CNMAC 2022
XLI Congresso Nacional de Matemática Aplicada e Computacional

Topics in Applied Machine Learning:
A Hands-on Approach – MS12 (Vibration)

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UNIFEI - Universidade Federal de Itajubá, Brazil

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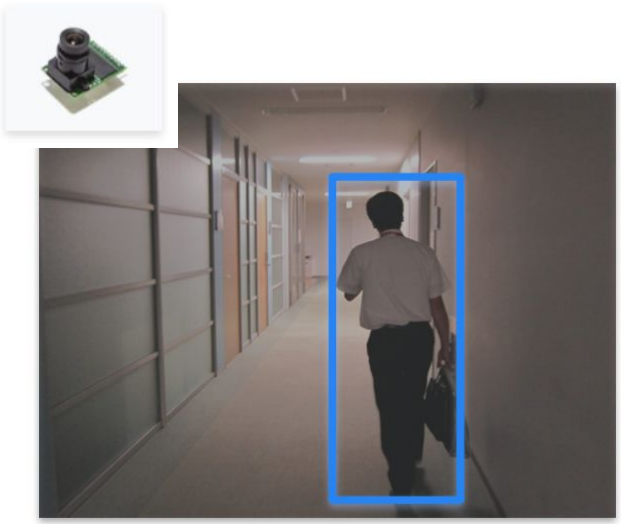
Harvard University, USA

Sound

Vibration

Vision



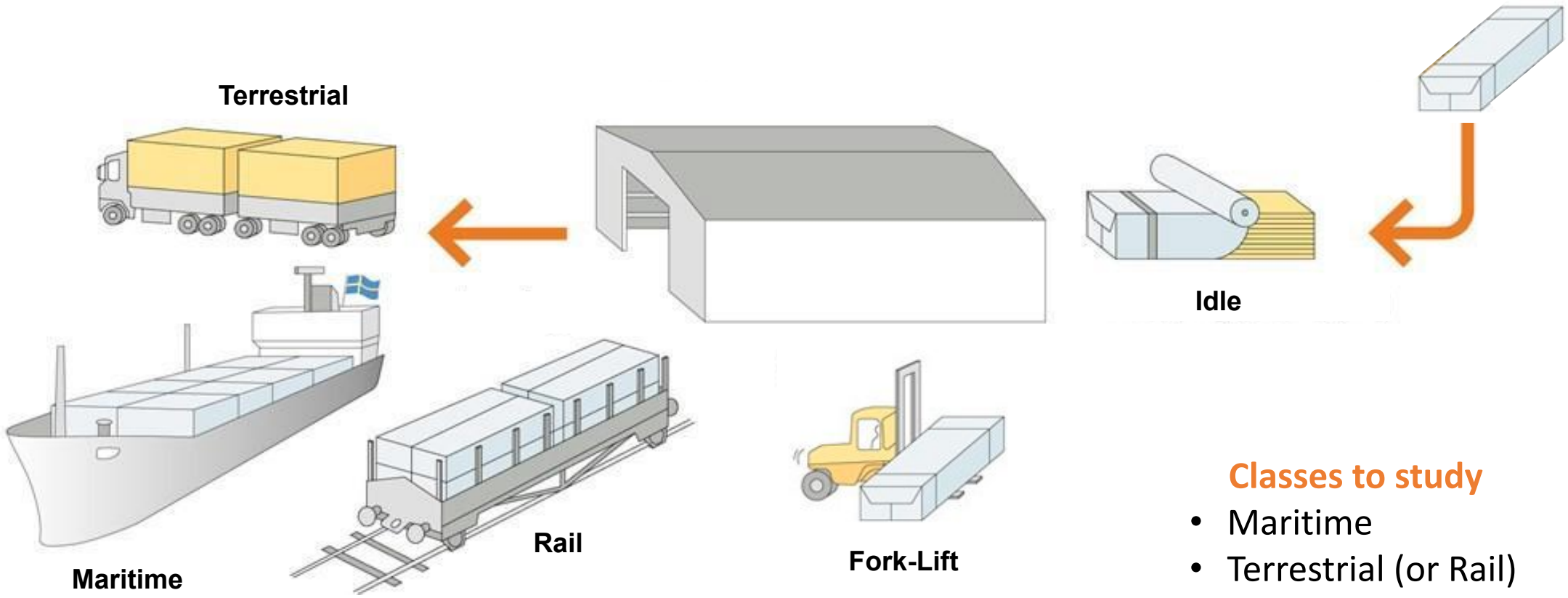
Sound

Vibration

Vision

Motion Classification

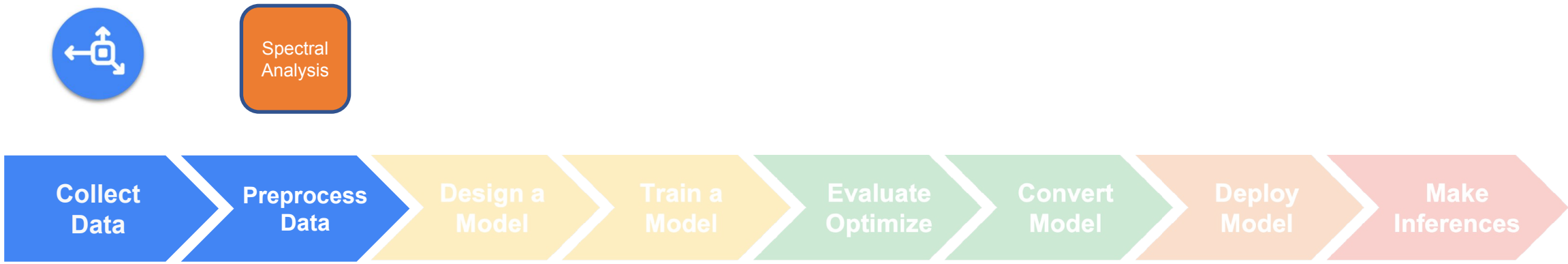
Case Study: Mechanical Stresses in Transport



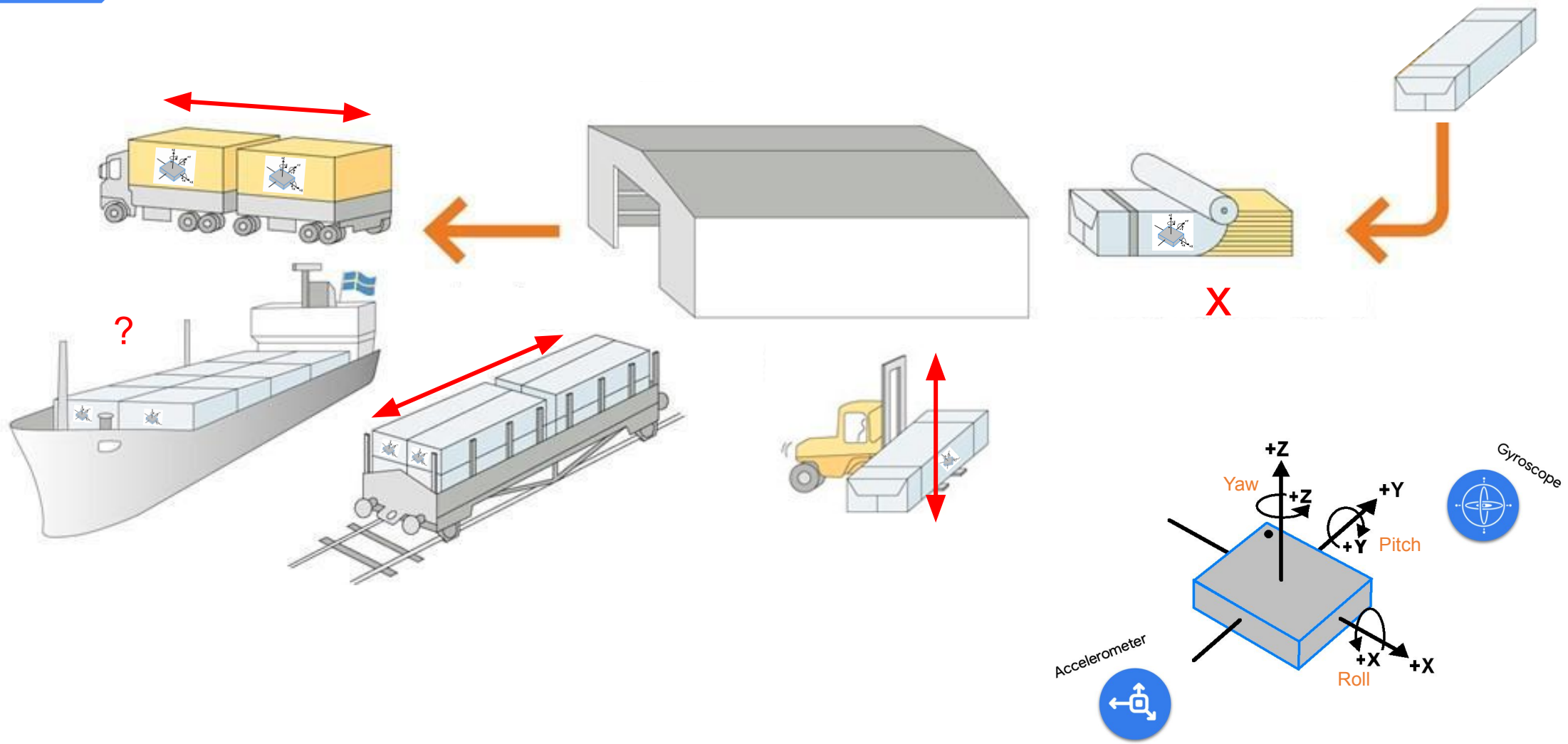
Classes to study

- Maritime
- Terrestrial (or Rail)
- Lift
- Idle

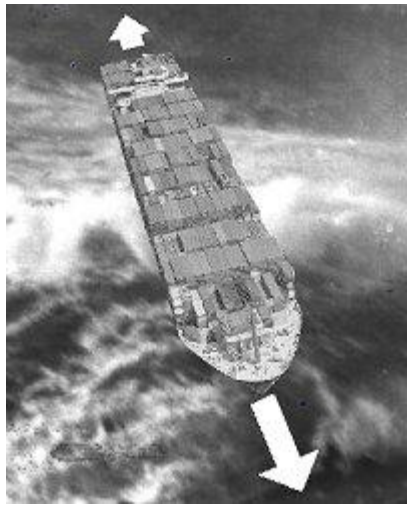
Data Pre-Processing

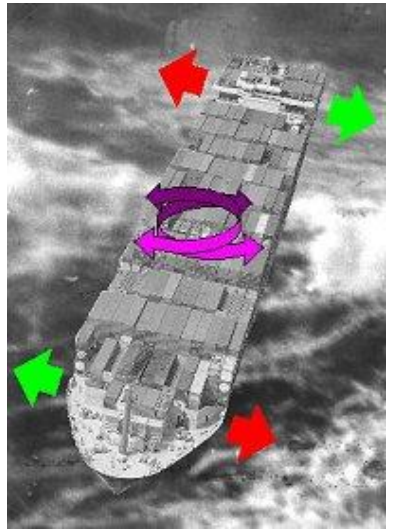


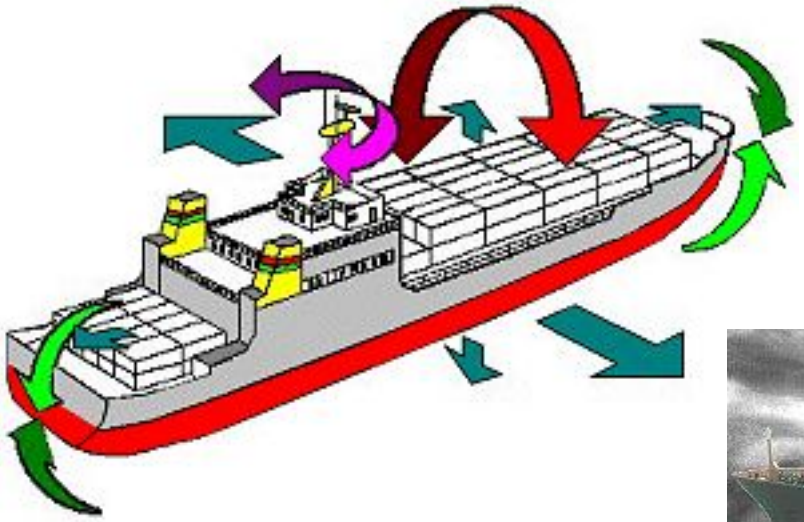
Collect Data

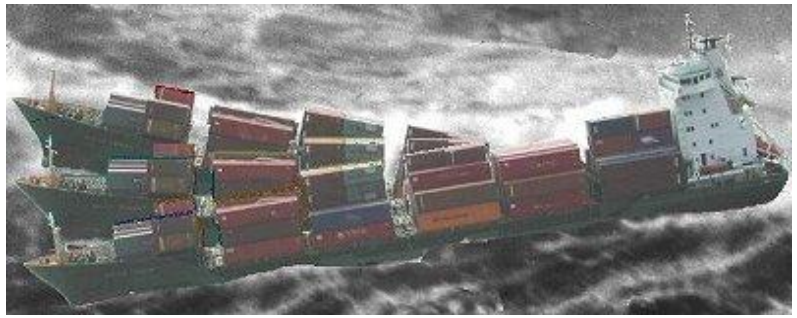


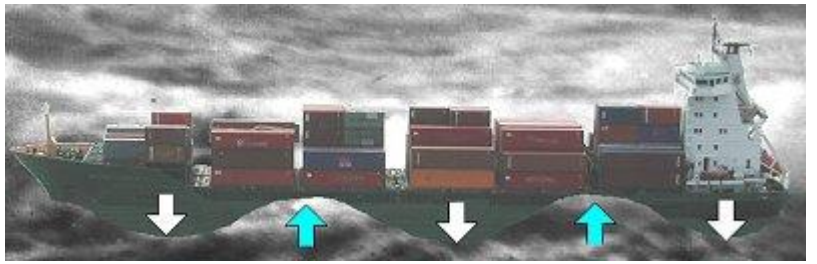
Mechanical Stresses in Maritime Transport





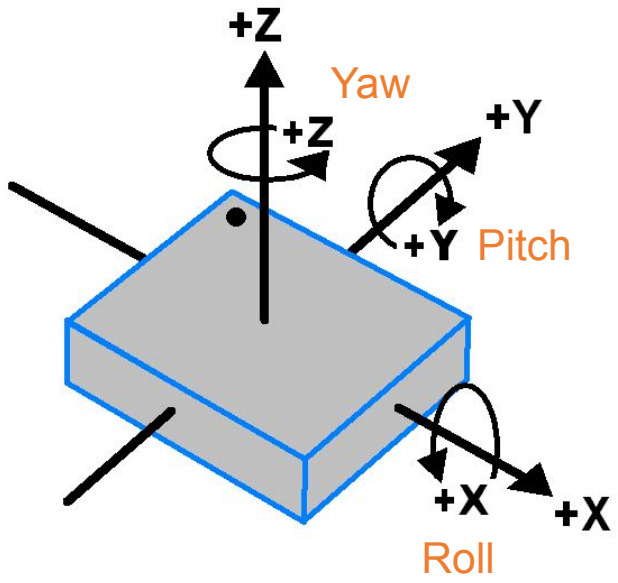


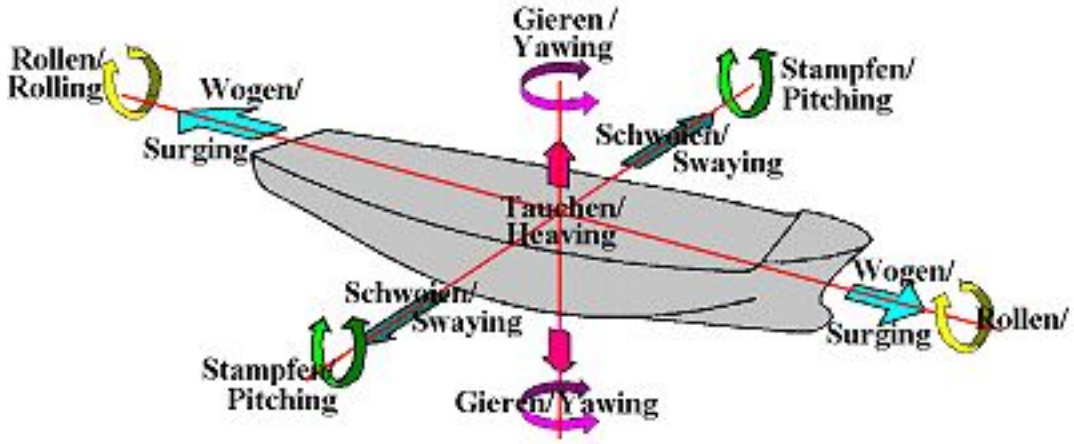




https://www.containerhandbuch.de/chb_e/stra/index.html?/chb_e/stra/stra_02_03_03.html

