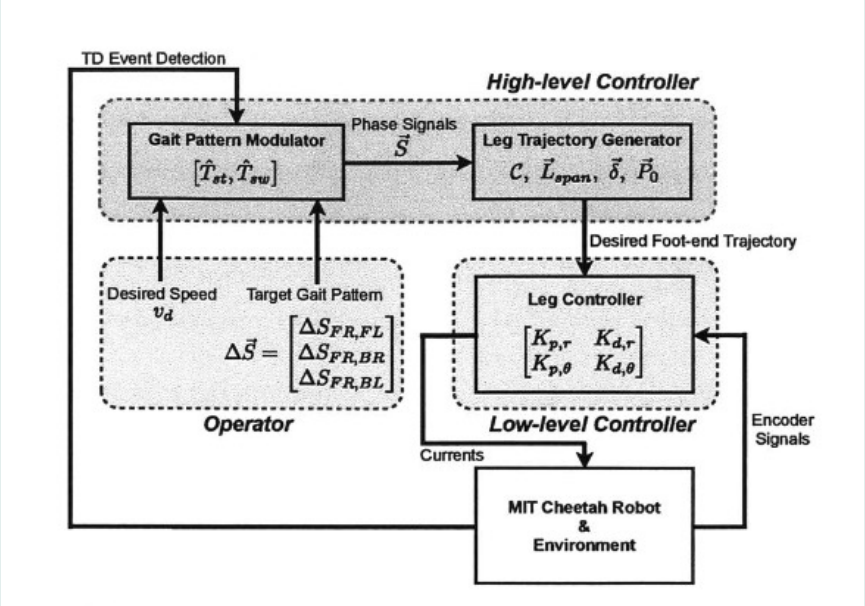
Simulated scene

Control panel

# 02

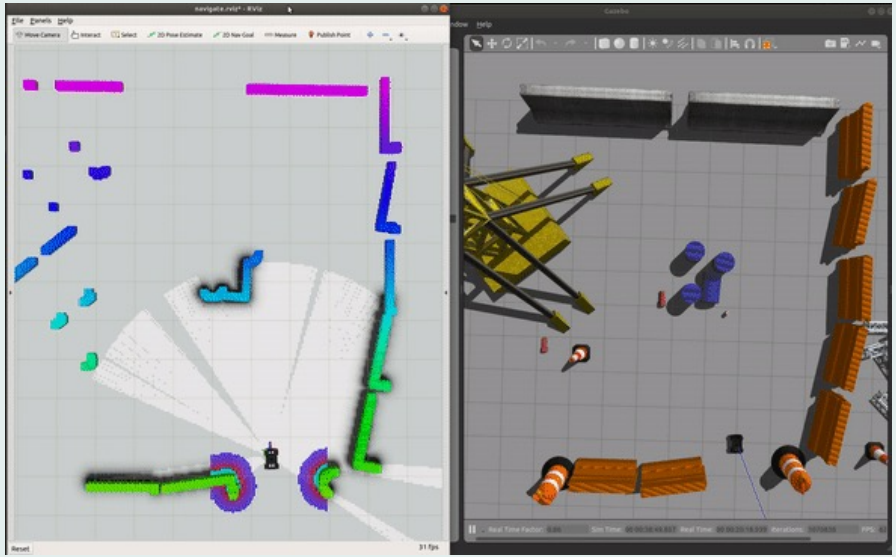
# Recap

# Hierarchical Controller Algorithm




- **Operator:** velocity and gait pattern control [1]
- **Gait Pattern Modulator:** stance and swing signals
- **Leg Trajectory Generator:** foot-end trajectories by phase
- **Leg Controller:** hardware signals *(different from CHAMP)*

# Champ

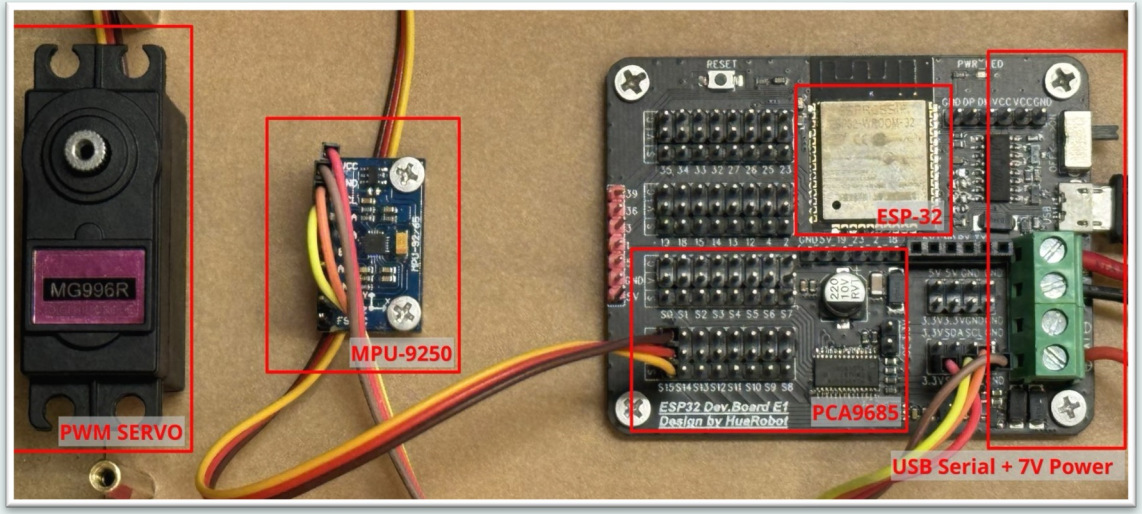


SLAM demo from Champ [2]

Features:

- Inverse Kinematics engine
- Gait configuration
- ***Simultaneous localization and mapping (SLAM)***
- ***Autonomous navigation***

# Firmware




## IMU: MPU-9250

- Accelerometer, gyroscope, and magnetometer
- Digital Motion Processor: calculate orientation

## PWM Servo

- PCA9685: 16 channel PWM driver (12-bit res)
- Convert joint angles to PWM signals

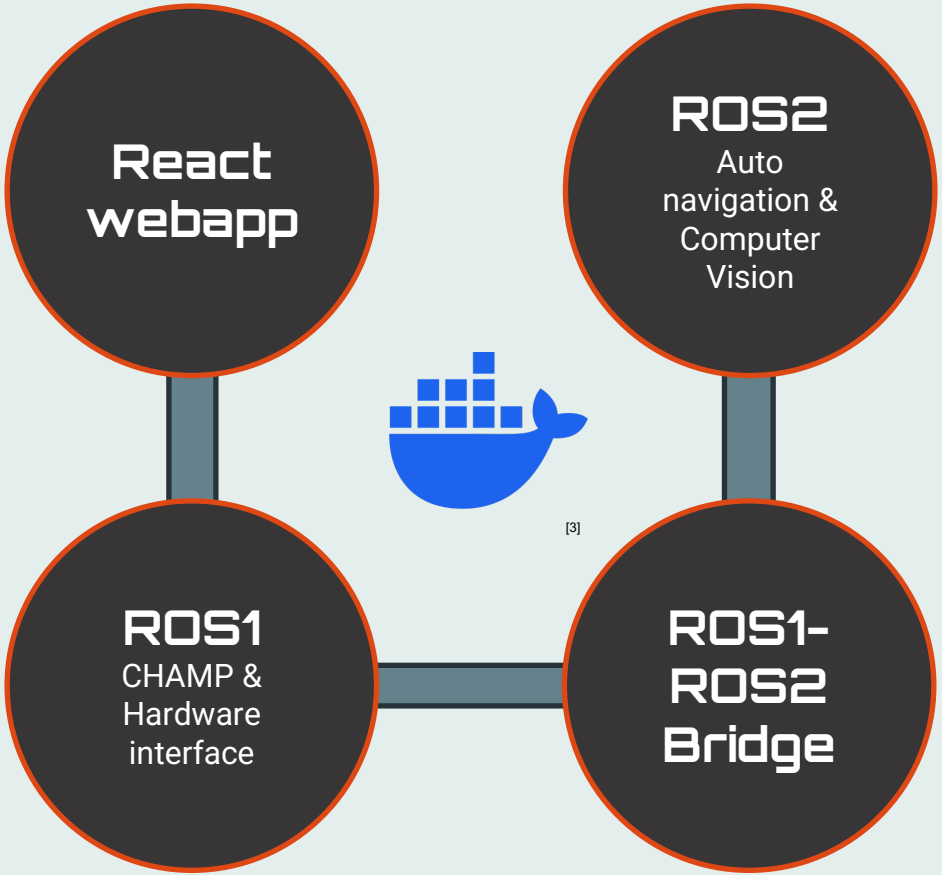
## ROS Serial

- Protocols: Serial, Bluetooth, WiFi
- Communicate with ROS network
- Send IMU data; receive joint angles