Mechanical Stresses in Maritime Transport





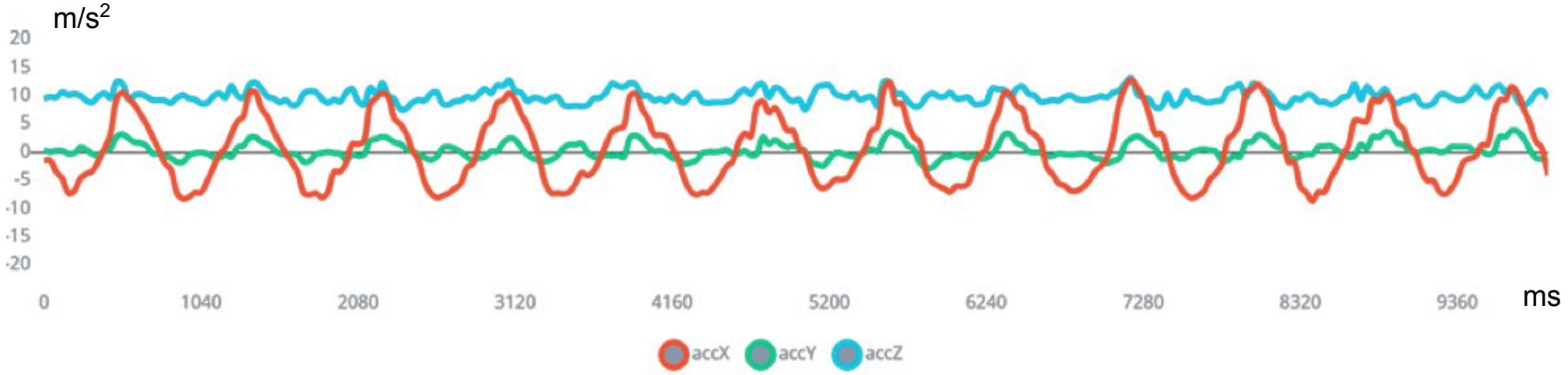
Accelerometer

Gyroscope

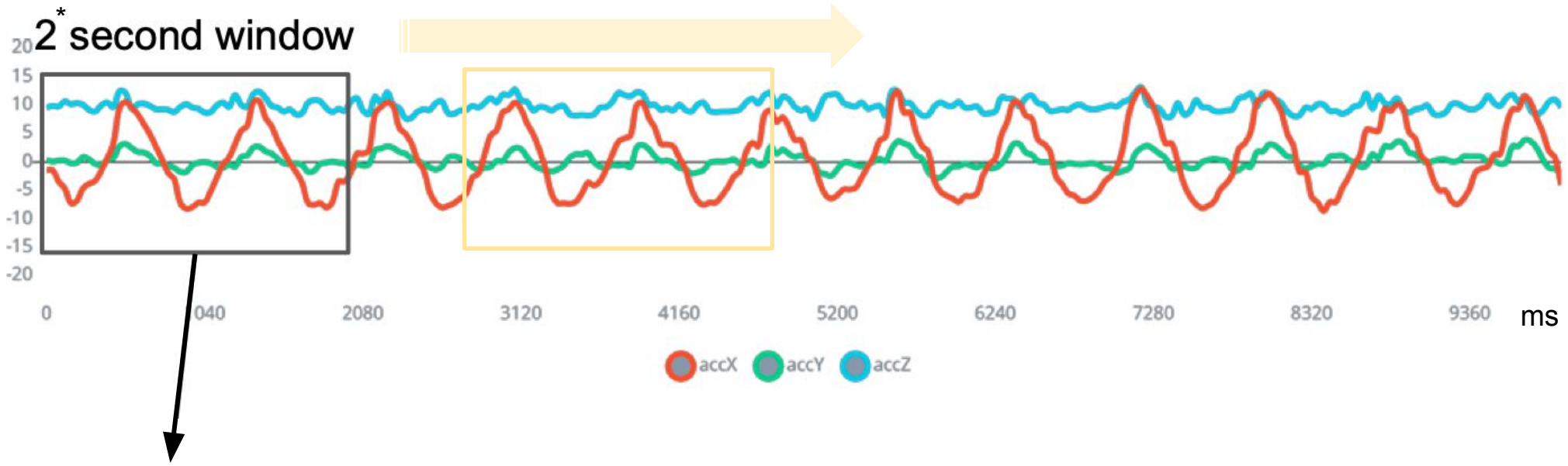
	Linear motion	Rotational motion	
X	Surging is motion along the longitudinal axis.	Rolling is motion around the longitudinal axis.	Roll
Y	Swaying is motion along the transverse axis.	Pitching is motion around the transverse axis.	Pitch
Z	Heaving is motion along the vertical axis.	Yawing is motion around the vertical axis.	Yaw

Summary of ship movement

Example: 10 seconds of accelerometer data, captured with a sample rate: 62.5 Hz




Window
20
15
10
5
0
-5
-10
-15
-20
0
1040
2080
3120
4160
5200
6240
7280
8320
9360
ms
accX
accY
accZ

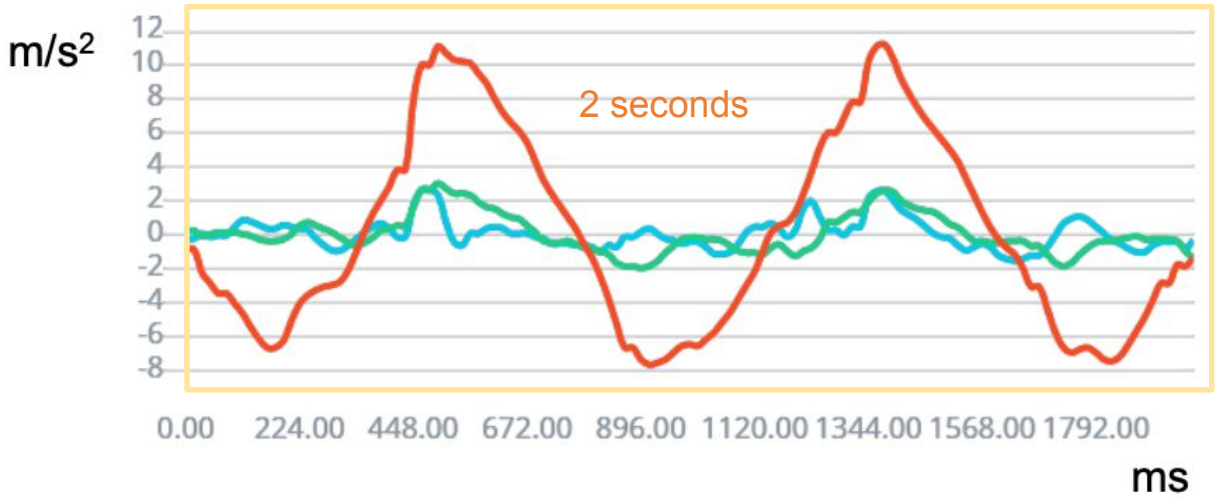


Raw Features as a window

- 125** samples for each axis (62.5Hz x 2s)
- 375 total features (125 x 3 axis)

* 2 seconds is needed to capture 1 or 2 cycles of movement

** 2 seconds at sample rate of 62.5 Hz -> 125 samples



Manual Feature Extraction

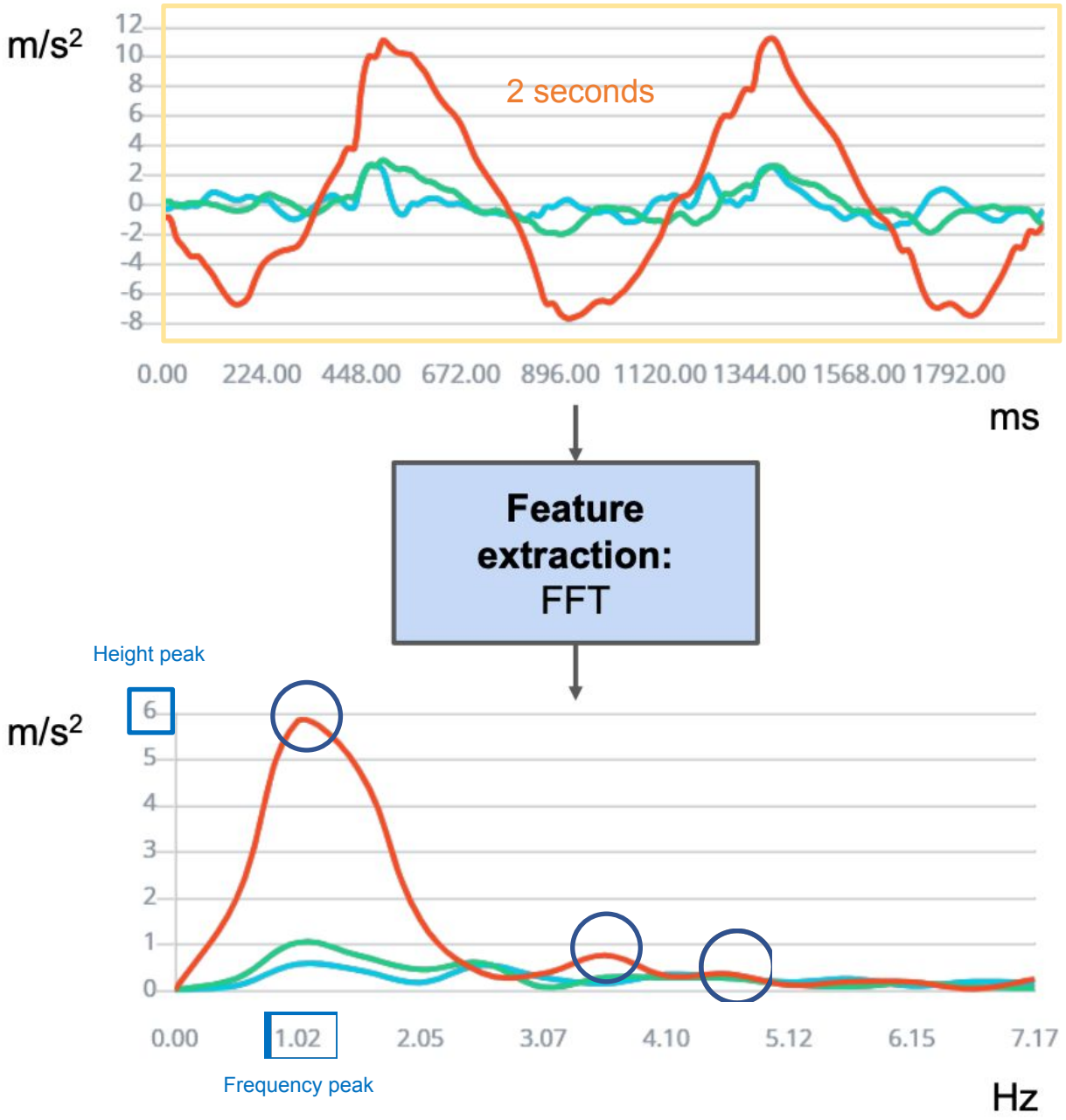
3 RMS (Root Mean Square) values

- one for each axis (x, y, z)

$$x_{\mathrm{RMS}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}.$$

125

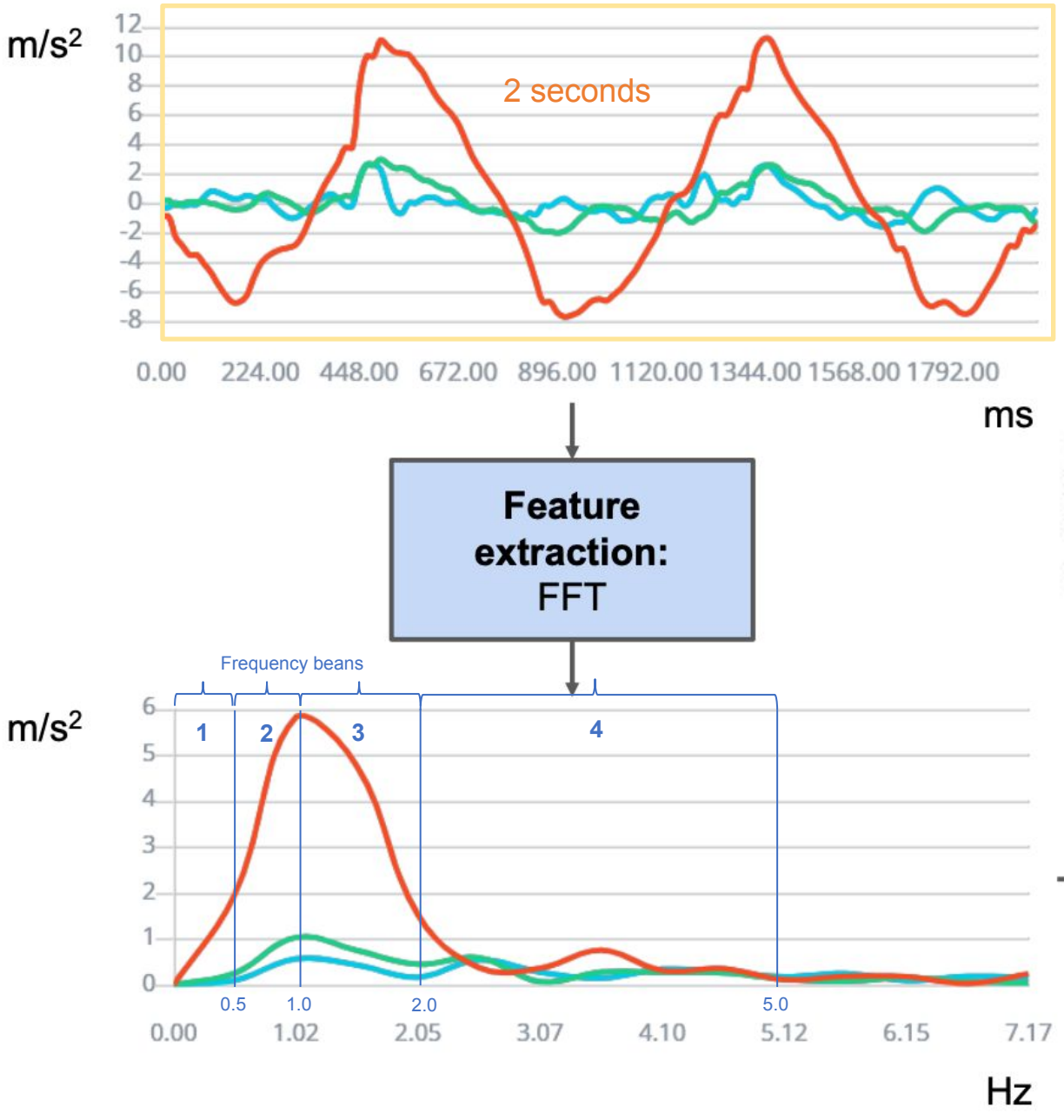
Manual Feature Extraction



3 RMS

9 Height + **9** Freq. peak values

Manual Feature Extraction



3 RMS + **9** HP + **9** FP + **12** PSD values

4 Frequency bins per axix

Feature extraction: PSD

https://blog.endaq.com/why-the-power-spectral-density-psd-is-the-gold-standard-of-vibration-analysis

Sliding Window: 80 ms

375 Raw Features

- Raw Data from sensor

Manual Feature Extraction

Spectral Analysis

11 Features

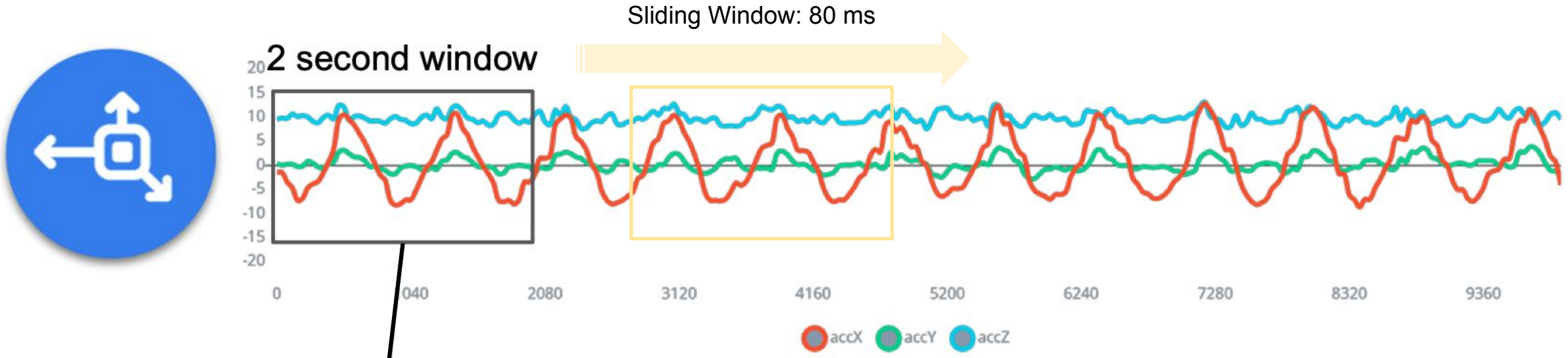
11 Features

11 Features

accX RMS
accX Peak
accX Peak
accX Peak
accX Peak
accX Peak
accX Spec
accX Spec
accX Spec
accX Spec

accY RMS
accY Peak
accY Peak
accY Peak
accY Peak
accY Peak
accY Spec
accY Spec
accY Spec
accY Spec

accZ RMS
accZ Peak 1 Freq
accZ Peak 1 Height
accZ Peak 2 Freq
accZ Peak 2 Height
accZ Peak 3 Freq
accZ Peak 3 Height
accZ Spectral Power 0.1 - 0.5
accZ Spectral Power 0.5 - 1.0
accZ Spectral Power 1.0 - 2.0
accZ Spectral Power 2.0 - 5.0



375 Raw Features

- Raw Data from sensor

Manual Feature Extraction

Spectral Analysis

33 Features

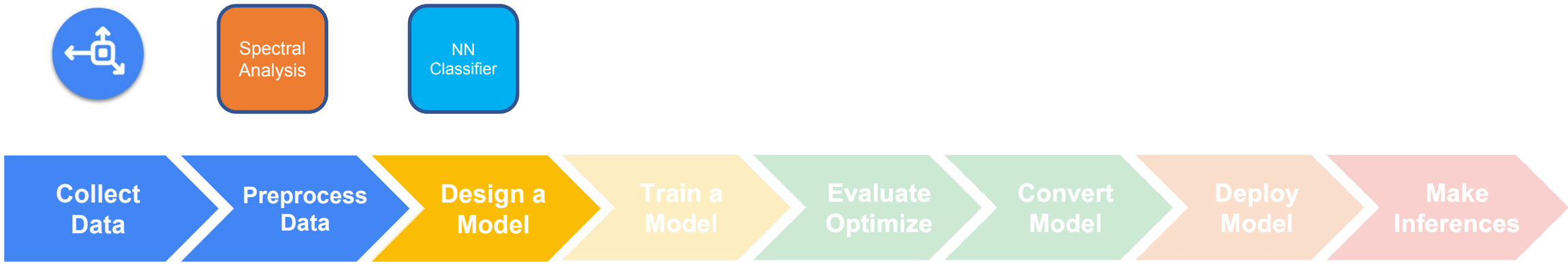
- RMS
- FFT
- PSD

NN Classifier

Classes

- Lift
- Terrestrial
- Maritime
- Iddle

Model Design (NN Classifier)



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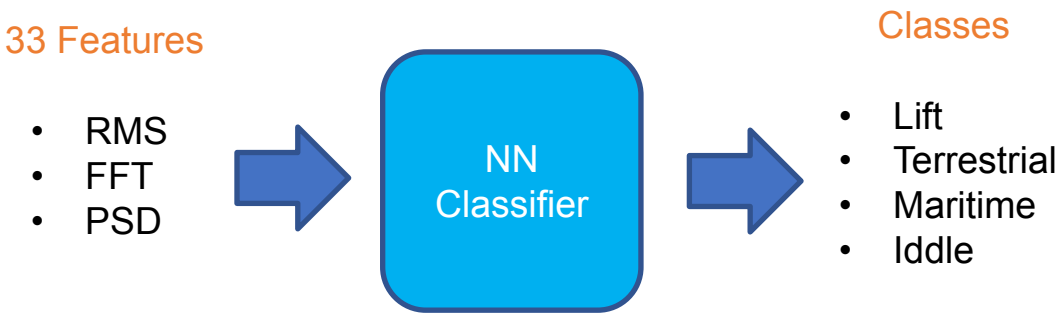
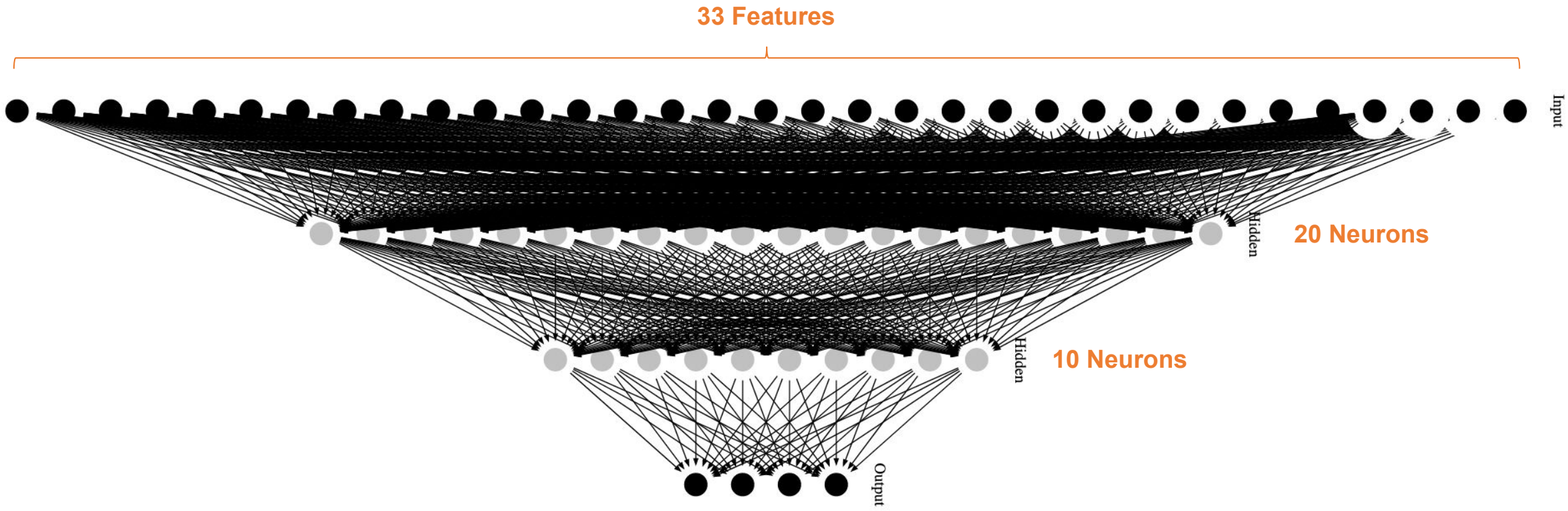
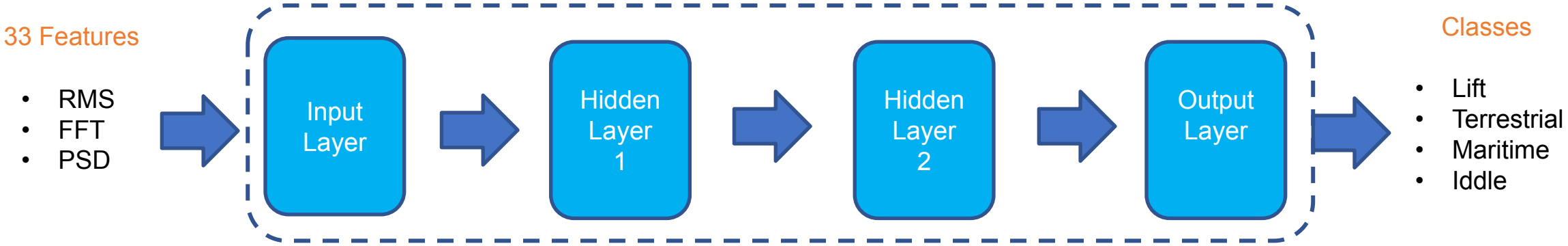


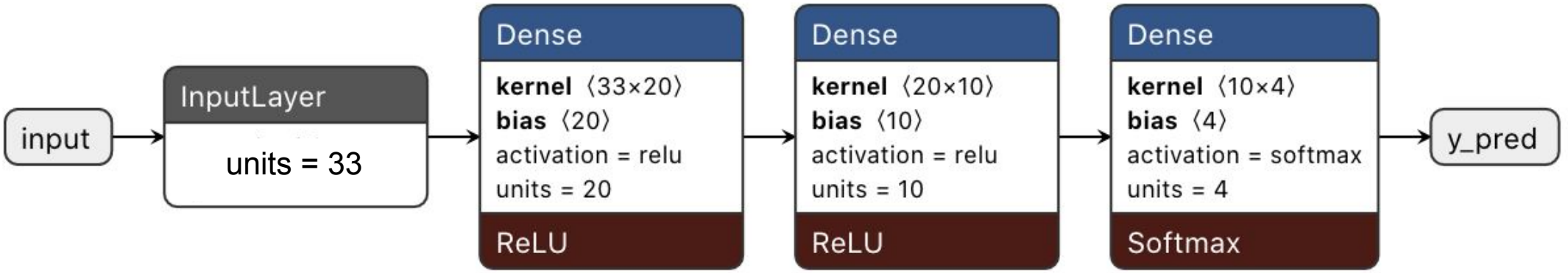
Model Design (DNN Classifier)

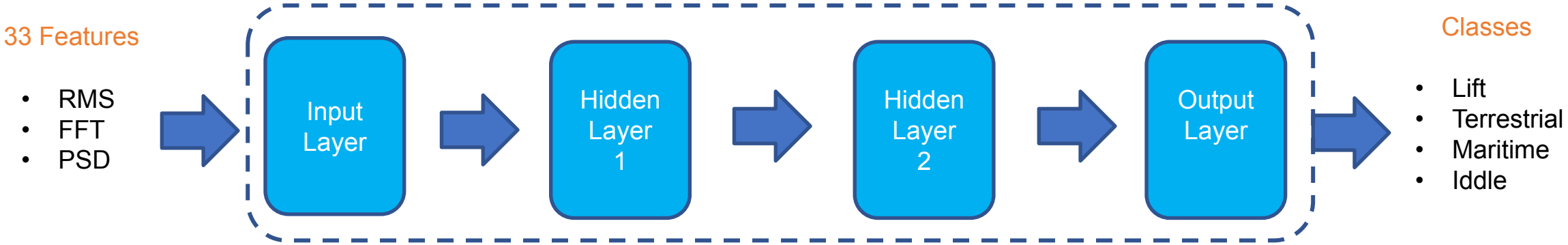


Model Design (DNN Classifier)

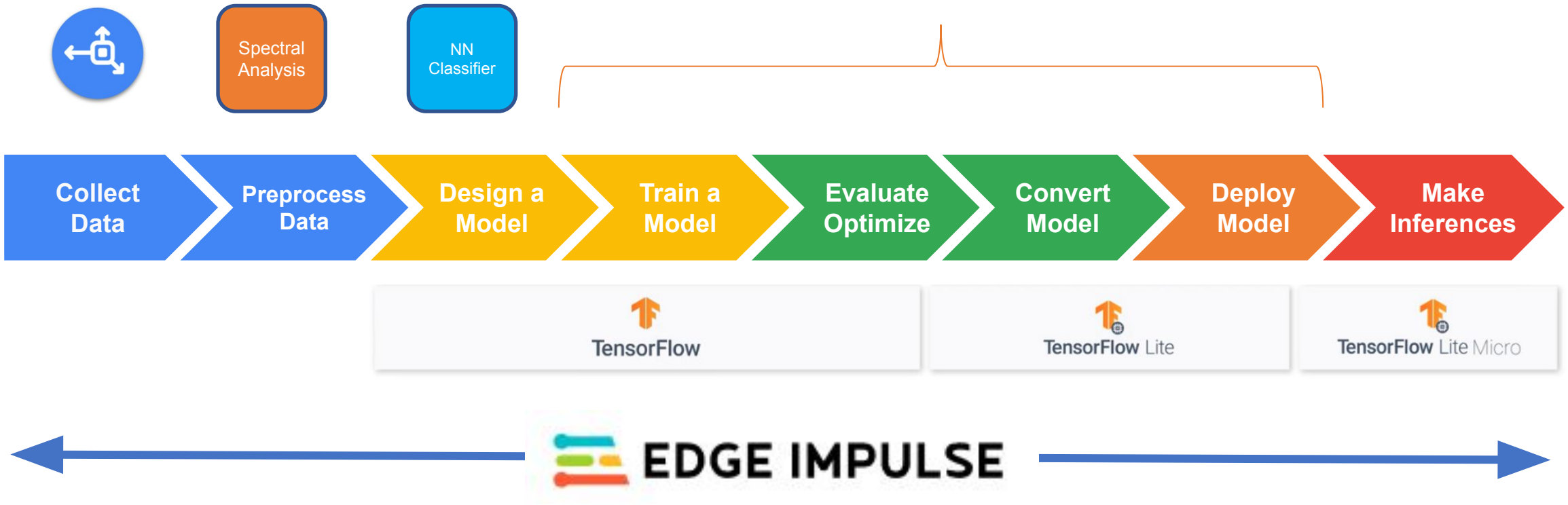


Model Design (DNN Classifier)





Train, Evaluate, Convert, Deploy the Model



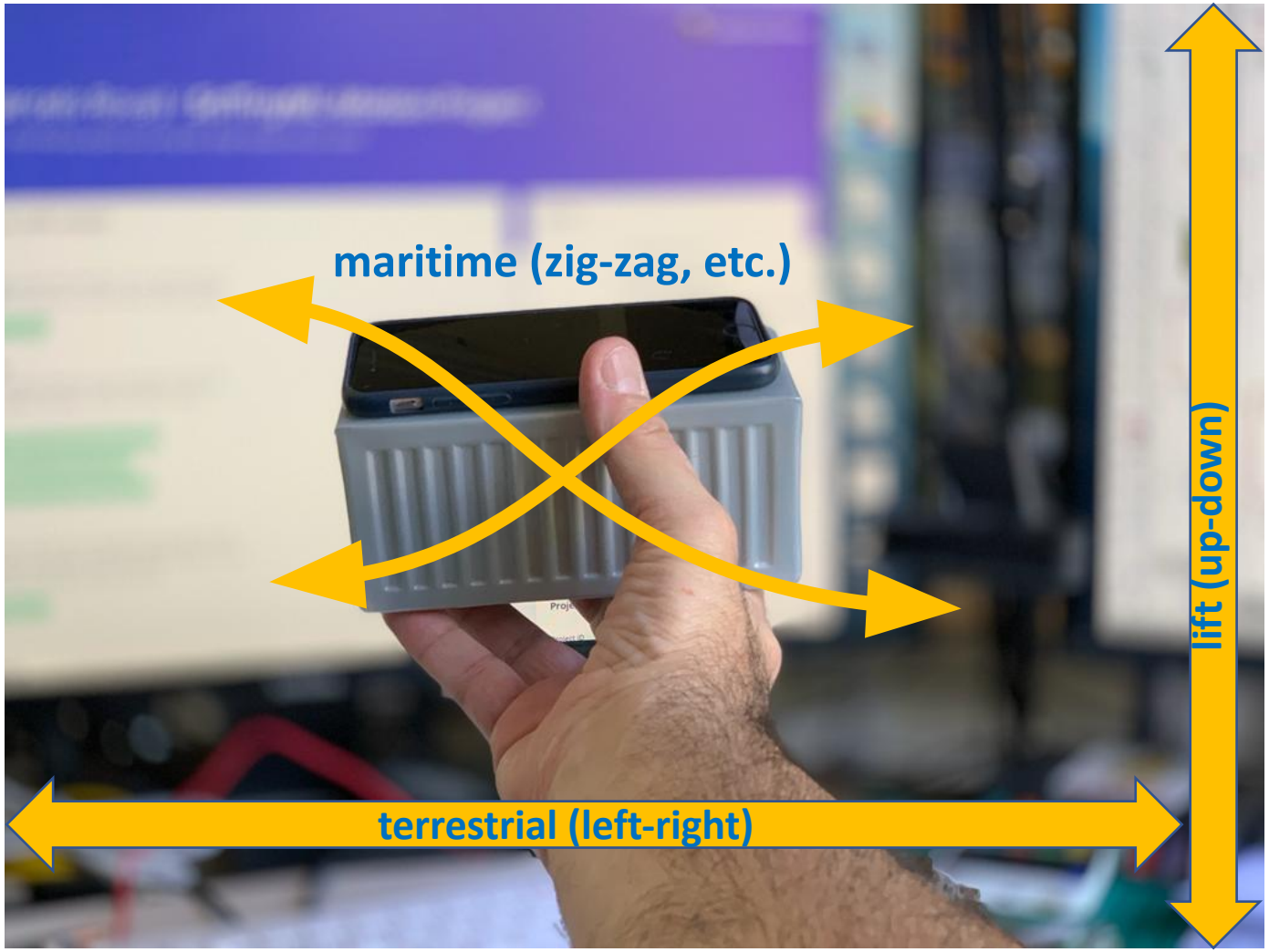
Motion Classification
Hands-On

https://studio.edgeimpulse.com/public/139905/latest

Motion Classification

Transportation Classes

- **lift** (up-down)
- **terrestrial** (left-right)
- **maritime** (zig-zag, etc.)
- **idle**



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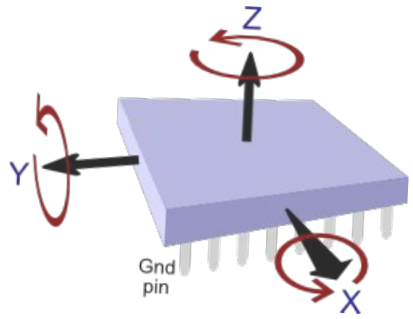
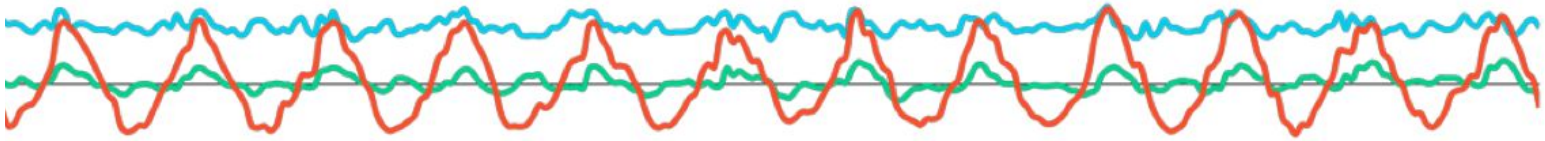
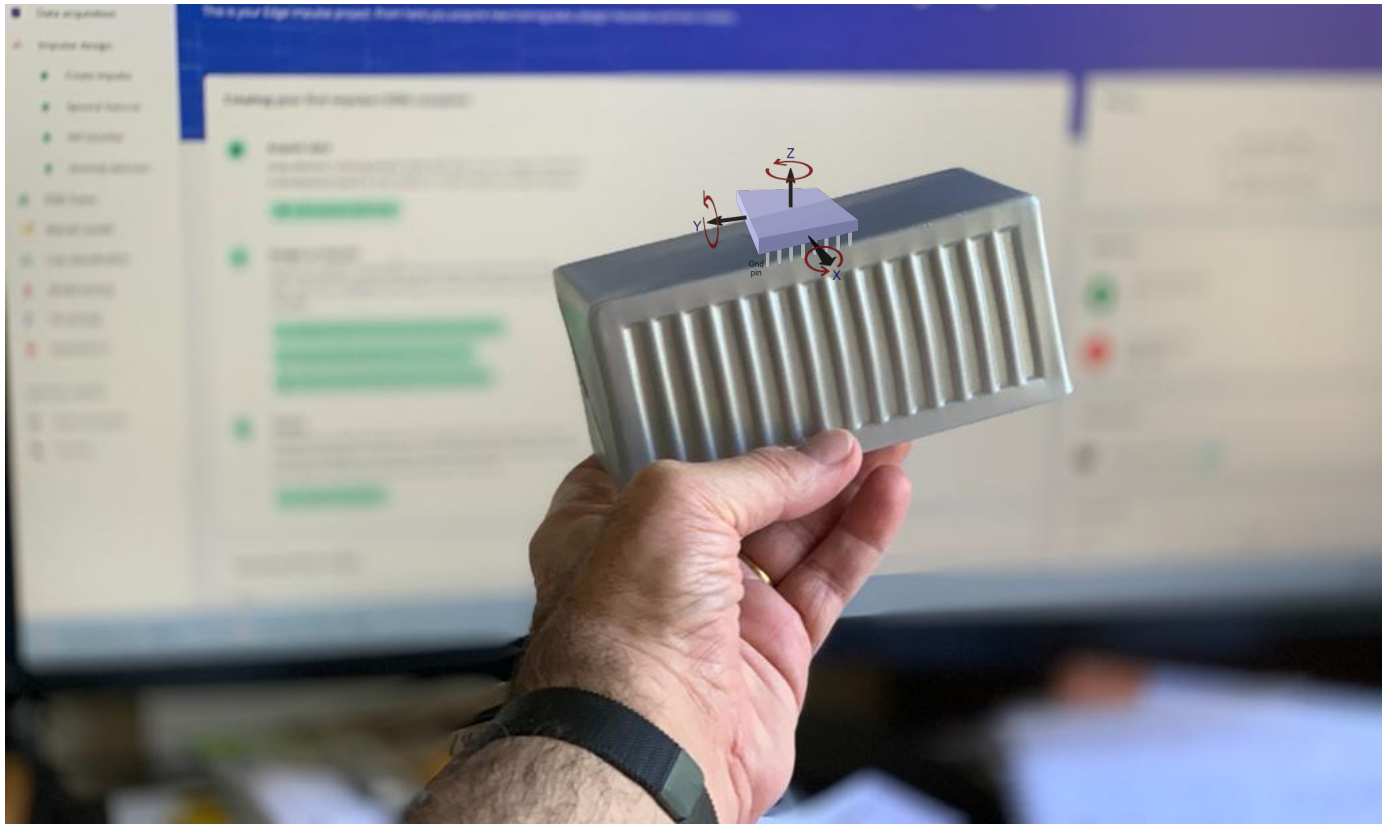
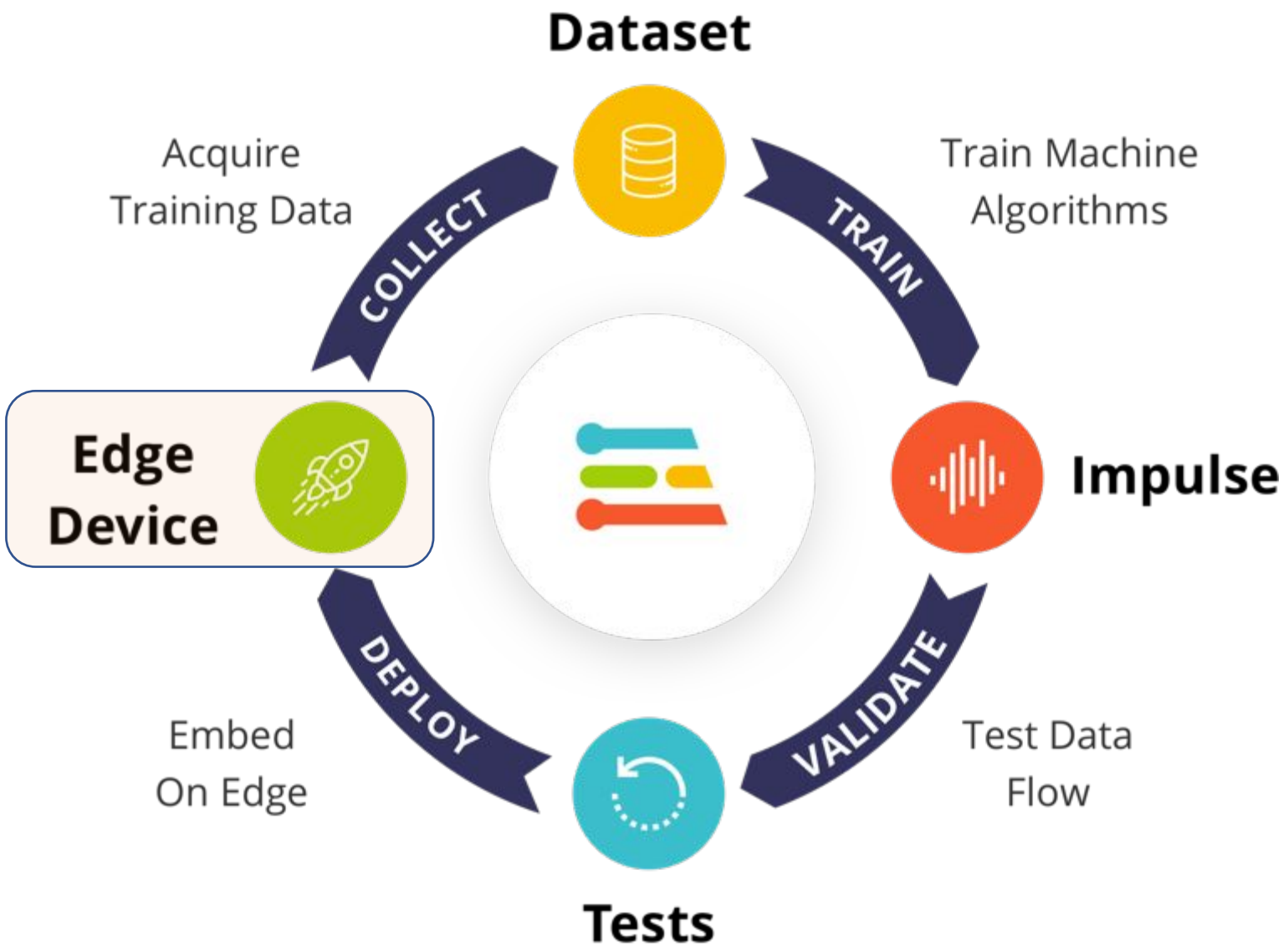