# 03

# Architecture

# Architecture



# Docker [3]

## Hardware agnostic

- Single set-up procedure
- Accommodate different dev environments

## Quick setup

- Docker-compose: open several containers at once
- Build upon base images (OS)

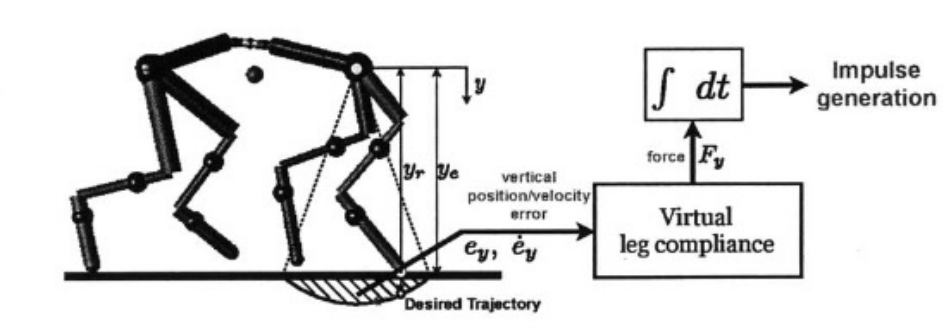
## Deployment

- Images can be prebuilt and reused
- Align dev and prod environments
- Easy to manage from host machines

# 04

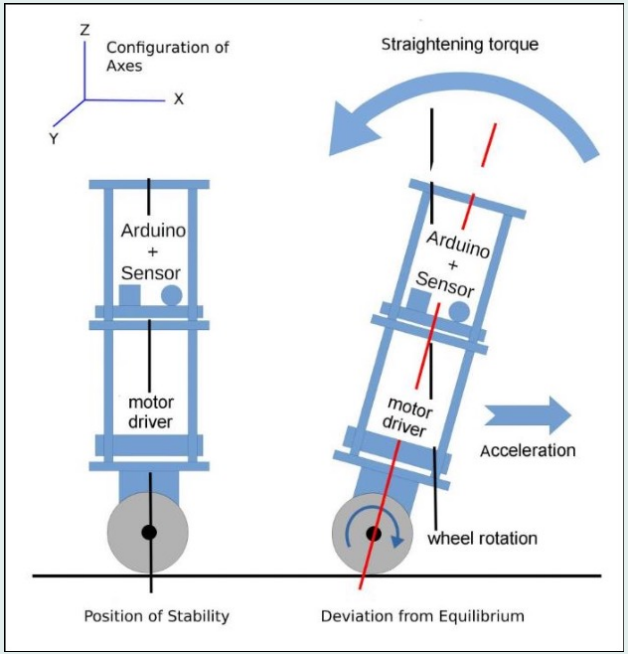
# Self-balancing

# Self-balancing: Virtual Compliance




- **MIT Paper**: [1] Stability achieved from feedback signal of motor encoders
- **Our robot**: No feedback signals from PWM servos – internal control loop
- **Challenge**: How to achieve self-balancing without virtual compliance?

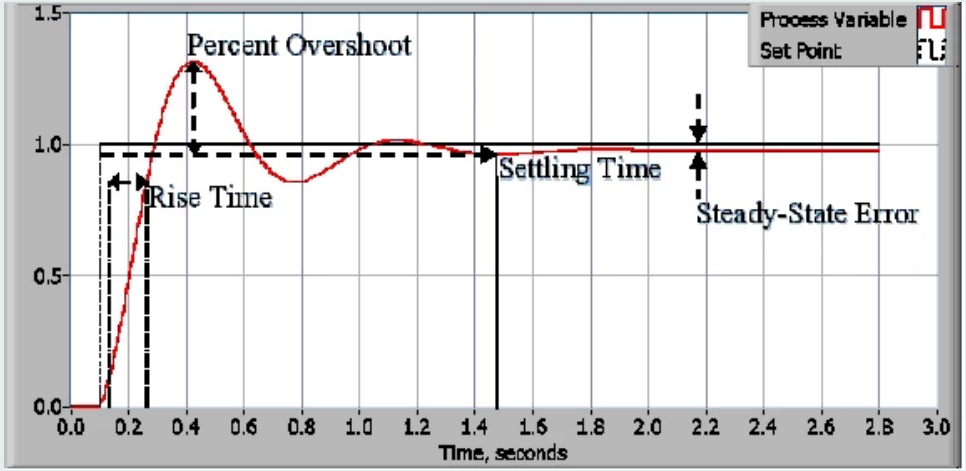
# Self-balancing with IMU




[4]

- **Idea:** integrate IMU orientation as feedback signals
- **Assumption**: the robot should try to level body when balancing
- **Action**: find the required motion to achieve the goal ***(How to achieve this?)***

# PID Controller




[5]

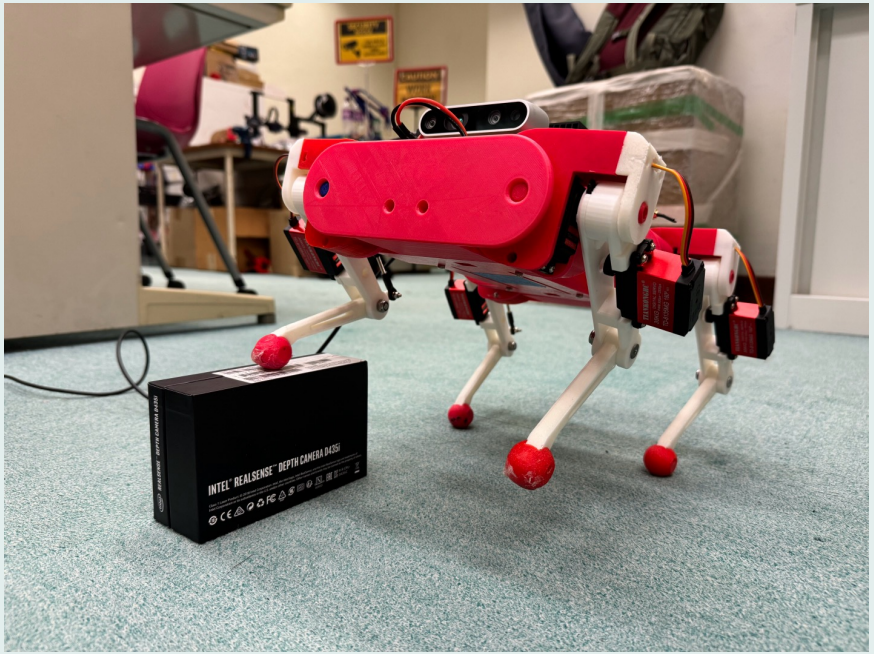
- **Error term**: process variable – set point
- **Proportion**: scaling the error term
- **Integral**: sums error terms over time
- **Derivative**: damping the error term using time derivative

*Find a combination that achieves a smooth and responsive transition*

# Self-balance Algorithm


1. Two variables: *Pitch* and *Roll*
2. PID: from error terms, find the pitch and roll values to counter-balance
3. Integrate the counter-balance values into IK calculation

# Limitations




- **Discontinuous terrain:** require foot sensors to check if the legs are touching the ground
- **PID tuning:** depends on hardware dynamics
- **IMU**: placement and drift