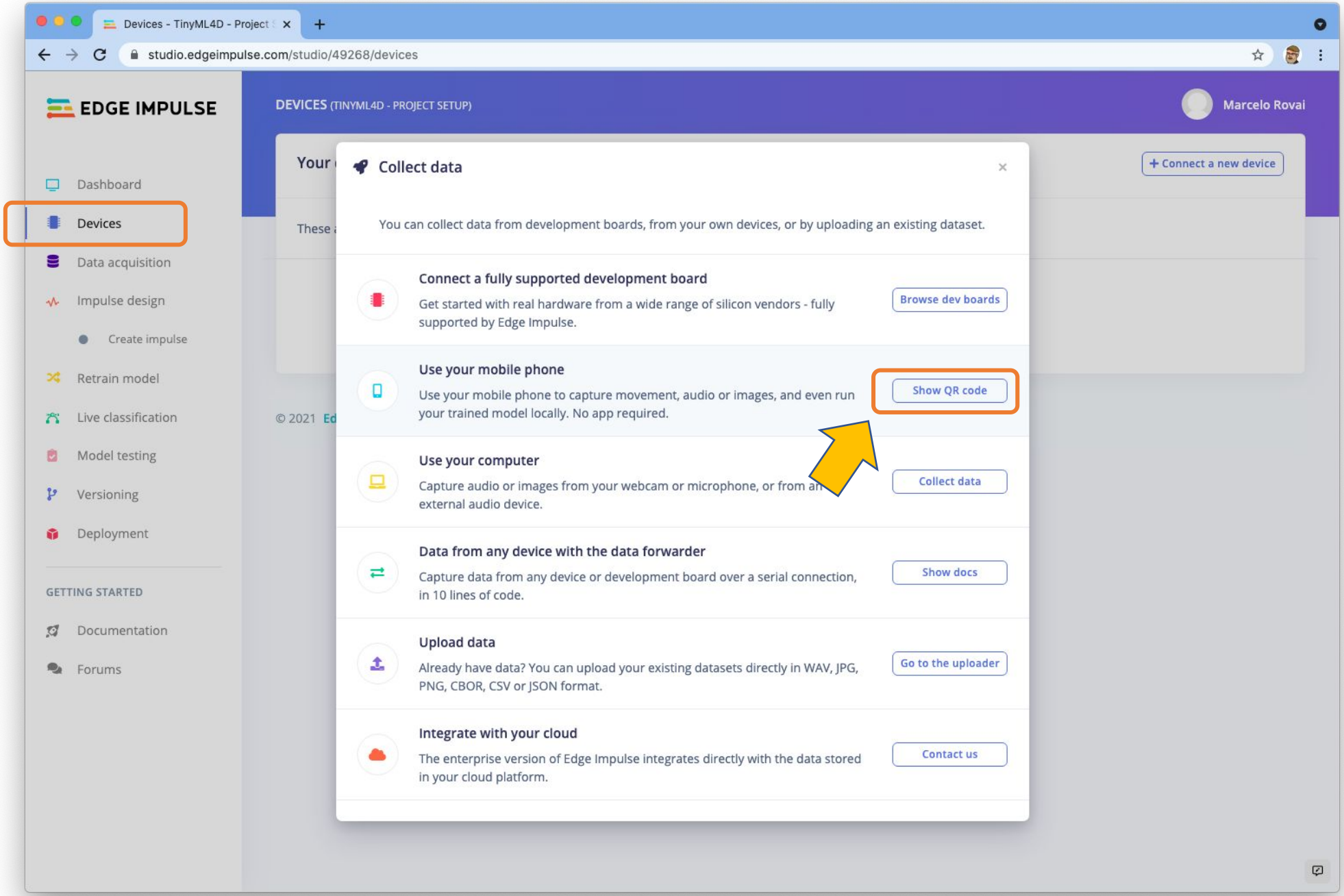




Data: collect & test using accelerometer as sensor



- Pre-Processing Data
- Design a Model
- Train a Model


Devices - TinyML4D - Project
studio.edgeimpulse.com/studio/49268/devices
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DEVICES (TINYML4D - PROJECT SETUP)
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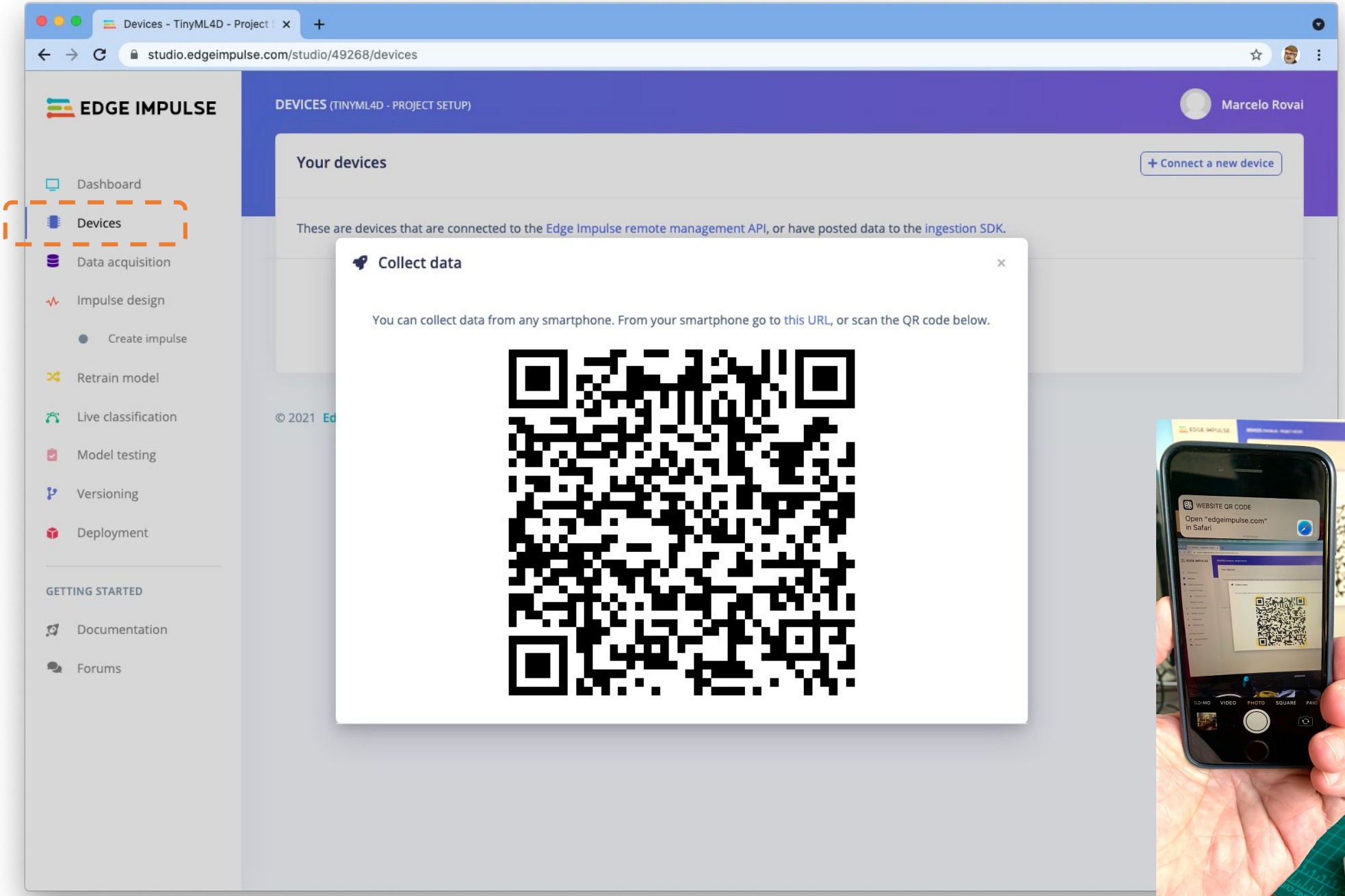
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
+ Connect a new device
Collect data
You can collect data from development boards, from your own devices, or by uploading an existing dataset.
Connect a fully supported development board
Get started with real hardware from a wide range of silicon vendors - fully supported by Edge Impulse.
Browse dev boards
Use your mobile phone
Use your mobile phone to capture movement, audio or images, and even run your trained model locally. No app required.
Show QR code
Use your computer
Capture audio or images from your webcam or microphone, or from an external audio device.
Collect data
Data from any device with the data forwarder
Capture data from any device or development board over a serial connection, in 10 lines of code.
Show docs
Upload data
Already have data? You can upload your existing datasets directly in WAV, JPG, PNG, CBOR, CSV or JSON format.
Go to the uploader
Integrate with your cloud
The enterprise version of Edge Impulse integrates directly with the data stored in your cloud platform.
Contact us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Collect data
You can collect data from any smartphone. From your smartphone go to this URL, or scan the QR code below.
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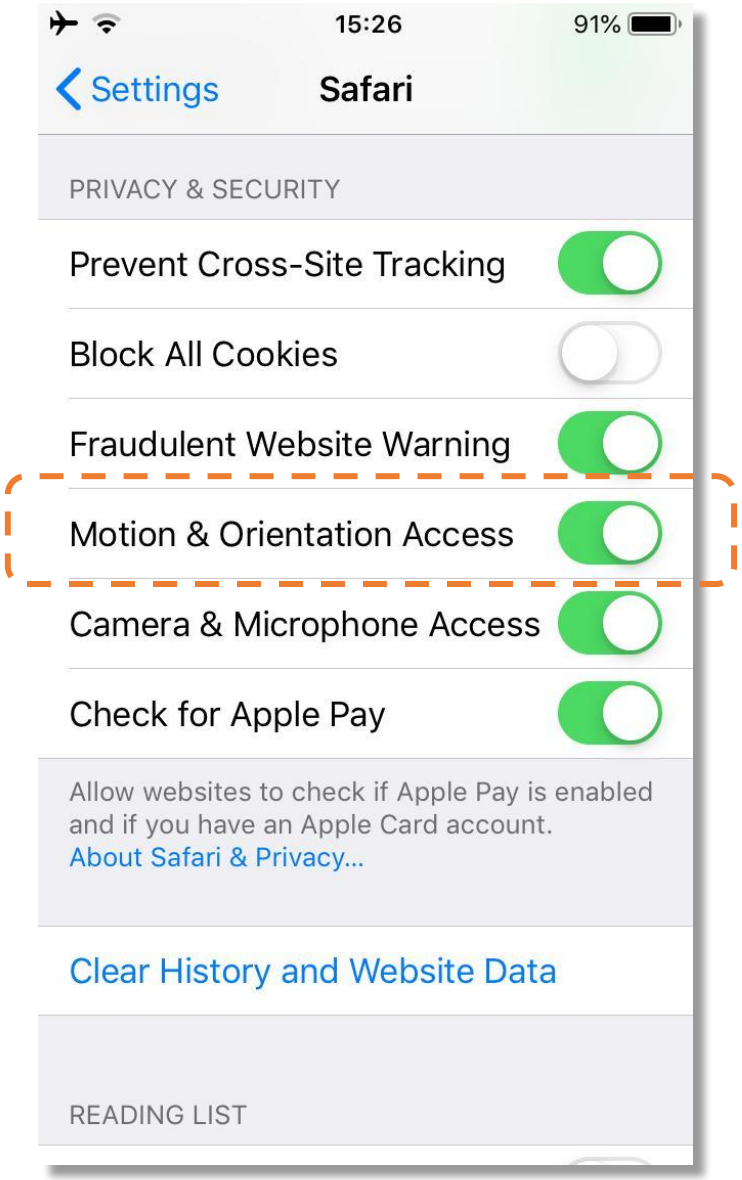
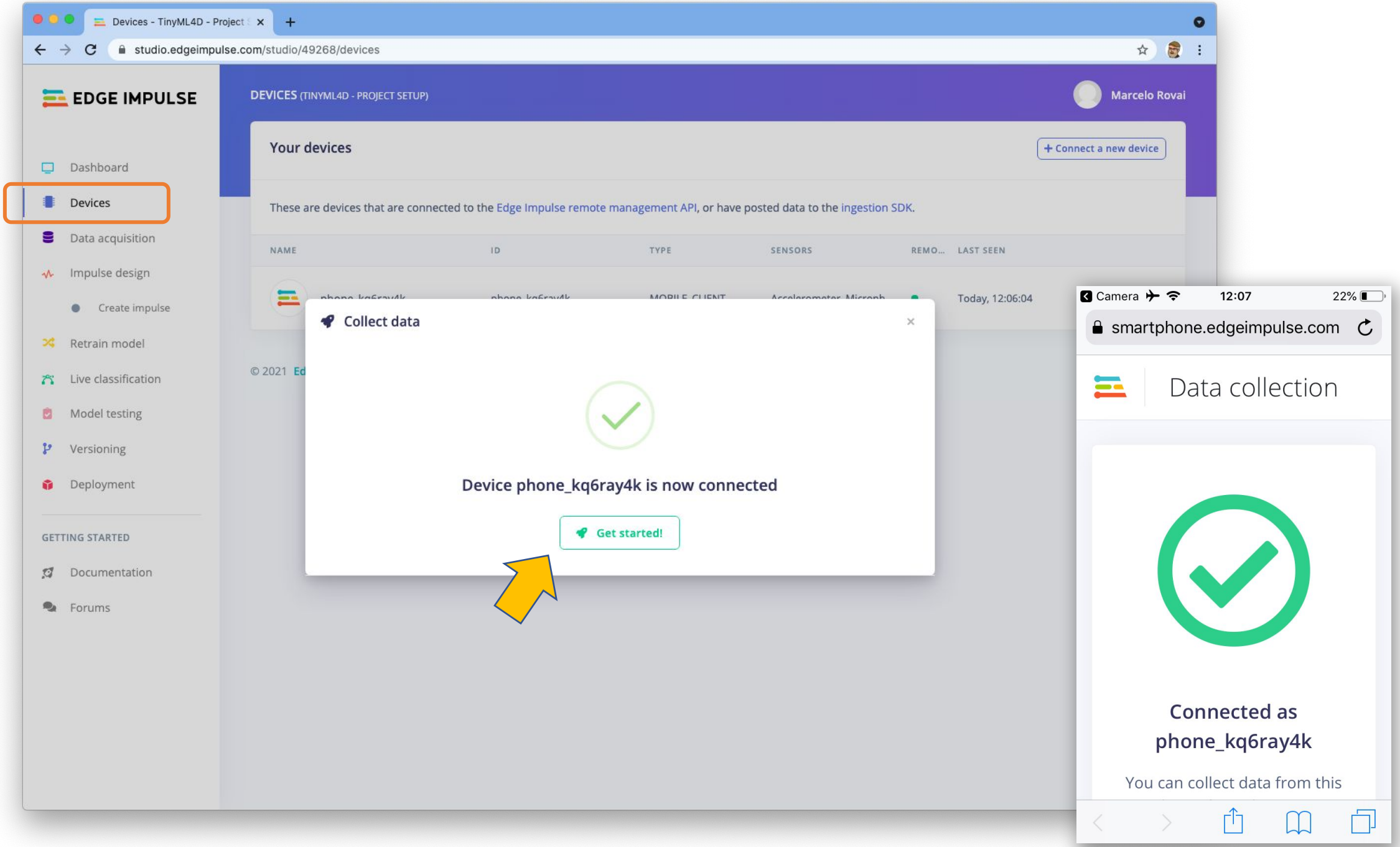
WEBSITE QR CODE
Open "edgeimpulse.com" in Safari



Depending on your mobile OS version and/or your Browser, could be necessary to give access to device IMU sensor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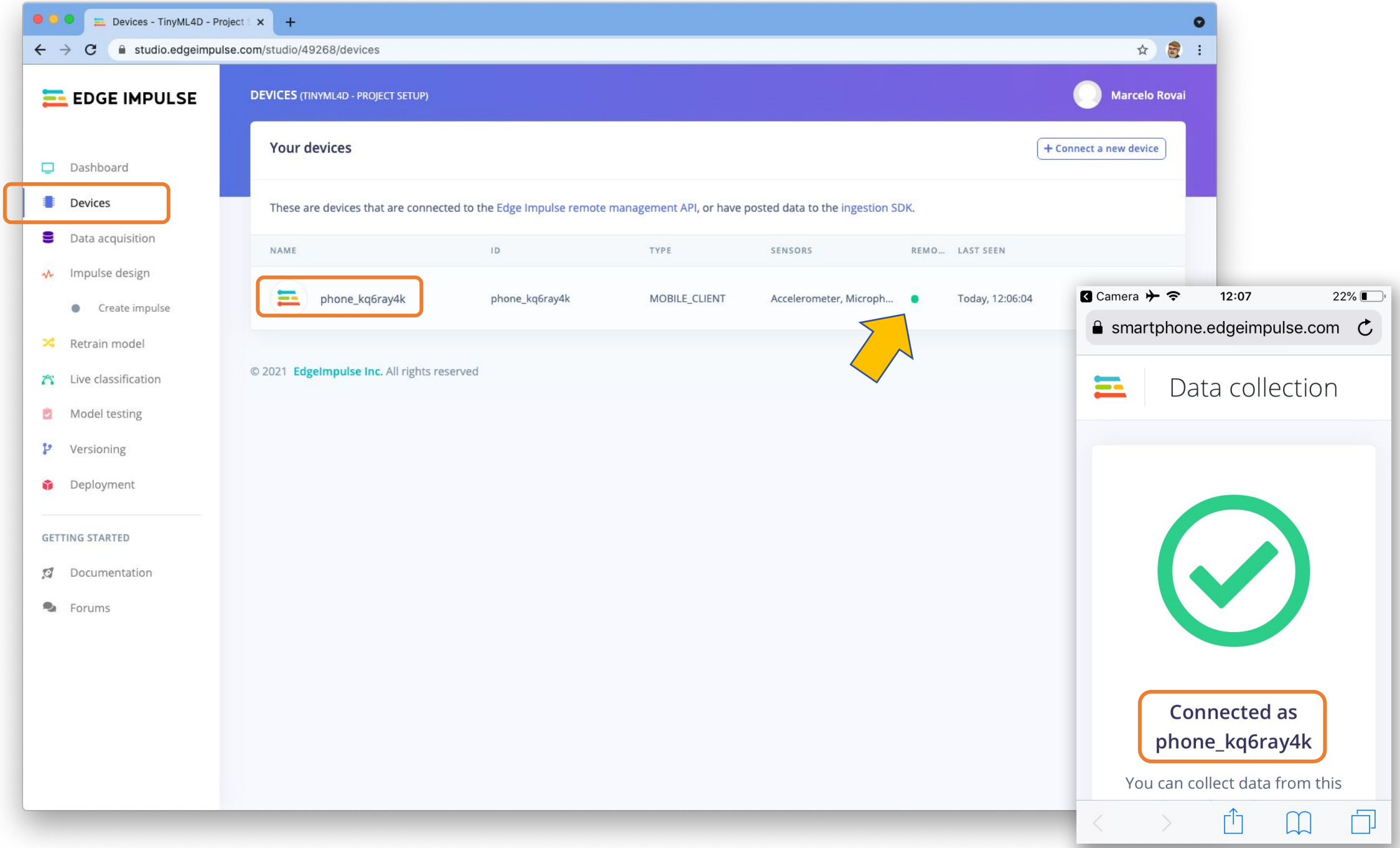
NAME
ID
TYPE
SENSORS
REMO...
LAST SEEN
Today, 12:06:04
© 2021
Collect data
Device phone_kq6ray4k is now connected
Get started!
Camera
12:07
22%
smartphone.edgeimpulse.com
Data collection
Connected as
phone_kq6ray4k
You can collect data from this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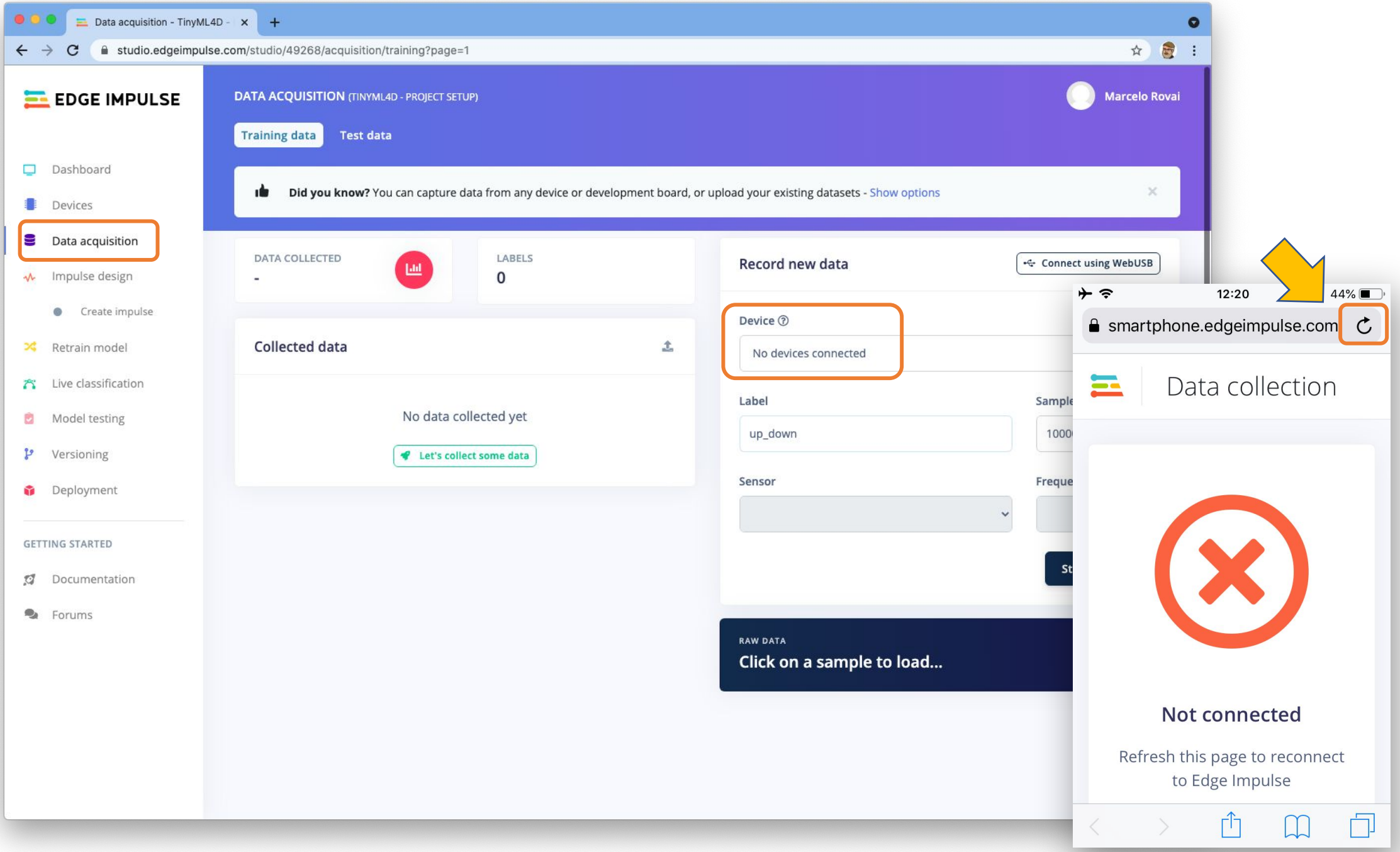
NAME
ID
TYPE
SENSORS
REMO...
LAST SEEN
phone_kq6ray4k
phone_kq6ray4k
MOBILE_CLIENT
Accelerometer, Microph...
Today, 12:06:04
© 2021 EdgeImpulse Inc. All rights reserved
Camera
12:07
22%
smartphone.edgeimpulse.com
Data collection
Connected as
phone_kq6ray4k
You can collect data from this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studio.edgeimpulse.com/studio/49268/acquisition/training?page=1
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DATA ACQUISITION (TINYML4D - PROJECT SETUP)
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Training data
Test data
Did you know? You can capture data from any device or development board, or upload your existing datasets - Show options
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GETTING STARTED
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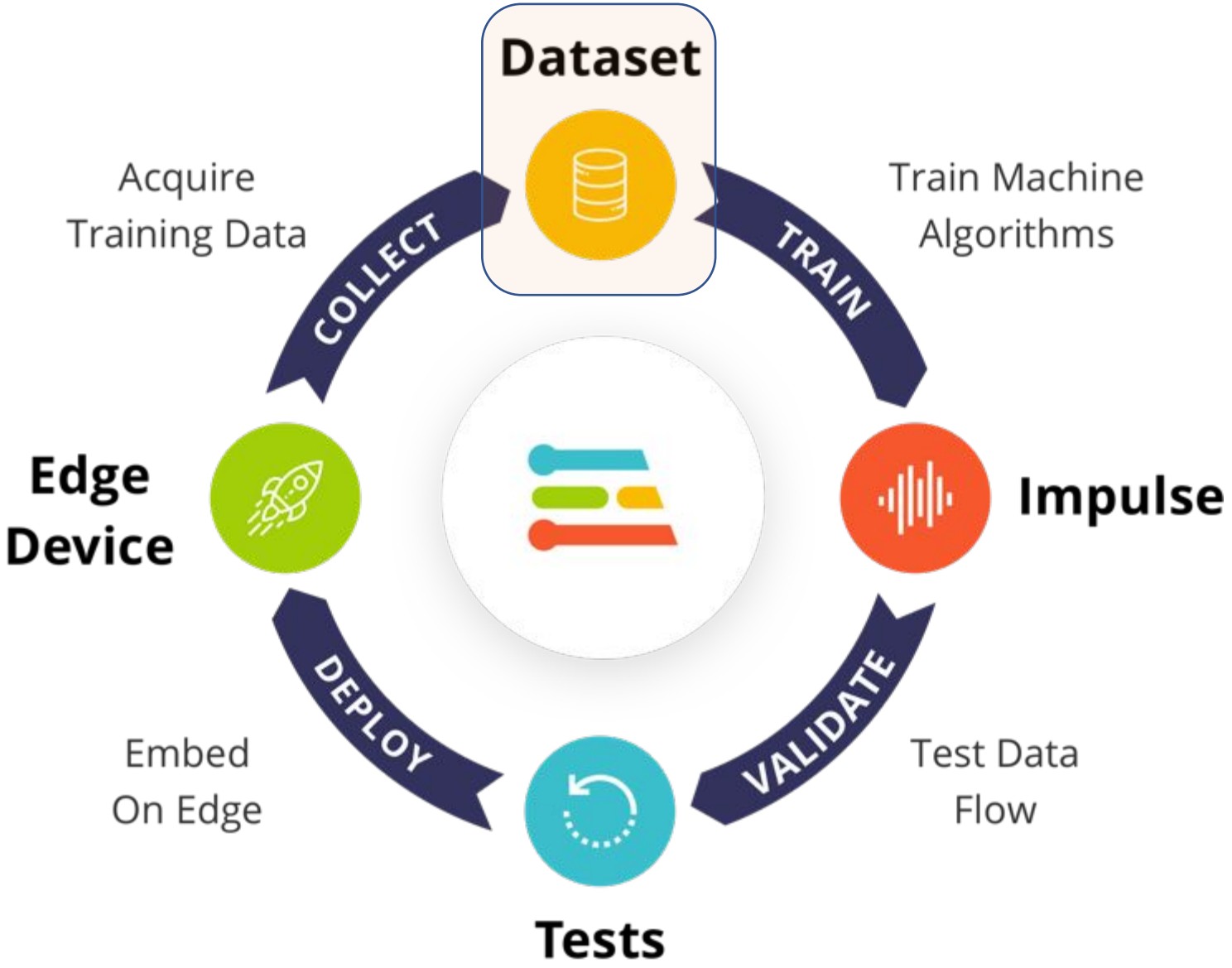
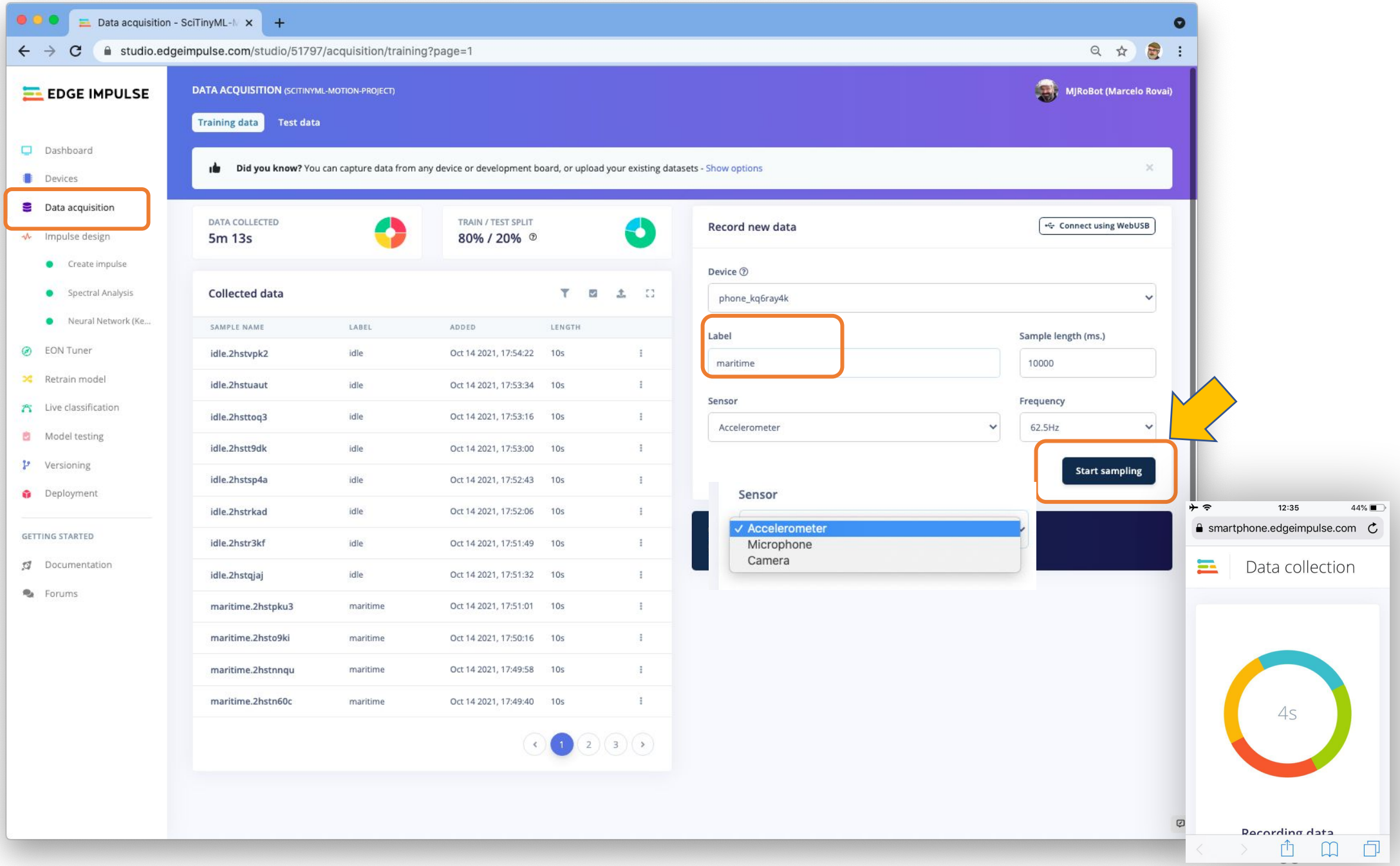
DATA COLLECTED
-
LABELS
0
Collected data
No data collected yet
Let's collect some data
Record new data
Connect using WebUSB
Device
No devices connected
Label
up_down
Sensor
RAW DATA
Click on a sample to load...
12:20
44%
smartphone.edgeimpulse.com
Data collection
Not connected
Refresh this page to reconnect to Edge Impulse