# 05

# Perception

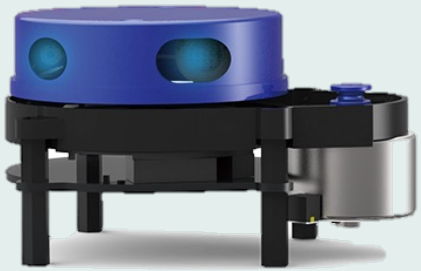
# Stereo Camera (Intel D435i)

- Provide single shot 3D reconstructions of the imaged scene by using perspective changes in two camera views
- Detailed 3D object information, but short range


[6]

# Planar LiDAR (YDLIDAR X4)

- Determining ranges by targeting an object or a surface with a laser
- Measuring the time for the reflected light to return to the receiver
- Long range, but only 2D information

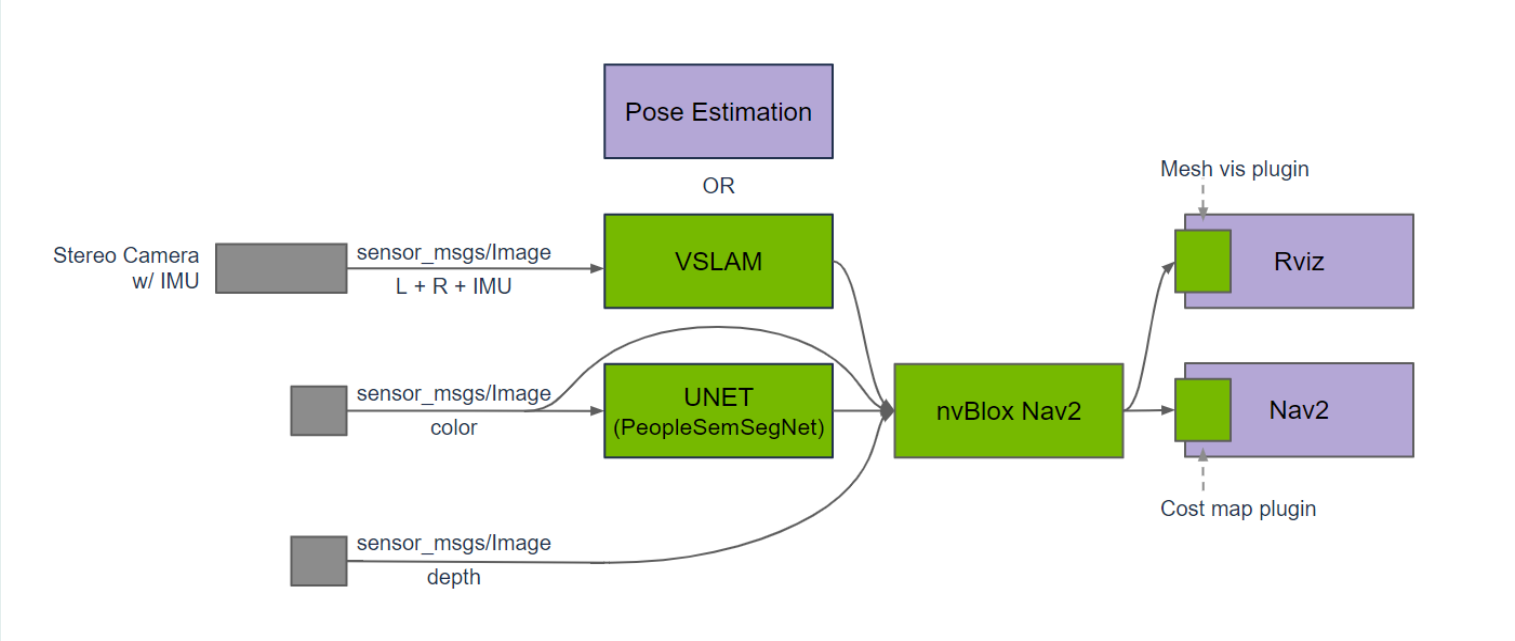


[7]

# 06
# Exploration & Navigation

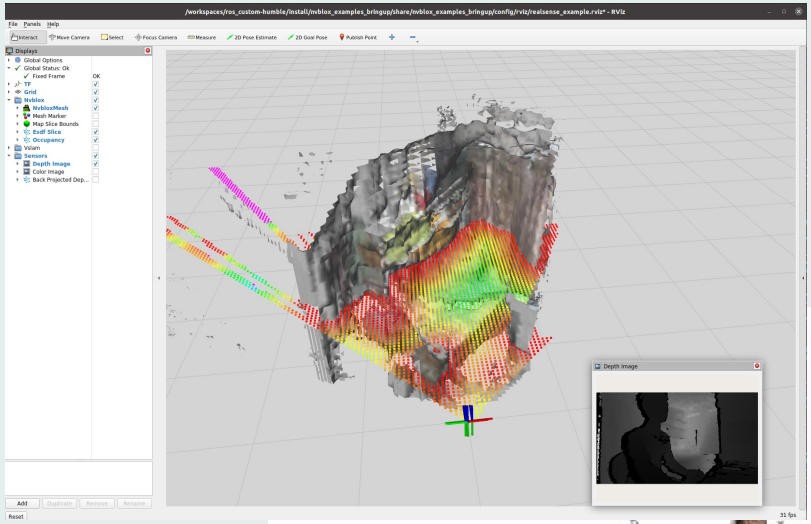
# Scene Reconstruction

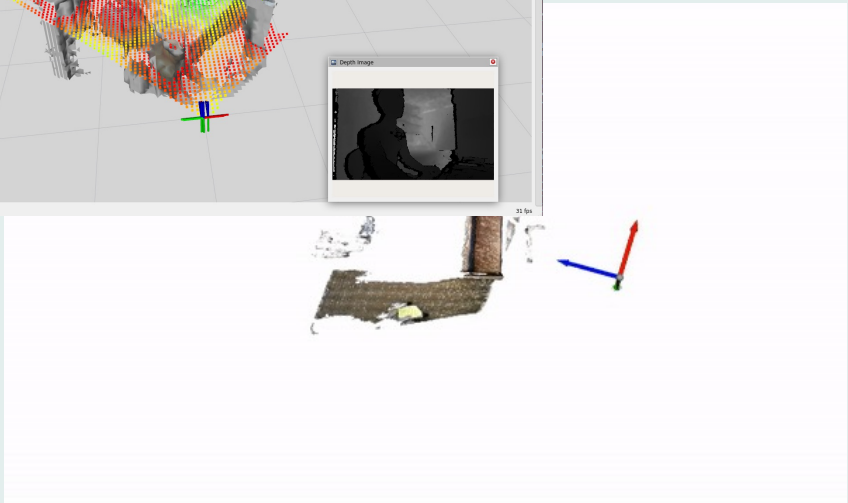
Nvblox: GPU-Accelerated Incremental Signed Distance Field Mapping




[8]

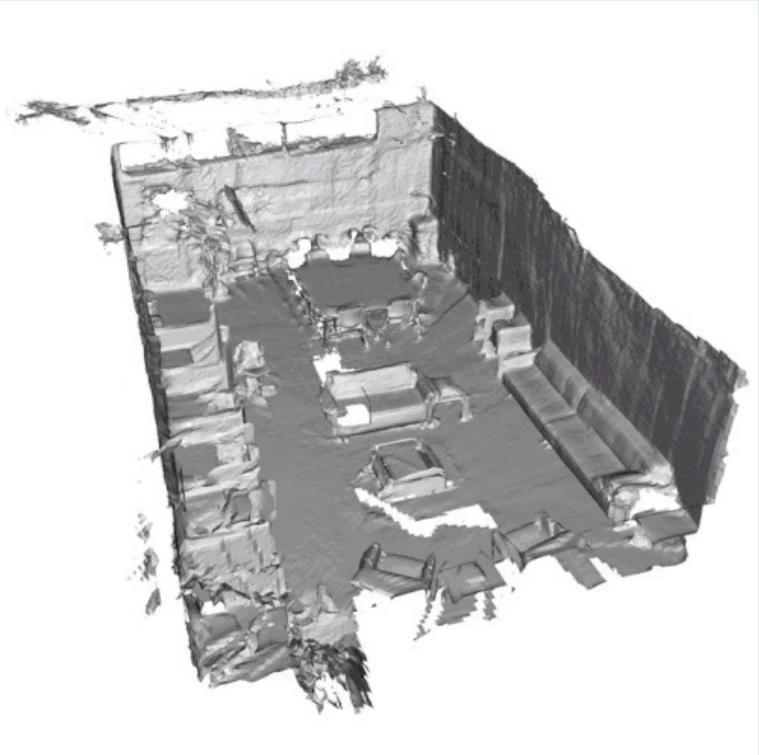
# Scene Reconstruction



- Critical task in robotics
- Typical SLAM packages build sparse representation of the environment [8]
- Nvblox constructs Truncated Signed Distance Field (TSDF), which is a voxel-based mapping technique