- Pre-Processing Data
- Design a Model
- Train a Model

Collect Data



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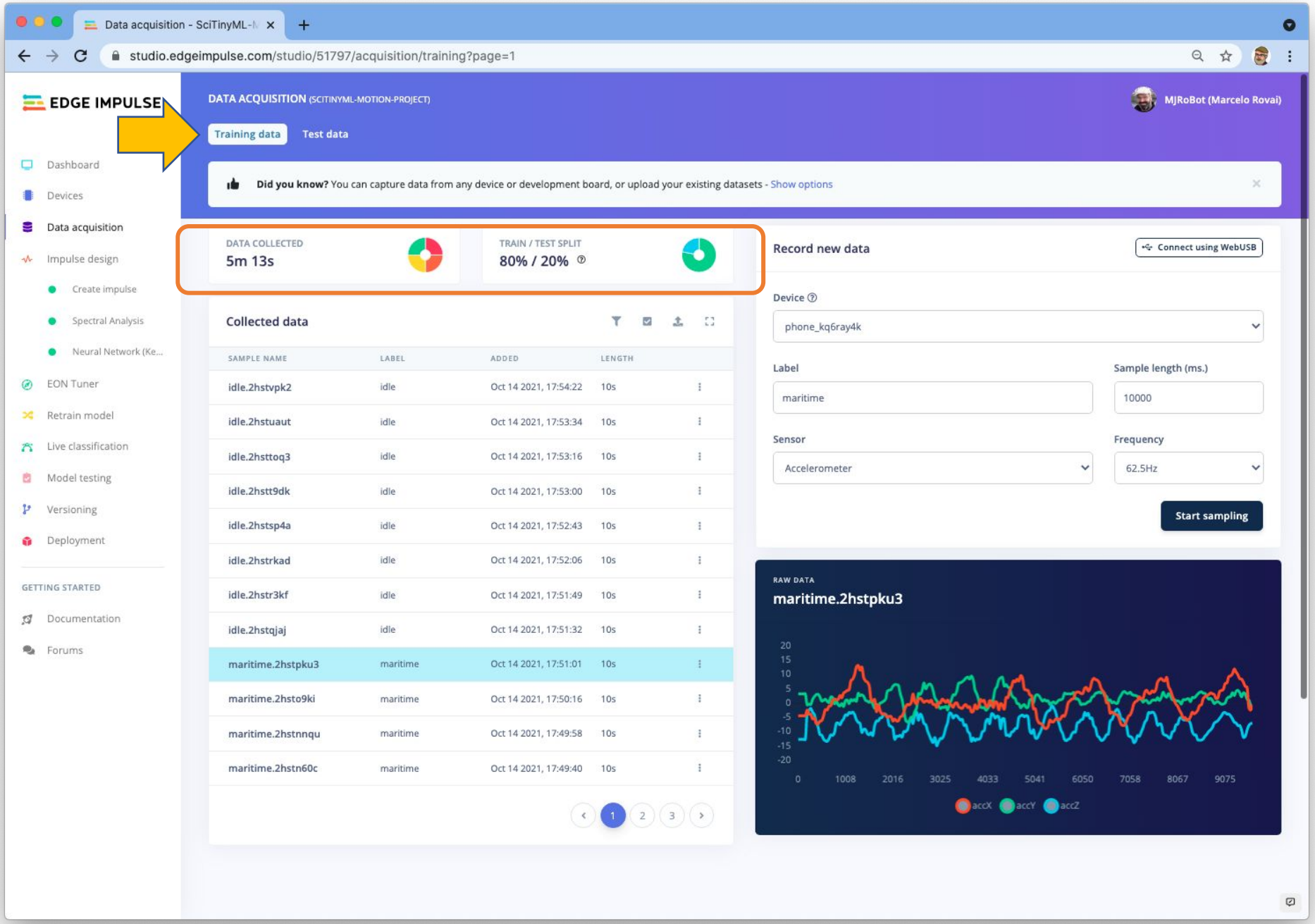
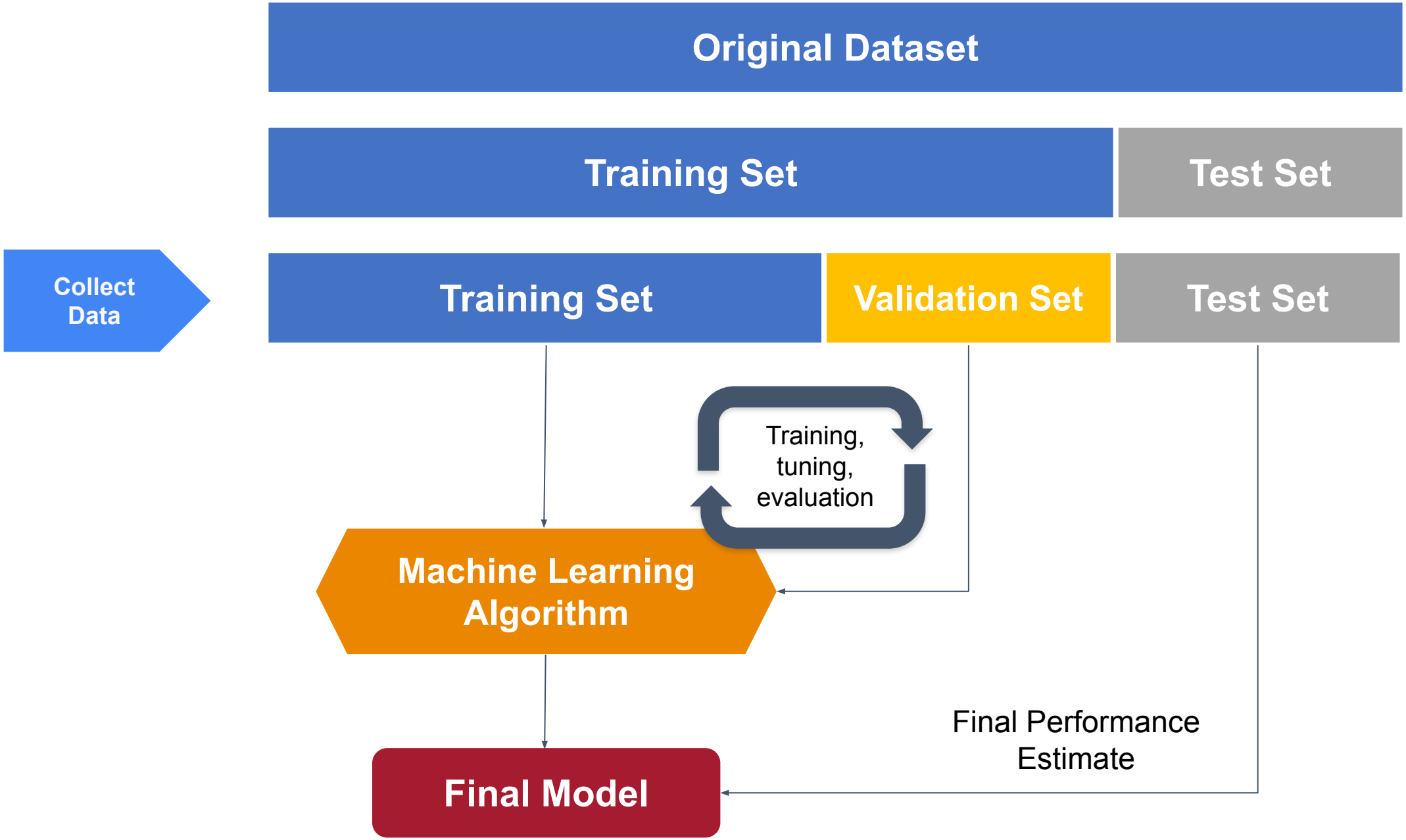
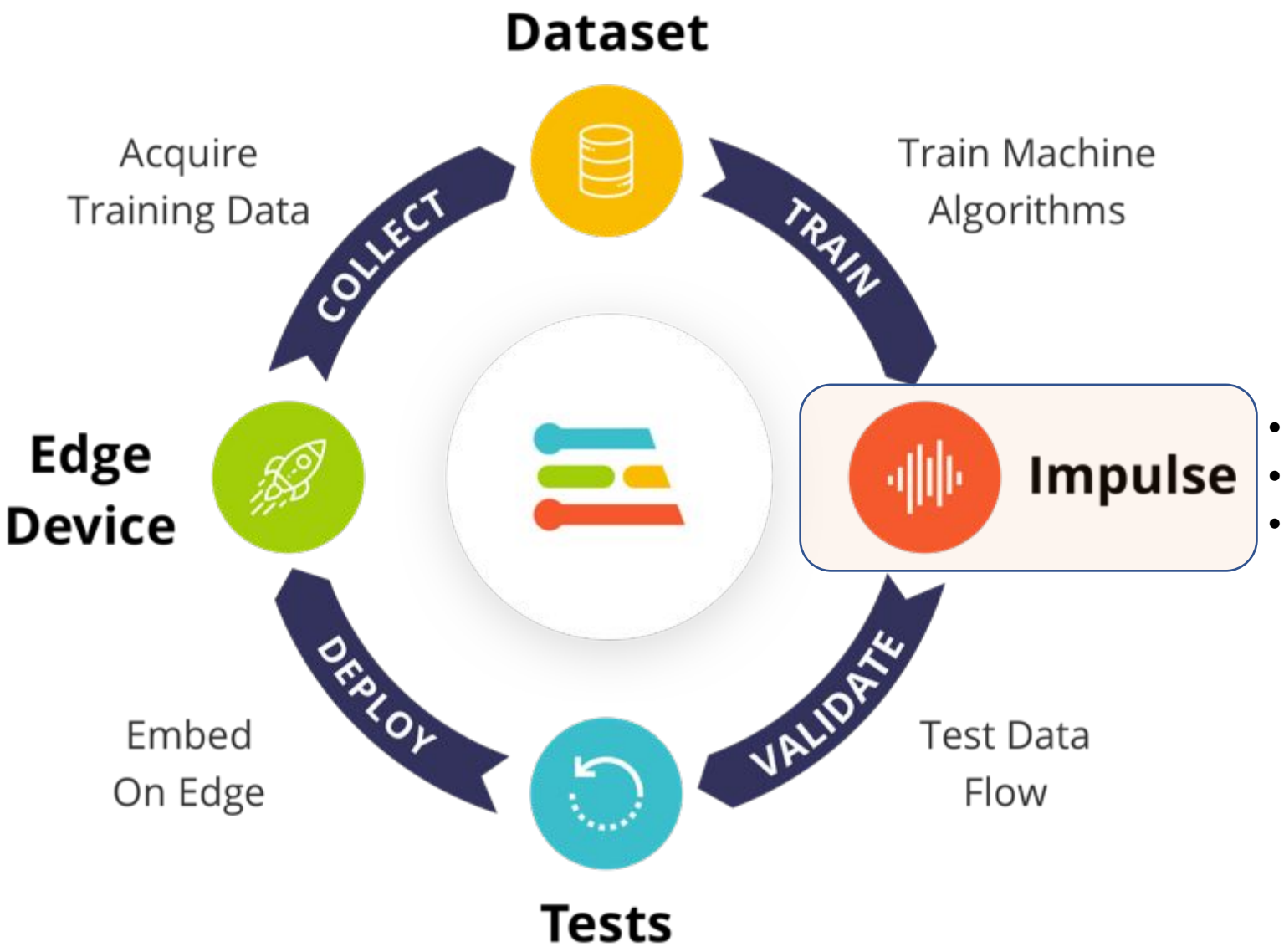



Original Dataset
Training Set
Test Set
Collect Data
Training Set
Validation Set
Test Set
Training, tuning, evaluation
Machine Learning Algorithm
Final Performance Estimate
Final Model



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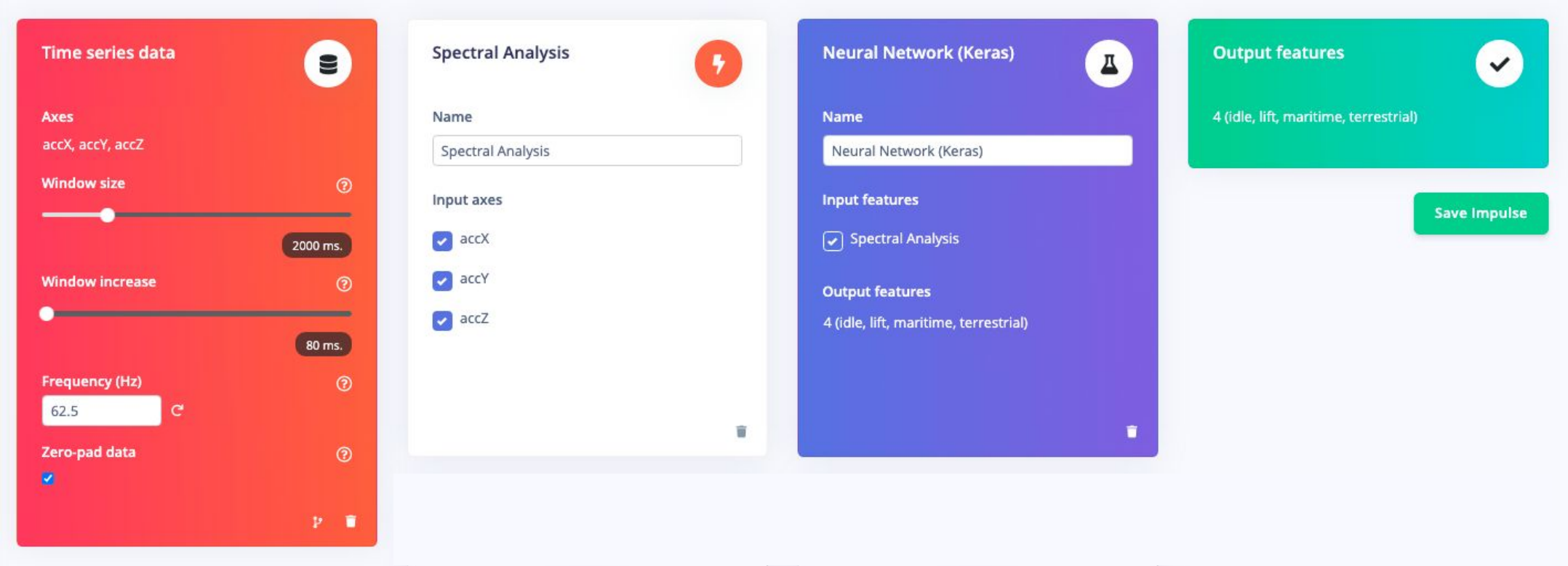
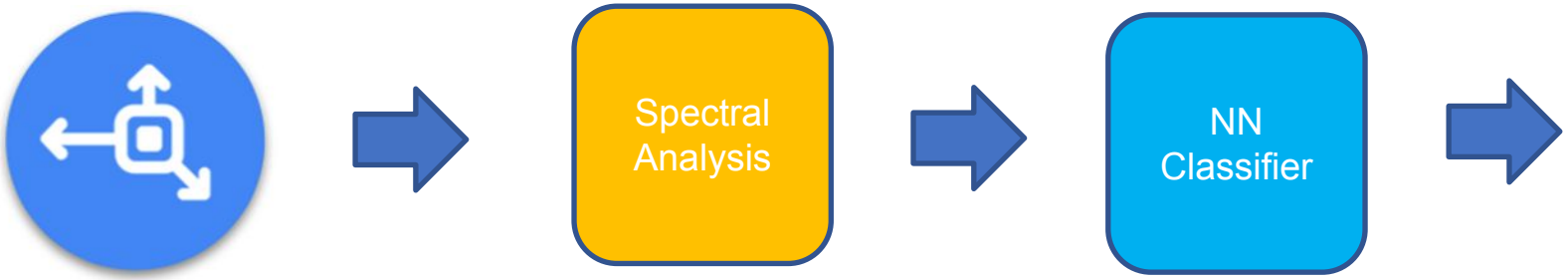
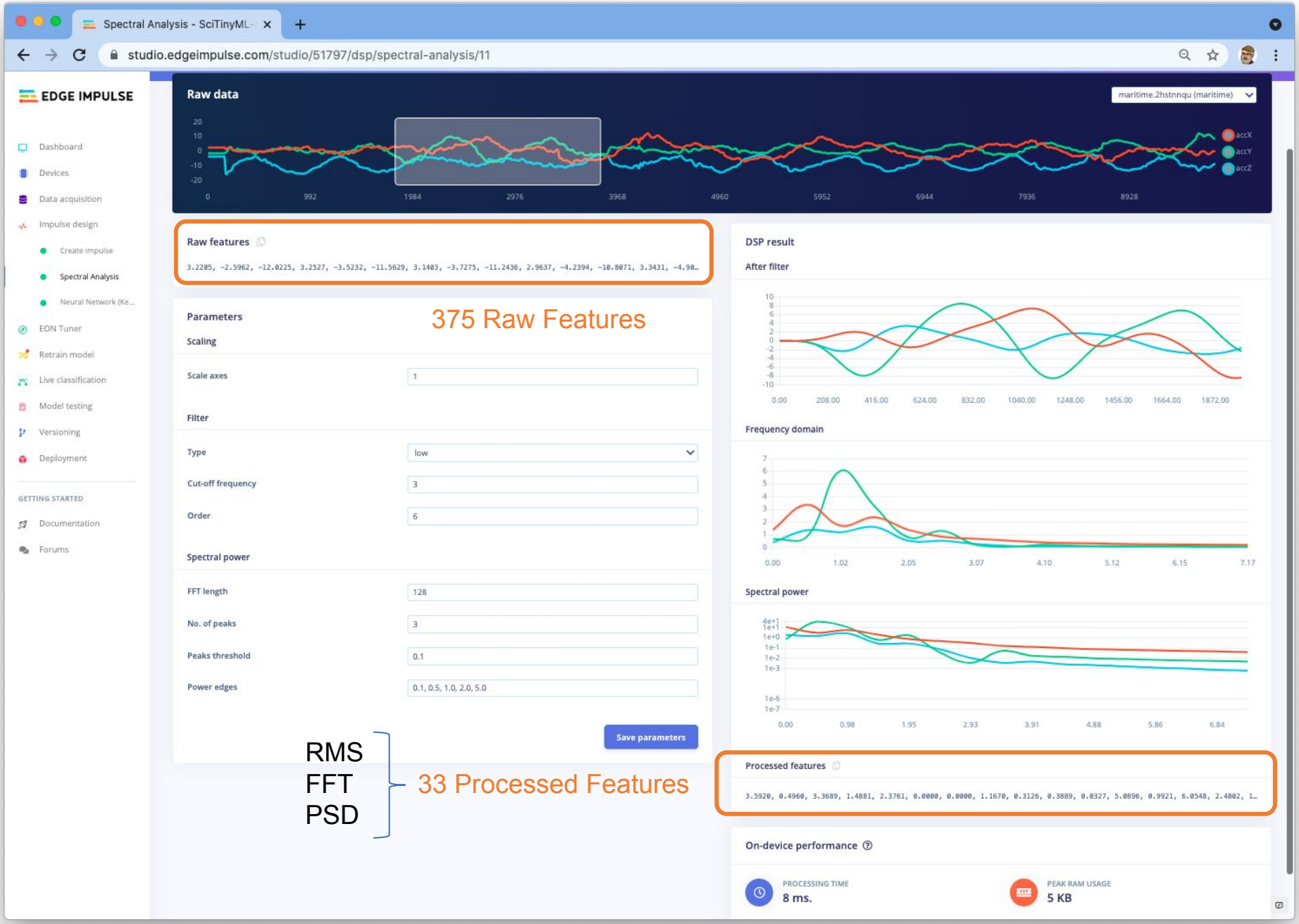




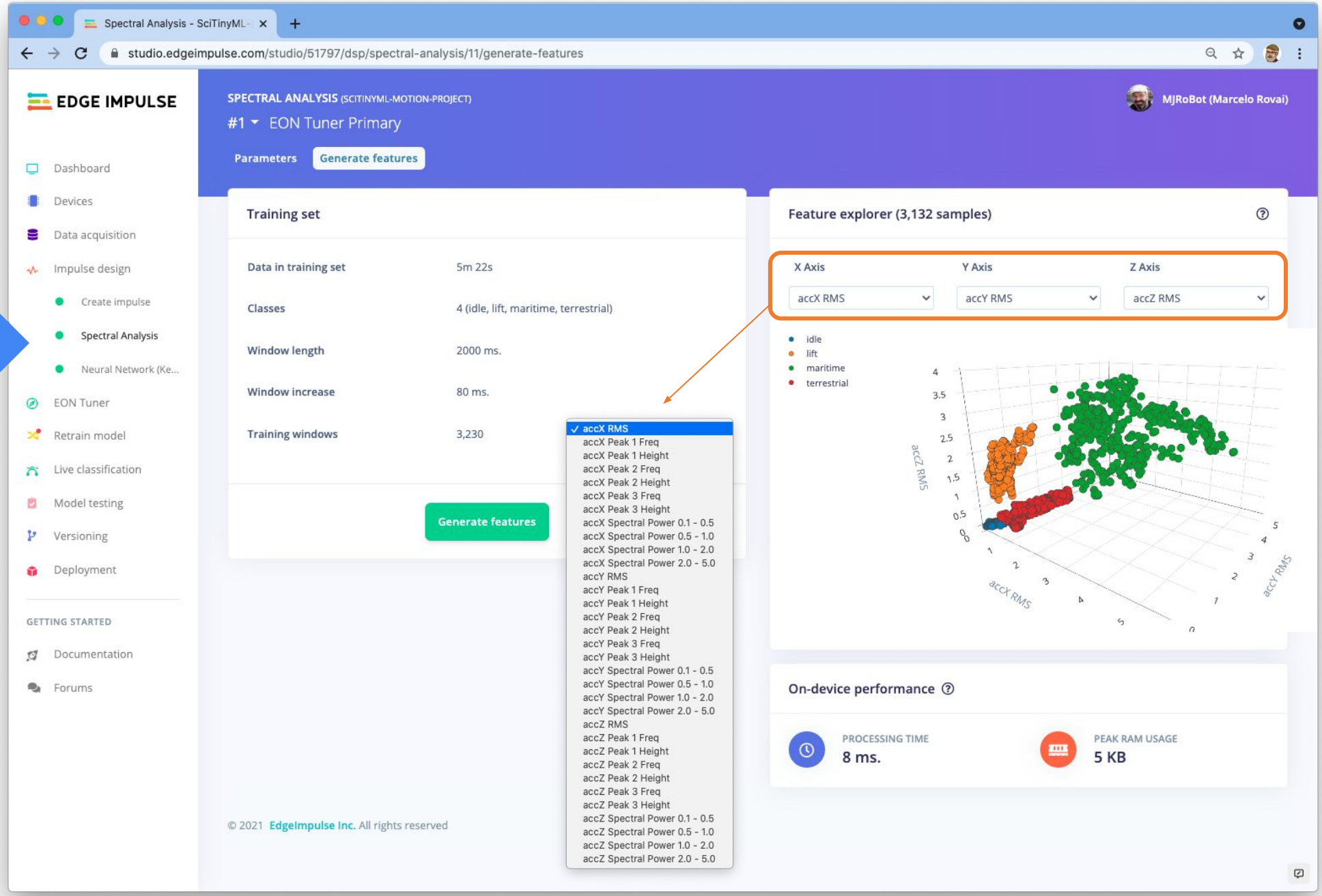
Classes

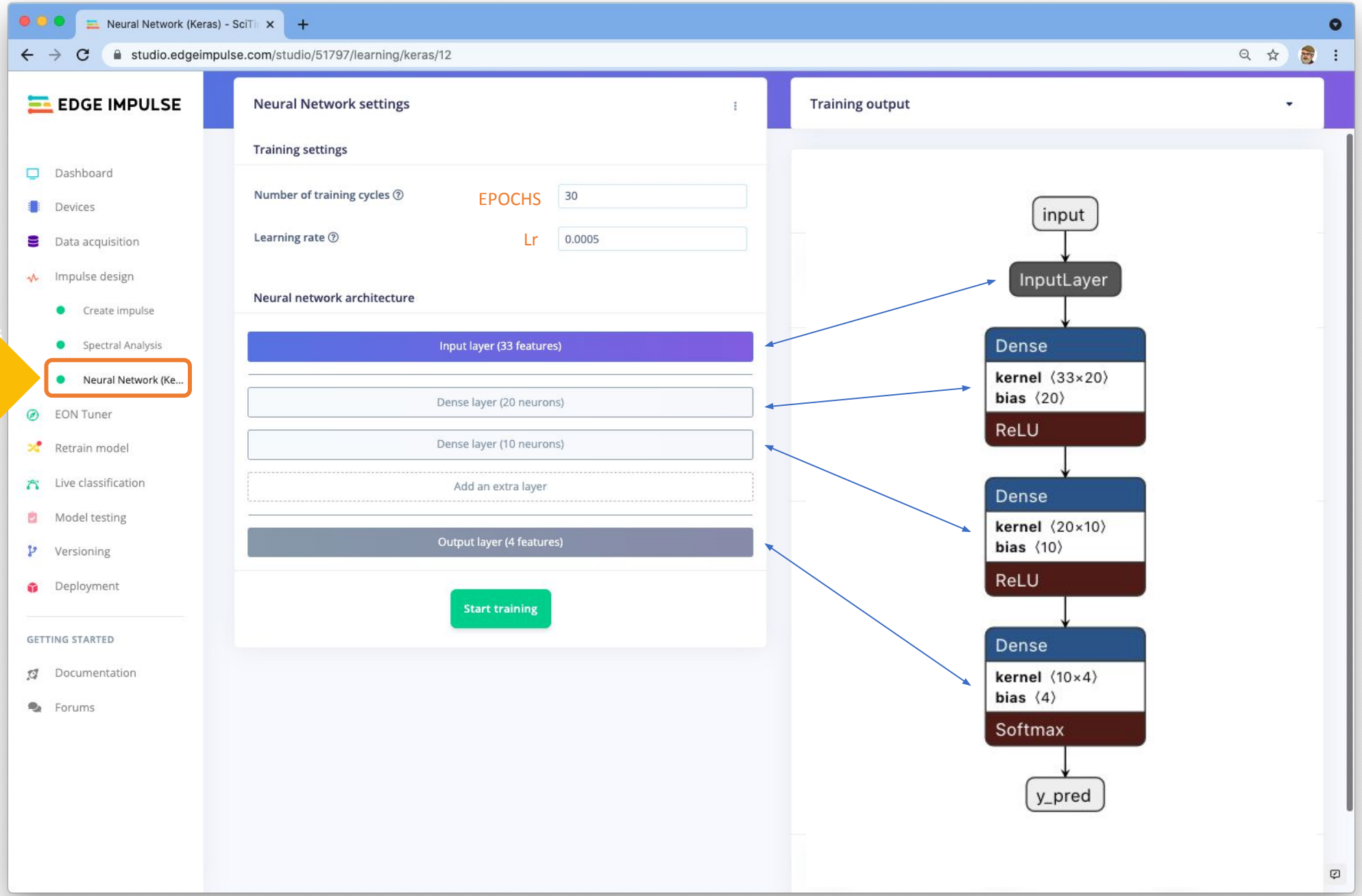
- Lift
- Terrestrial
- Maritime
- Iddle

Preprocess Data



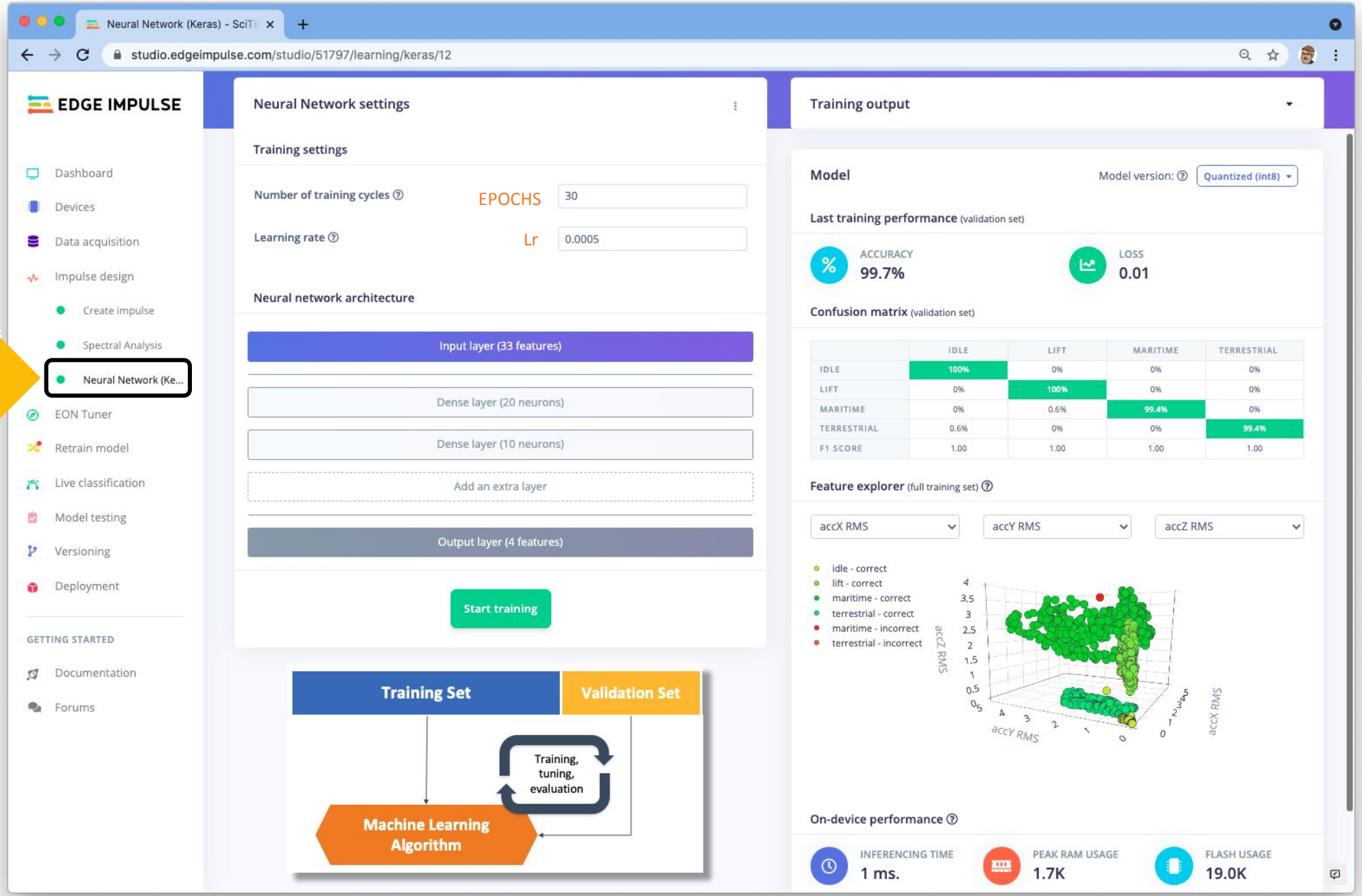
Preprocess Data



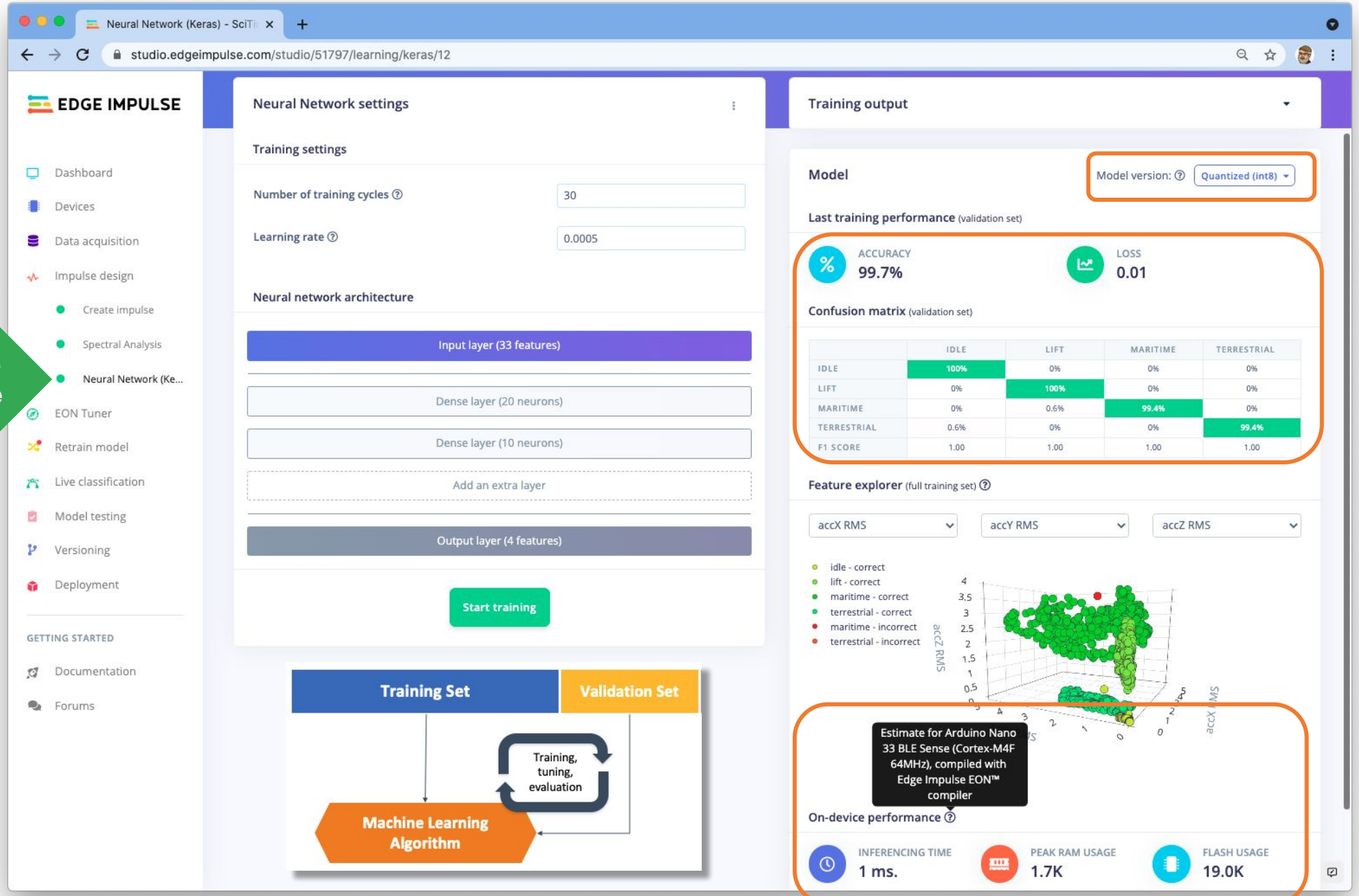


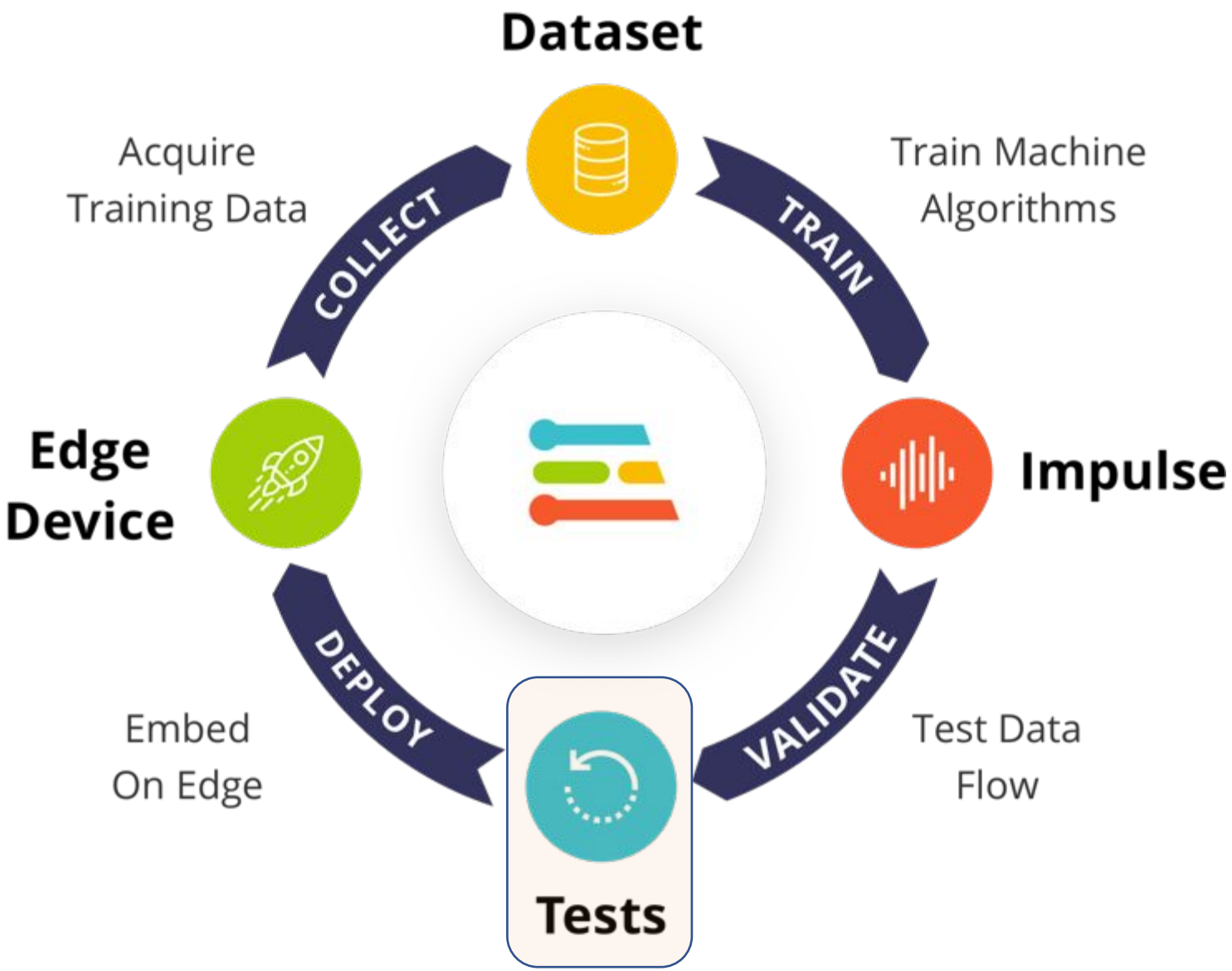
Design a Model

Train a Model



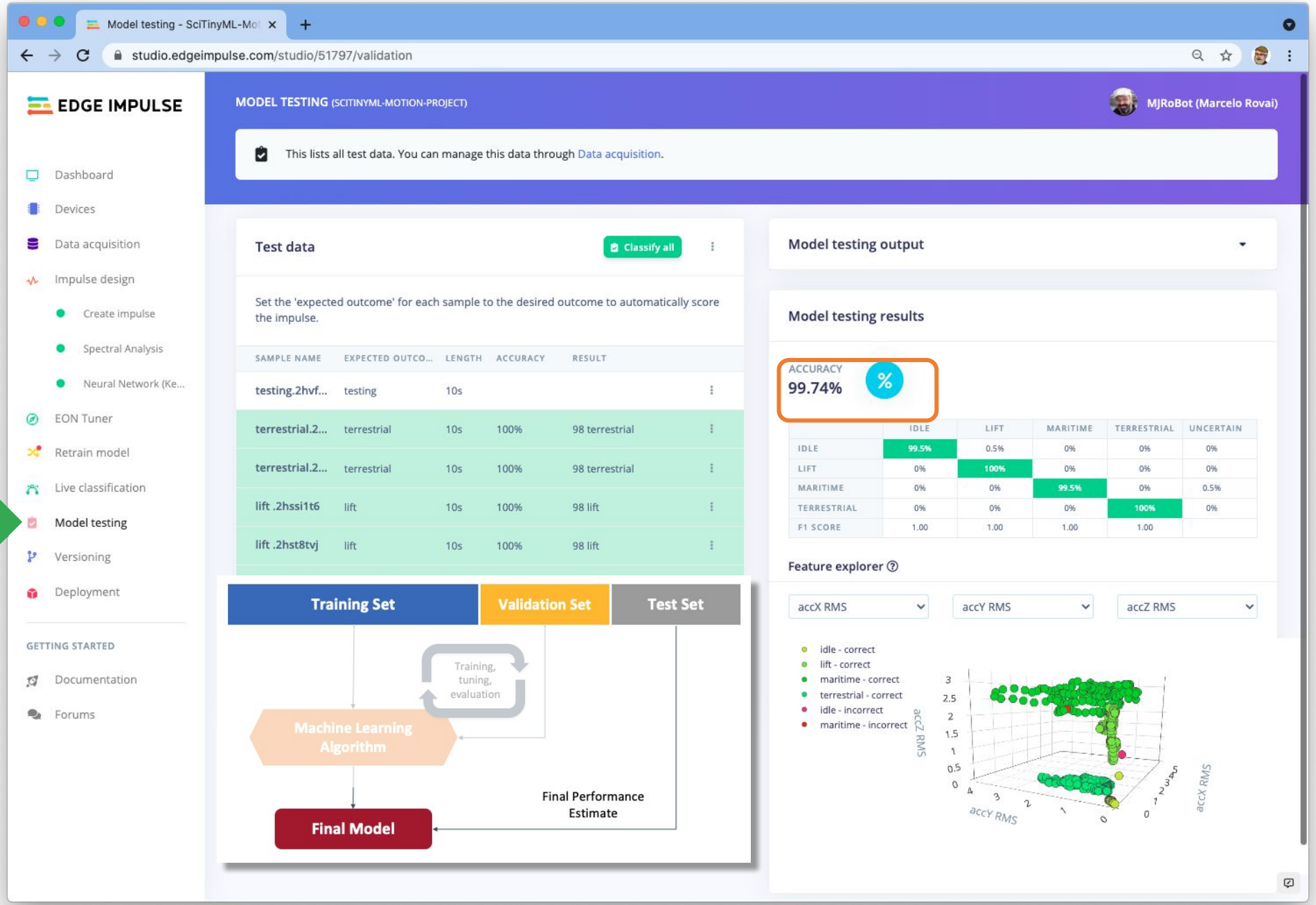
Evaluate
Optimize

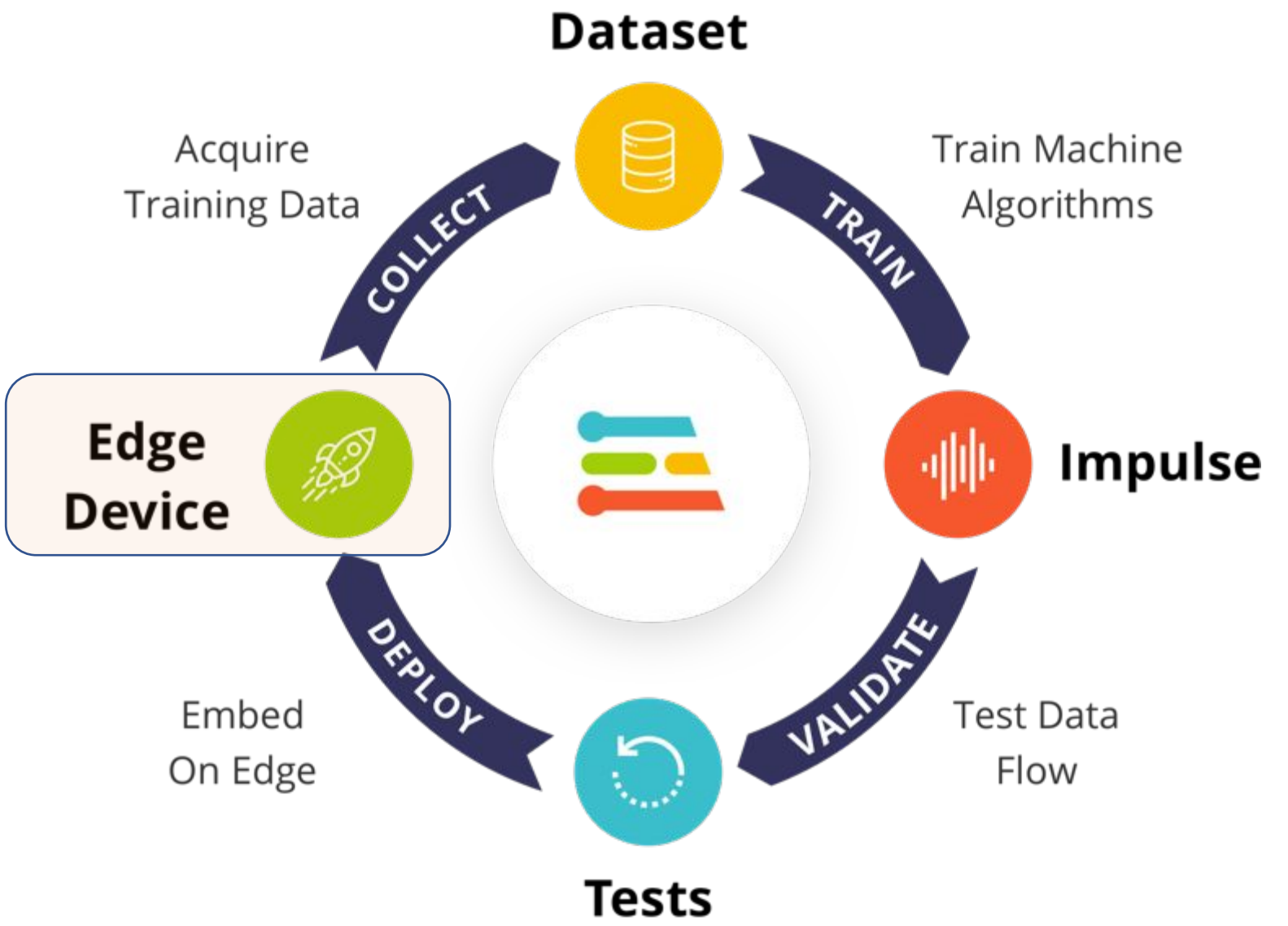




- Pre-Processing Data
- Design a Model
- Train a Model

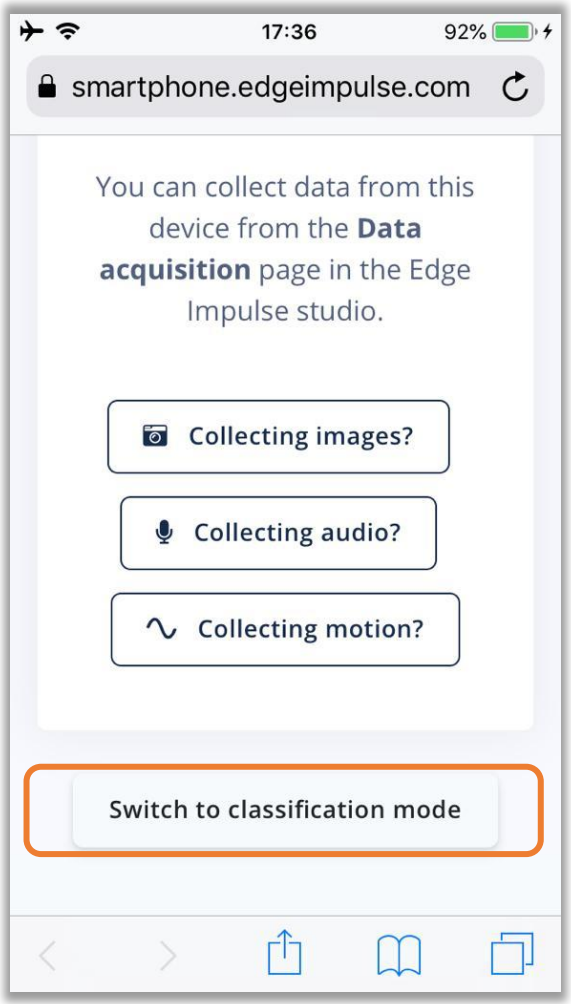
Evaluate
Optimize

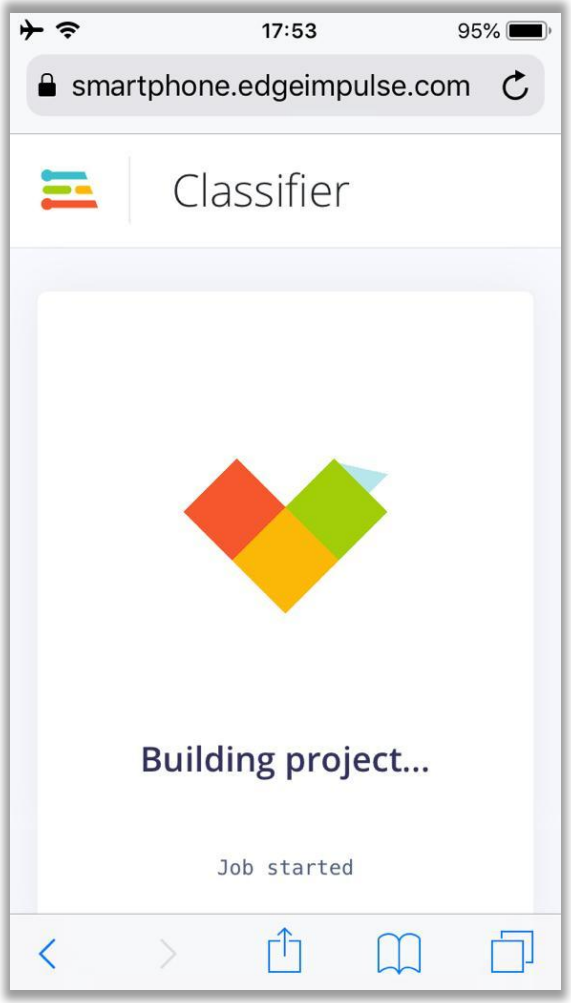




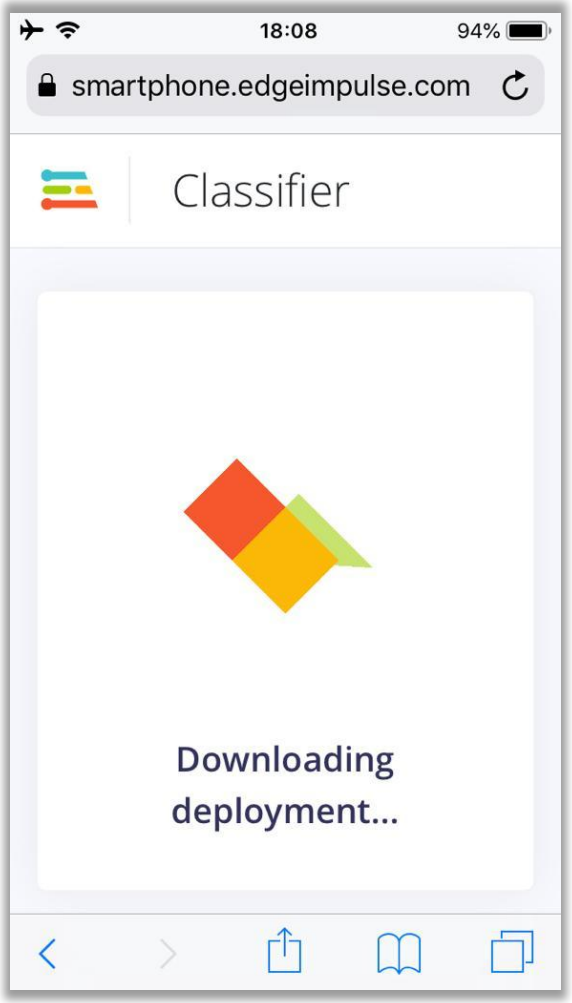
- Pre-Processing Data
- Design a Model
- Train a Model

Convert Model

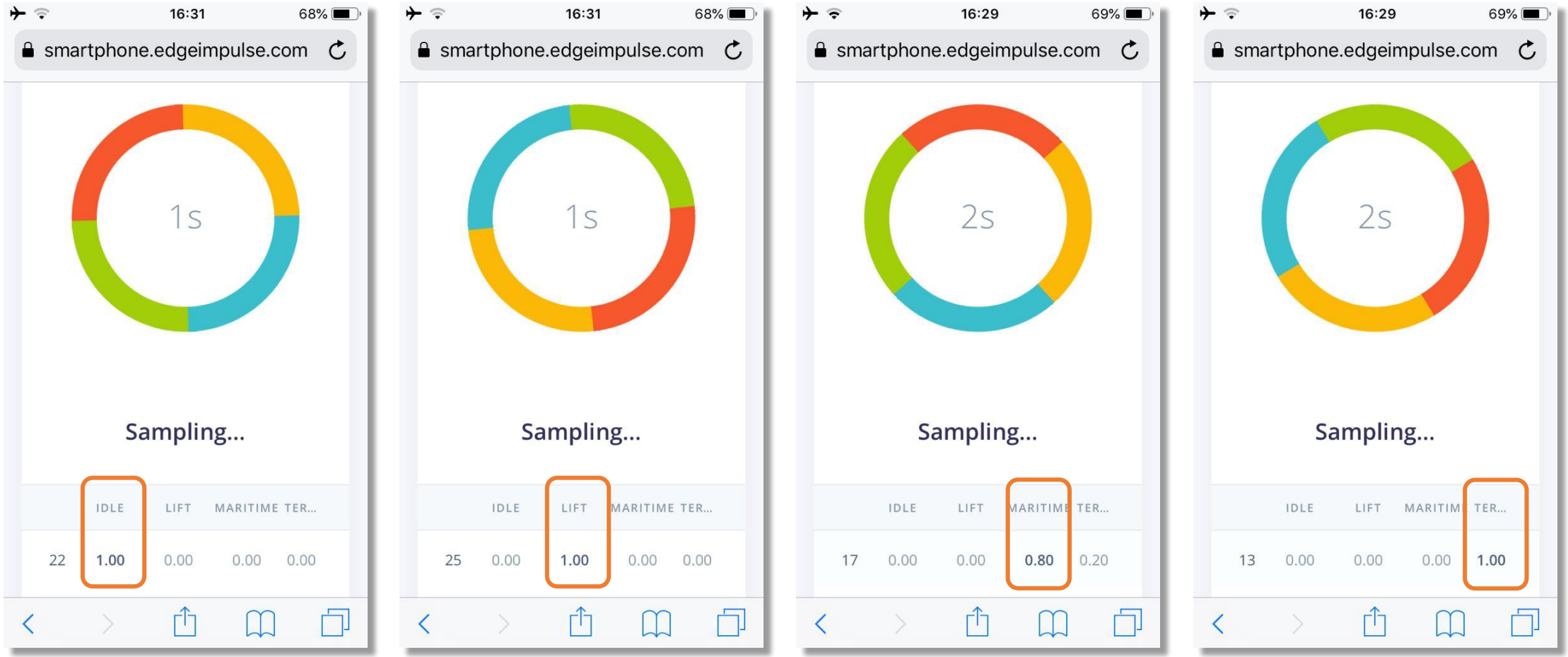




Deploy Model