# Scene Reconstruction



[8]

- Motivation: facilitate autonomous navigation in unknown environment
- Typical planner server understands the environment using cost map, which is in form of an occupancy grid
- Significant speed-ups with TSDF and ESDF-based maps by slicing

# Autonomous Navigation

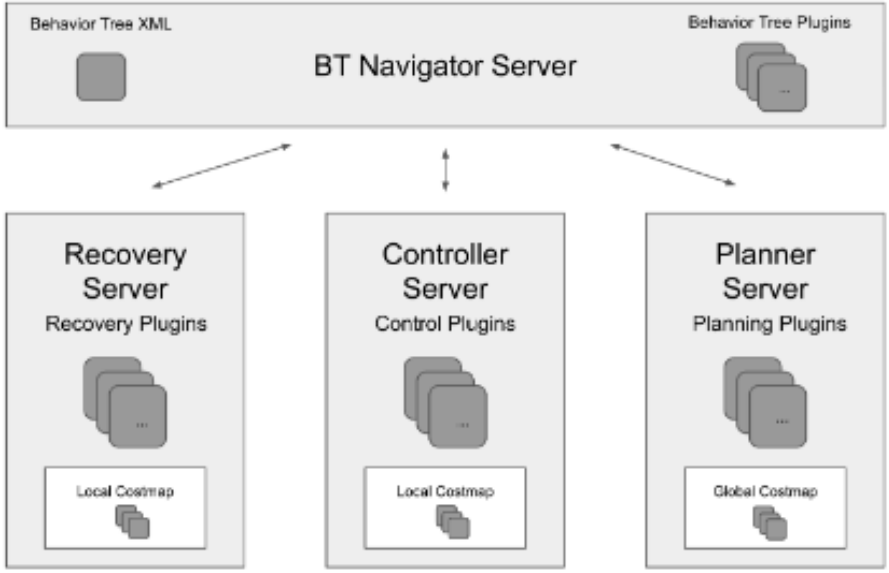


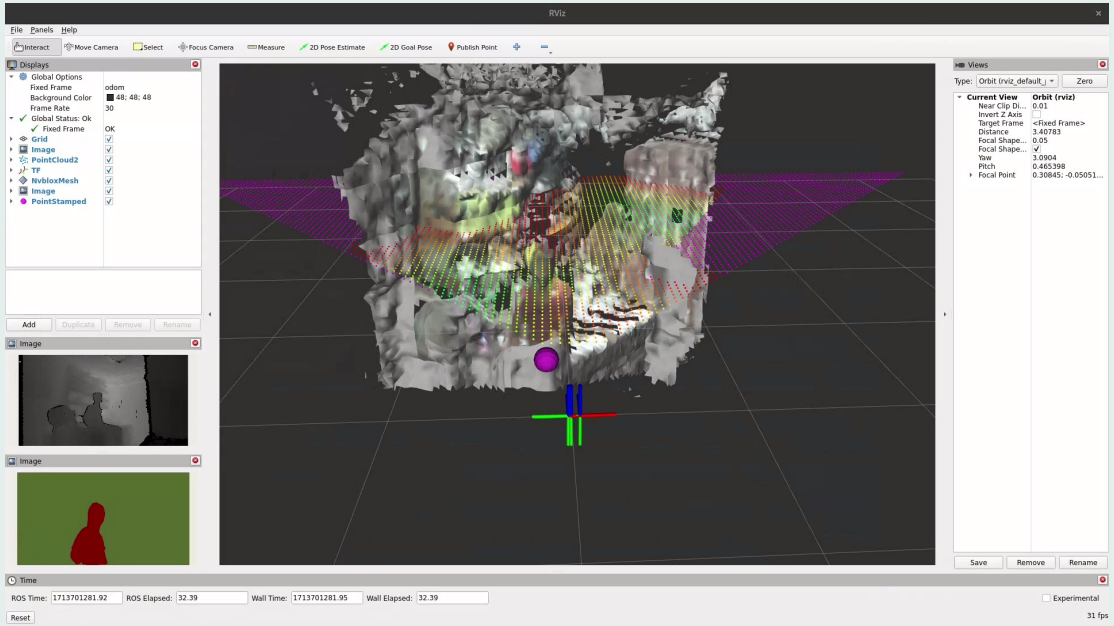

Fig. 2: Overview of Navigation2 design.

[9]

- Nav2 stack, modular behavior tree-based navigation
- **Behavior tree**: a tree-based execution model to represent navigation logics
  a. Human-understandable framework
  b. Able to construct complex behavior (e.g. dynamic following, handling charging needs)
  c. Easily extensible using plugins and XML

# 07
# Object Following & Detection

# Dynamic Object Following

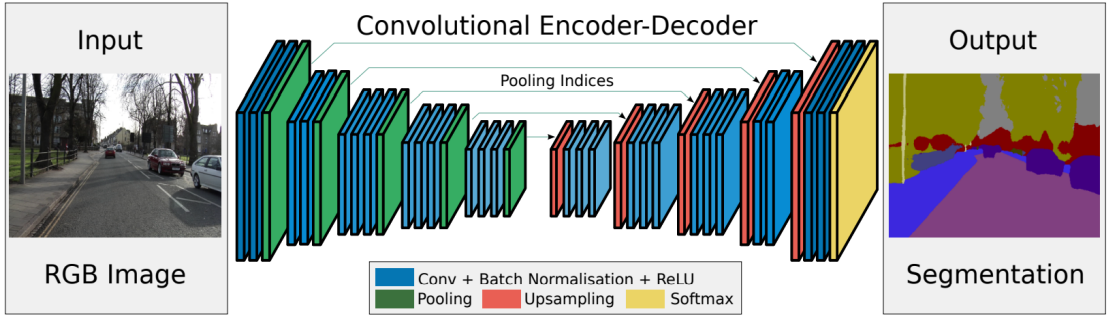



- Multi-step processes given RGB-D inputs
  a. Detect human presence
  b. Approximate the 2D coordinate in image
  c. Deproject the 2D coordinate to 3D world coordinate
  d. Update the goal pose with appropriate behavior tree

# Dynamic Object Following


- Process the color image with an image segmentation neural network
- Assign a class label to each pixel (e.g., background, human)
- Uses PeopleSemSegnet, which includes images with a variety of FoV in training dataset

# Dynamic Object Following




[10]

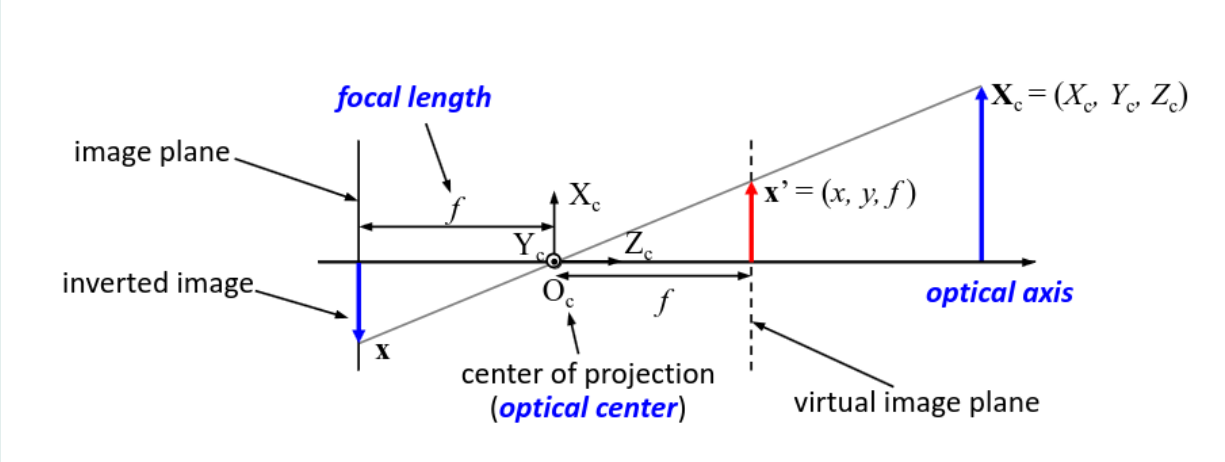
Fig. 2. An illustration of the SegNet architecture. There are no fully connected layers and hence it is only convolutional. A decoder upsamples its input using the transferred pool indices from its encoder to produce a sparse feature map(s). It then performs convolution with a trainable filter bank to densify the feature map. The final decoder output feature maps are fed to a soft-max classifier for pixel-wise classification.

- Potential issues:
  a. Occlusion problem might affect determining the goal pose
     - Deploy instance segmentation model and calculate closest distance to previous target
  b. High computational requirement despite downsampling
     - Deploy object detection model to get bounding boxes output

# Dynamic Object Following

- To obtain the ROI from segmentation output
  a. Find all connected components
  b. Sort the components by their area
  c. Select the largest component and compute its centroid (x, y)
- Recover the depth information
  a. By aligning the depth images with segmentation output, simply access the depth value d

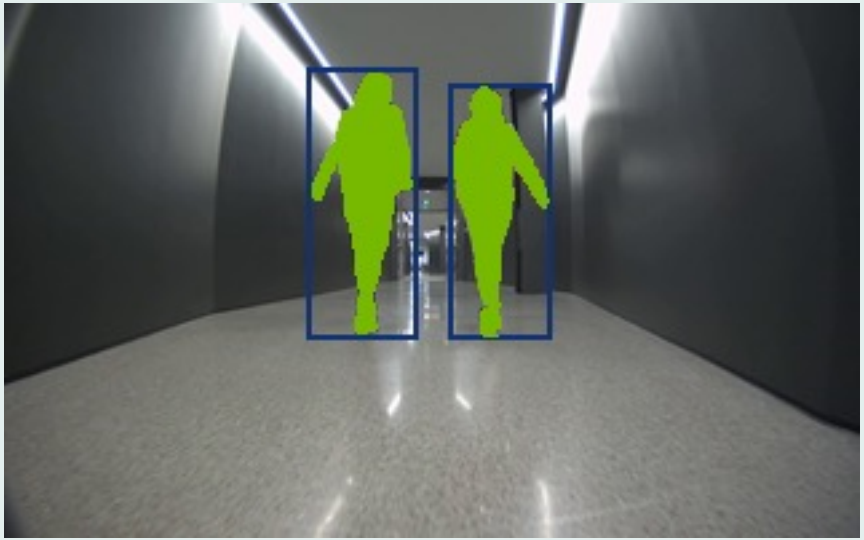
# Dynamic Object Following




[11]

- With camera intrinsic and extrinsic parameters, one can deproject the 2D pixel coordinate to 3D world coordinate
- Update the goal pose in the dynamic following behavior tree, which frequently replan the path and listen for goal updates

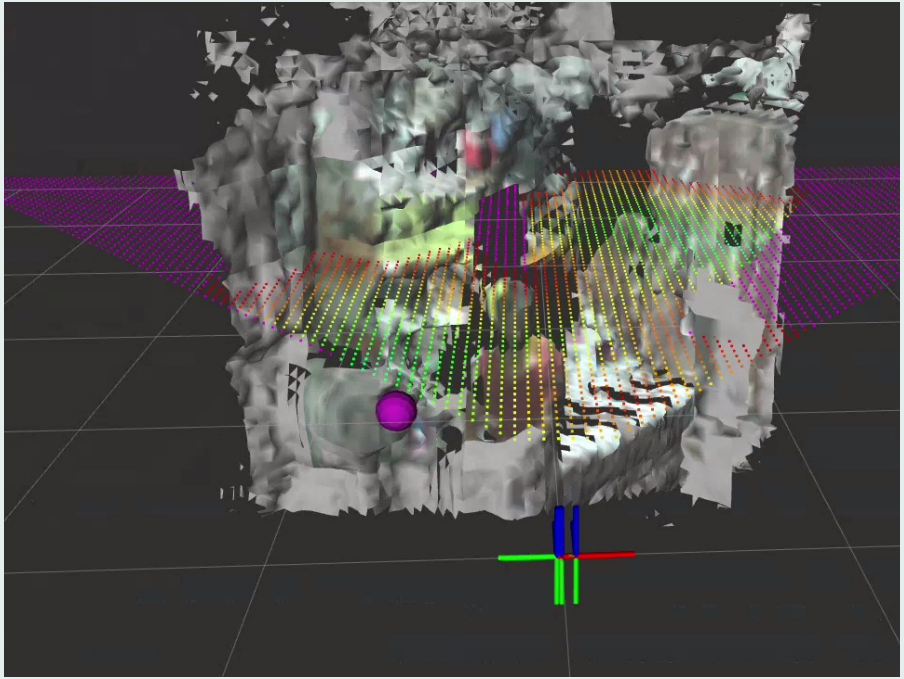
# Object Detection



[8]

- Opposed to image segmentation, object detection only provides a rough bounding box representation
- Efficiently classify and locate a large number of objects
- Easier dataset preparation for specialized application (e.g., Semi-Automatic Annotation)

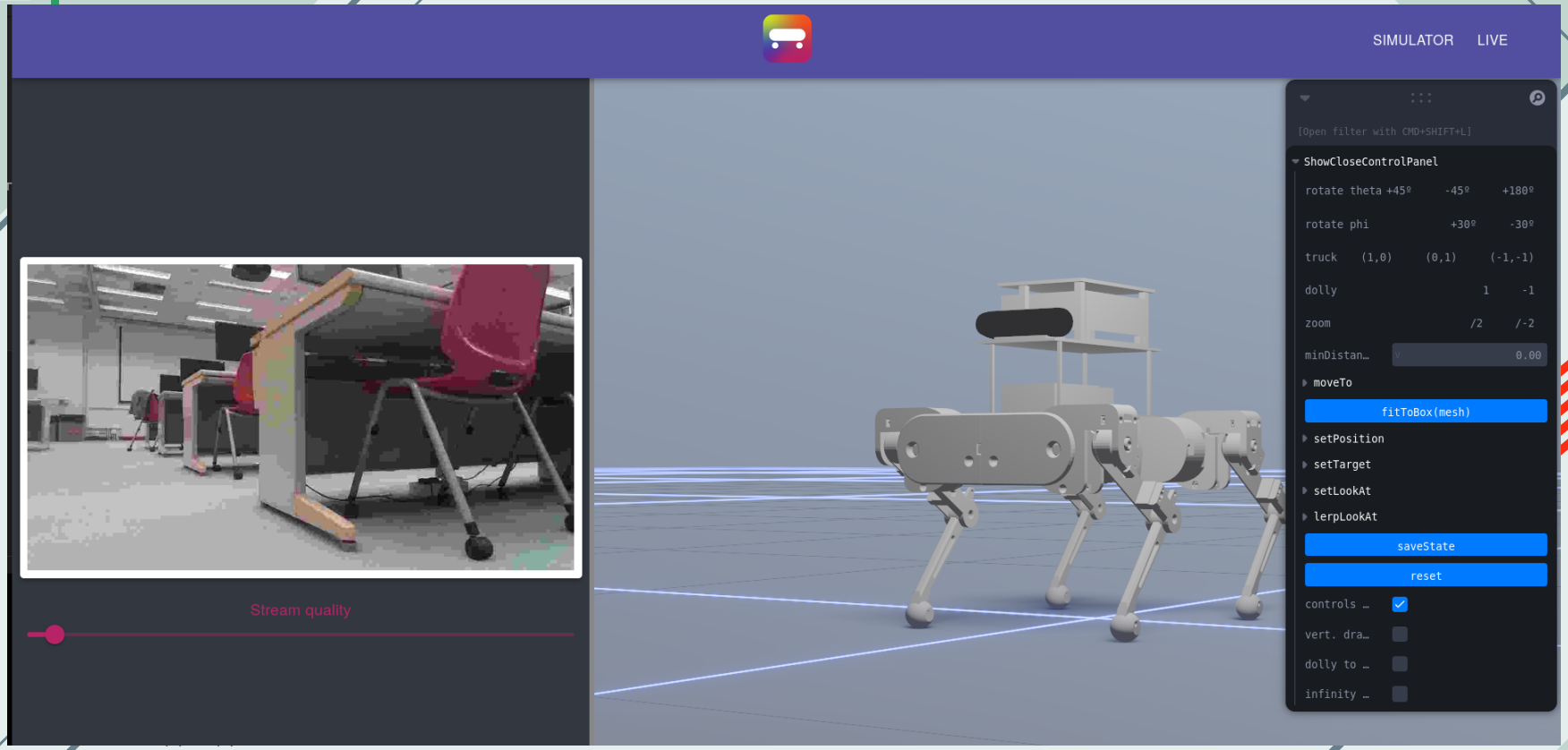
# Limitations



- Synchronization issue
  a. Depth image and color image might not be time synchronized
  b. Segmentation processing incurs additional delays
- Hardware invariance
  a. Legged machine experiences significant vibration
  b. Cause inaccurate information of camera extrinsic parameters impacting deprojection

# 08

# Web App


SIMULATOR
LIVE
Stream quality
[Open filter with CMD+SHIFT+L]
ShowCloseControlPanel
rotate theta +45º -45º +180º
rotate phi +30º -30º
truck (1,0) (0,1) (-1,-1)
dolly 1 -1
zoom /2 /-2
minDistan… 0.00
moveTo
fitToBox(mesh)
setPosition
setTarget
setLookAt
lerpLookAt
saveState
reset
controls …
vert. dra…
dolly to …
infinity …

# Features

Live Stream

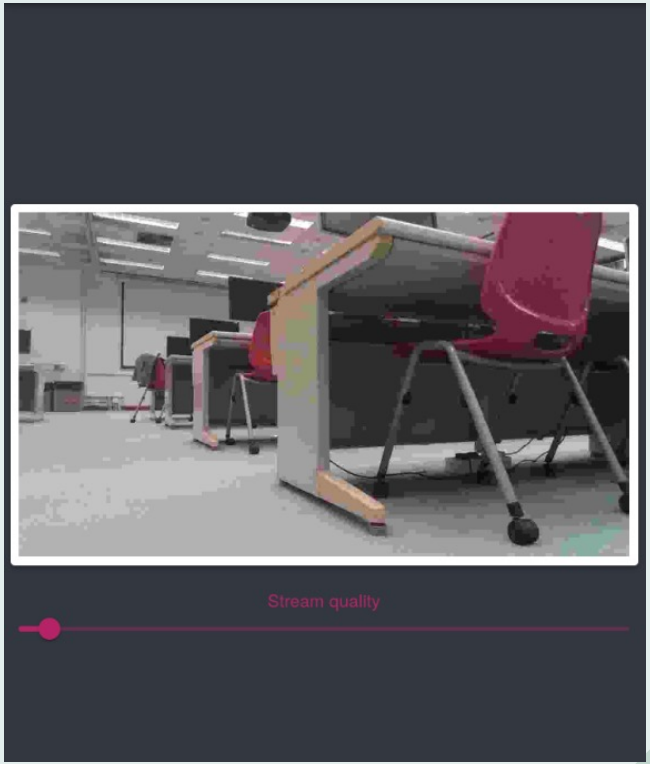
URDF web viewer

User Authentication

Push Notifications

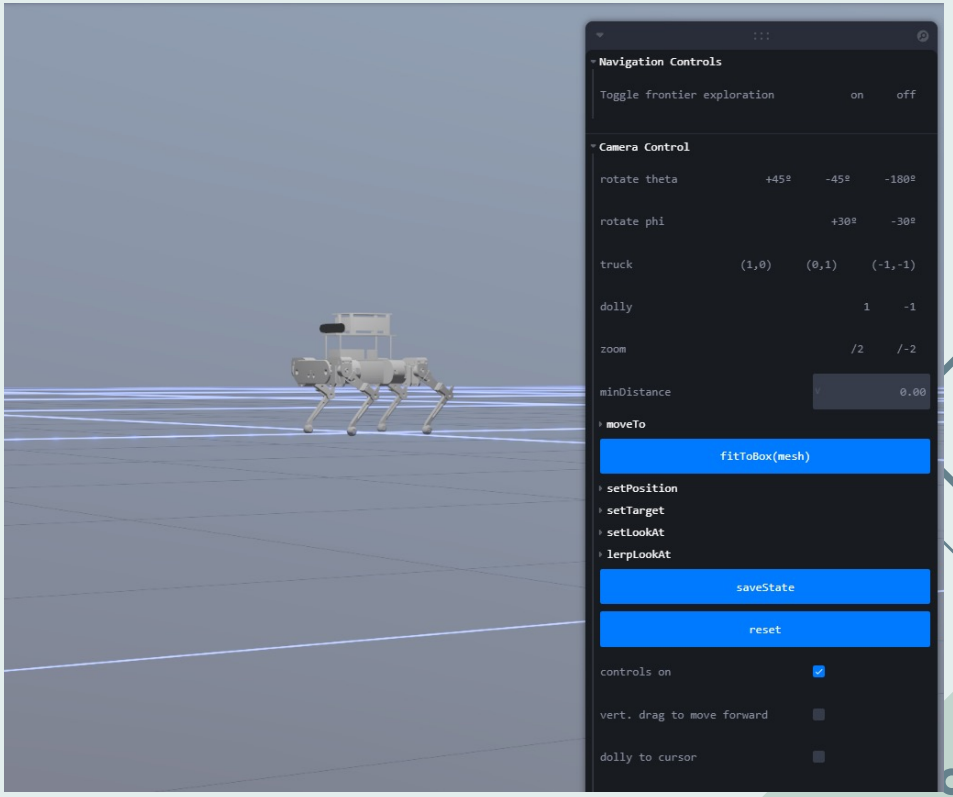
# Live Stream

- Showing the live images captured by the stereo camera of the robot using ROS packages web_video_server
- Allow adjustment of stream quality of the video playing
- Capture recording of the live and save it to local storage



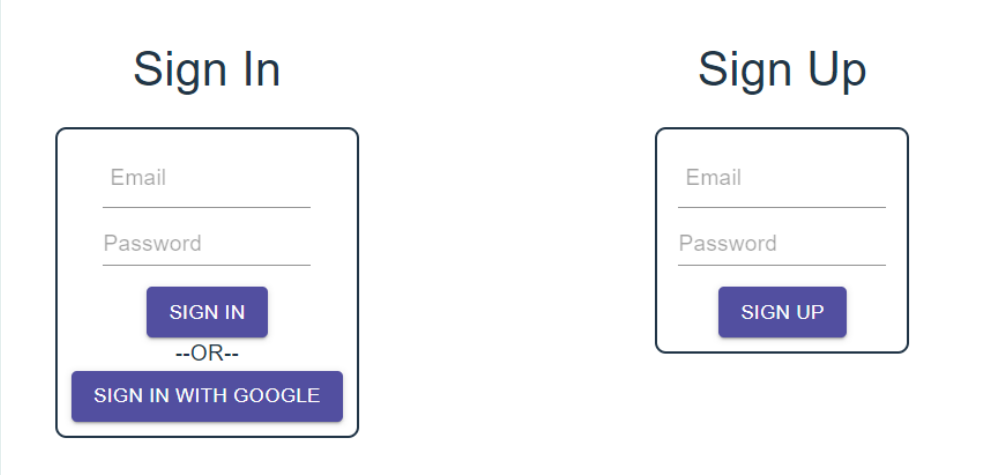
# URDF Web Viewer

- Dynamically update the robot using subscribed joint angle data
- Movements are replicated
- Control panel for adjusting view angle on screen



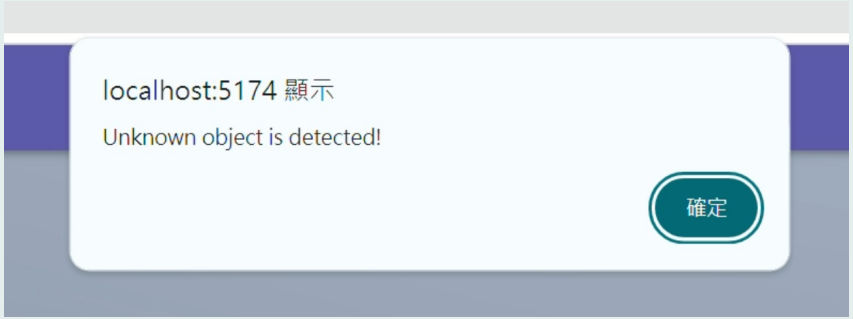
# User Authentication

- User registration and sign in functions
- Only signed in users can access the live-streaming video and 3D simulation
- ➔ Ensure data security & privacy



# Push Notifications

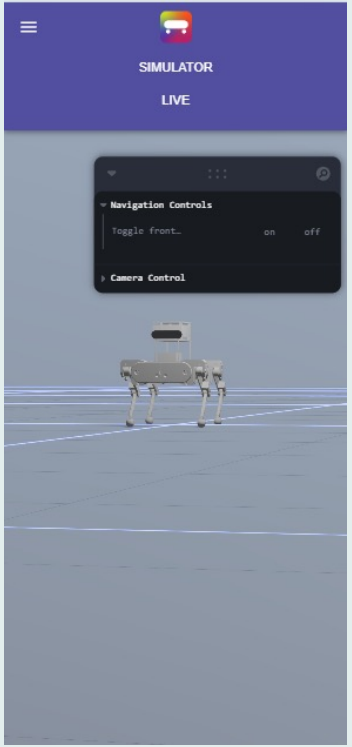
- Pop-up notifications when new objects detected



# Responsive Design

- Maximize contents to be included according to the orientation of the viewport


Desktop

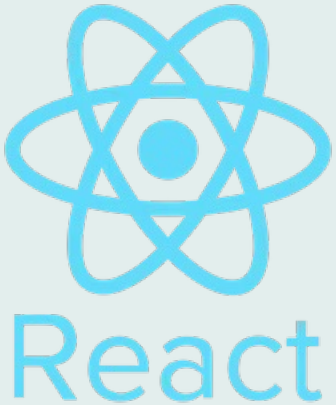



Mobile

# Technology

- **React**
  - A free and open-source front-end JavaScript library for building user interfaces based on components
  - **Advantages:**
    - Can reuse components (e.g. control, simulator)
    - High performance reinforced by virtual DOM

[12]



# Technology

[13]

- **ROS Web tools**
  - Provide web sockets as middleware
  - Subscribe to ROS nodes and get data
- **three.js**
  - Get 3D content on a webpage
  - Use WebGL graphics library to draw 3D
  - URDF loaders: load mesh and robot structures

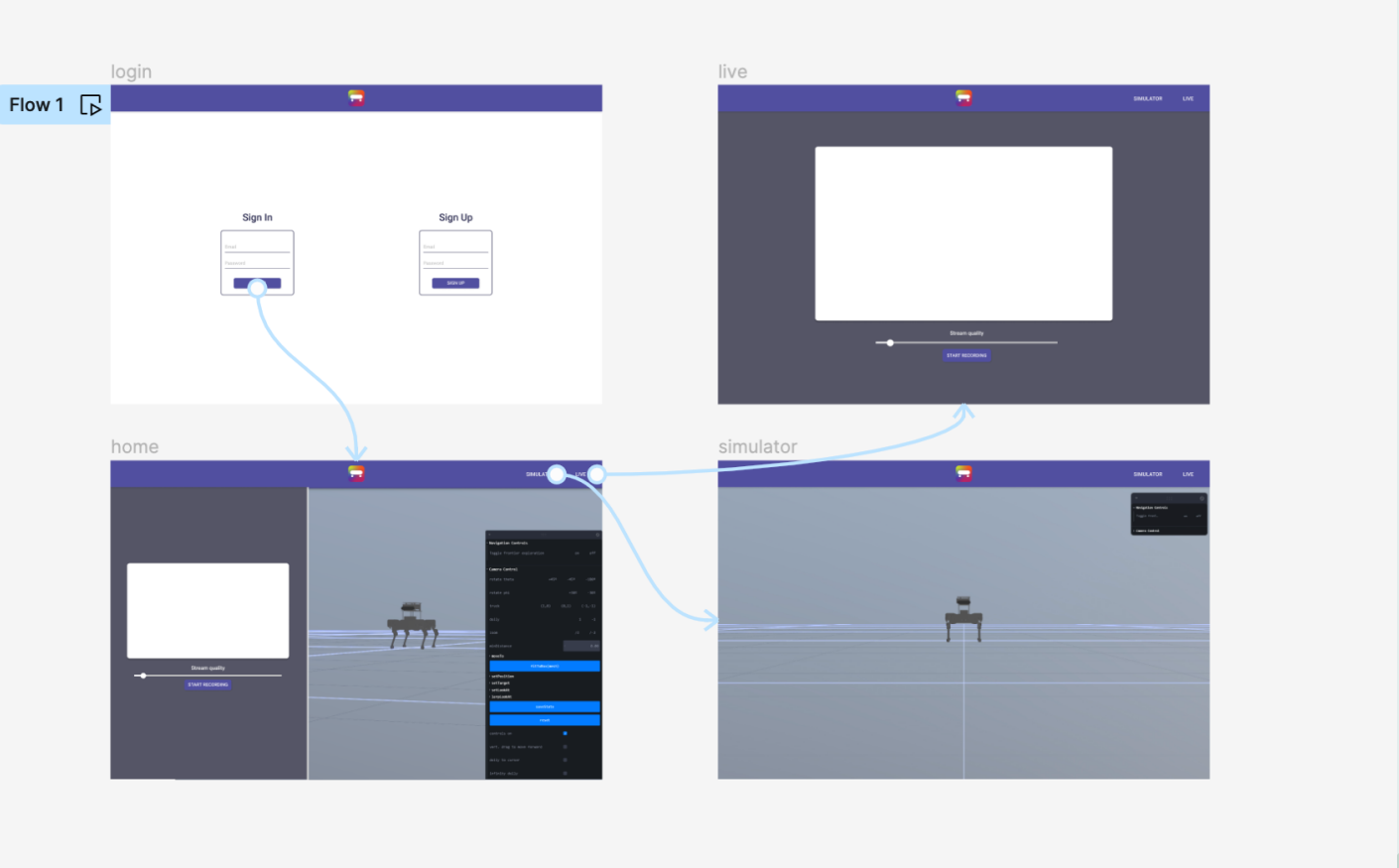
three.js

# Technology

[14]

- **Firebase**
  - An app development platform by Google
- **Firebase Authentication**
  - Provide backend services, easy-to-use SDKs & UI libraries for user authentication
  - Advantages:
    i. Easy setup
    ii. Wide range of sign-in providers/methods (e.g. email/password, Google login etc.)

# UI/UX Design


Flow 1
login
Sign In
Sign Up
live
SIMULATOR
LIVE
Stream quality
START RECORDING
home
Stream quality
START RECORDING
simulator
SIMULATOR
LIVE

# UI/UX Design

- **Intuitive navigation**
  - Top navigation bar
  - dragging to resize layout
  - Slider input
- **Cohesive Interface Design**
  - Unify color scheme
  - Material User Interface (MUI)

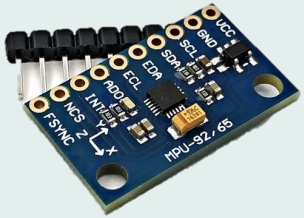
    → professional-looking elements

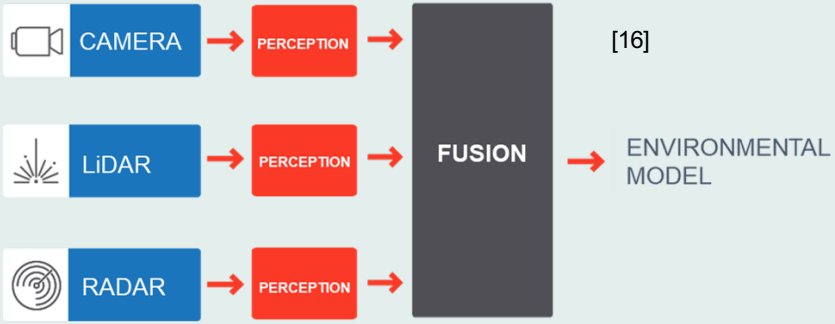
# 09

# Future work

# Odometry sources


[15]




[16]

- **MPU-9250:** DMP finds orientation well
- **Stereo Camera**: RGB-D information
- **Future work:** Sensor fusion - rely on multiple sensors (3D LiDAR); magnetometer...

# Actuators – Digital Motors

- **PWM servos:** good for precision control
- **Stalling** happens when the load is too much for the servos
- Servos will ***overheat*** and burn out
- **Future work:** use DC motors with high torque

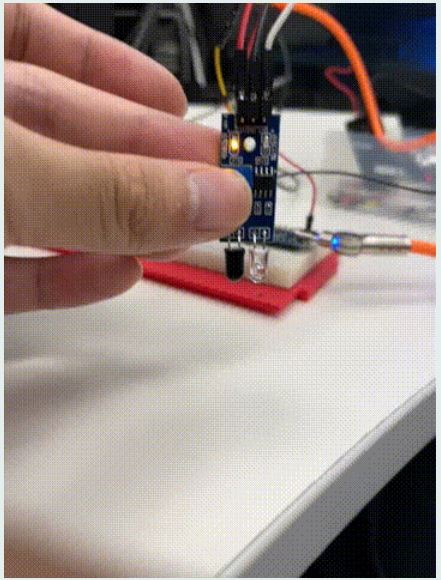

MG996R


TD-8135MG

# Actuators – Digital Motors

- **Brushless Motor:** control speed using PWM or CAN signals
- **Motor encoder:** find current motor position
- **PID**: find signal from positional error
- **Modelling:** redesign motor housing on the robot

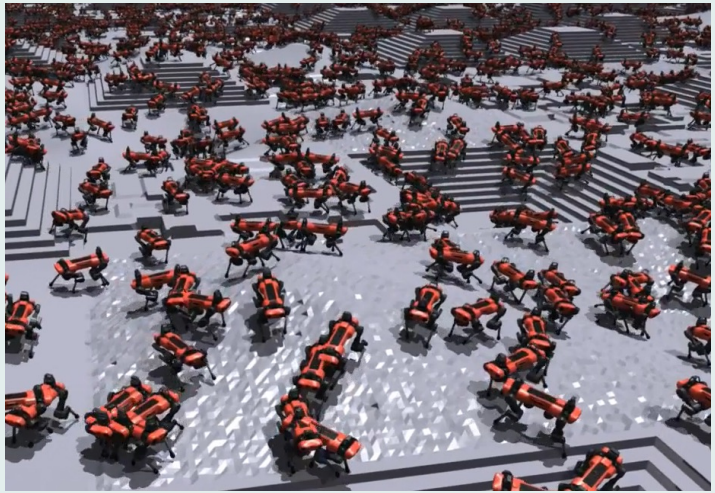
# Foot Sensors



Infrared sensor demo

- **Foot sensors**: give feedback to CHAMP
- **Challenge**: finding suitable sensors + redesigning legs
- **Alternative:** as the software is hardware agnostic, just try out another model.

# Motion planning - Deep learning

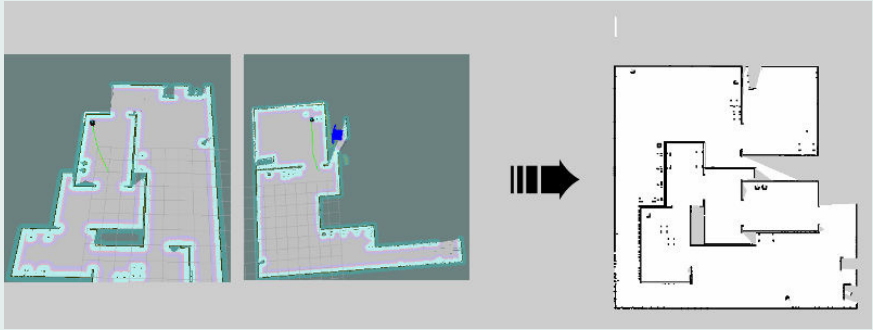


[18]

- **Challenge:** Quadrupeds have 12 DoFs, motion planning is a high-dimensional problem
- **Rough terrain:** many foot configurations to consider...
- **Reinforcement + Deep learning**: physical simulation using robot URDF
- **Nvidia Issac Gym:** GPU accelerated simulation

# Swarm robots

[19]

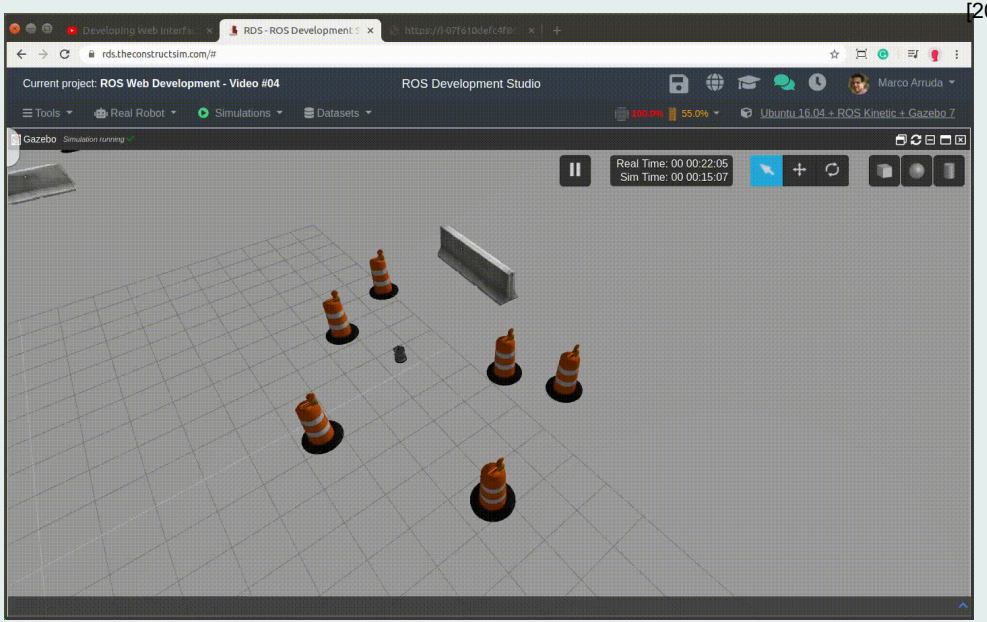


- **Idea**: have a few lighter robots to sense the environment and send data to a central machine
- **m-explore**: ROS2 package implementing SLAM map merging and frontier exploration
- **Web dashboard:** extend it to handle multiple robots

# Web Application

- **Integrate currently command-line controls**:
  - object detection
  - human tracking
  - Robot configuration
- **UI/UX upgrade**:
  - more cohesive design
- **Develop native mobile application:**
  - React Native

[20]



# THANKS!

# Q&A

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