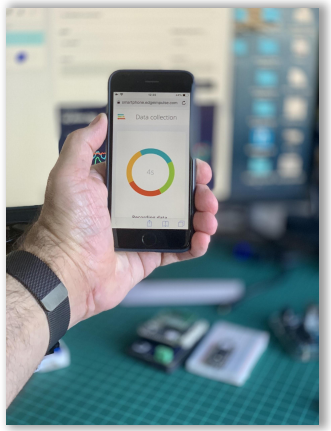


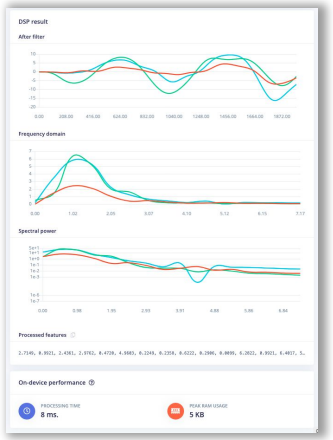
Make Inferences

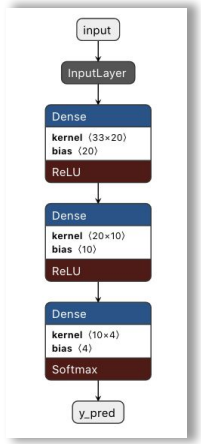


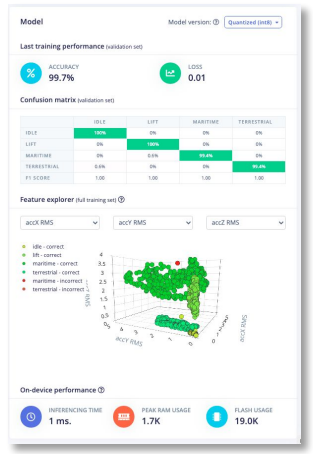
Motion Classification - Summary

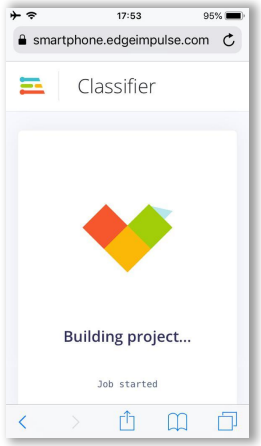
Collect Data → Preprocess Data → Design a Model → Train a Model → Evaluate Optimize → Convert Model → Deploy Model → Make Inferences

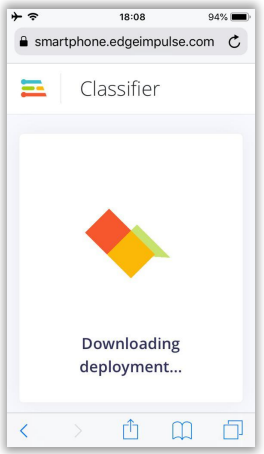


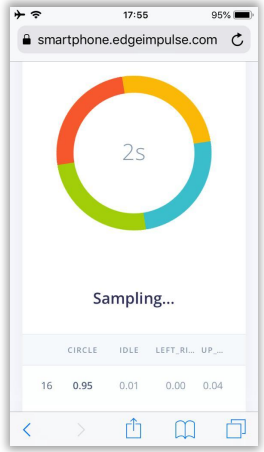






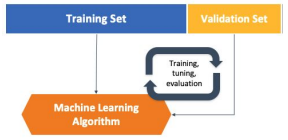


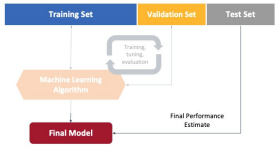




Spectral Analysis

NN Classifier



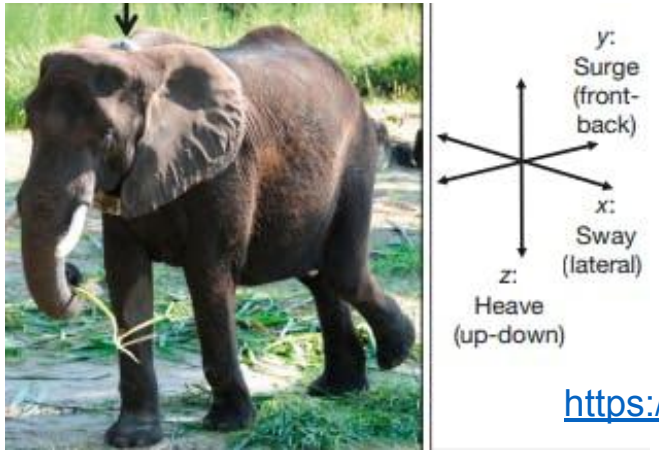


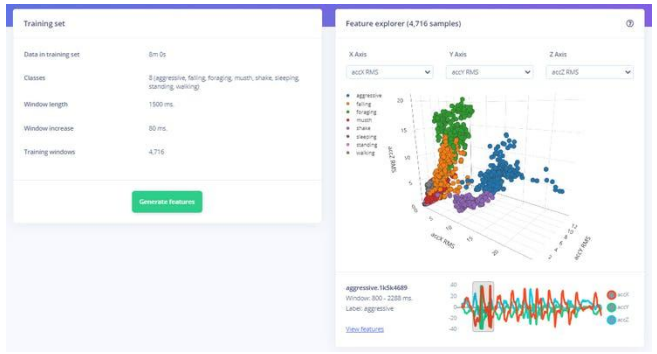
Predict and classify common Elephant behavior

Aggressive

Standing

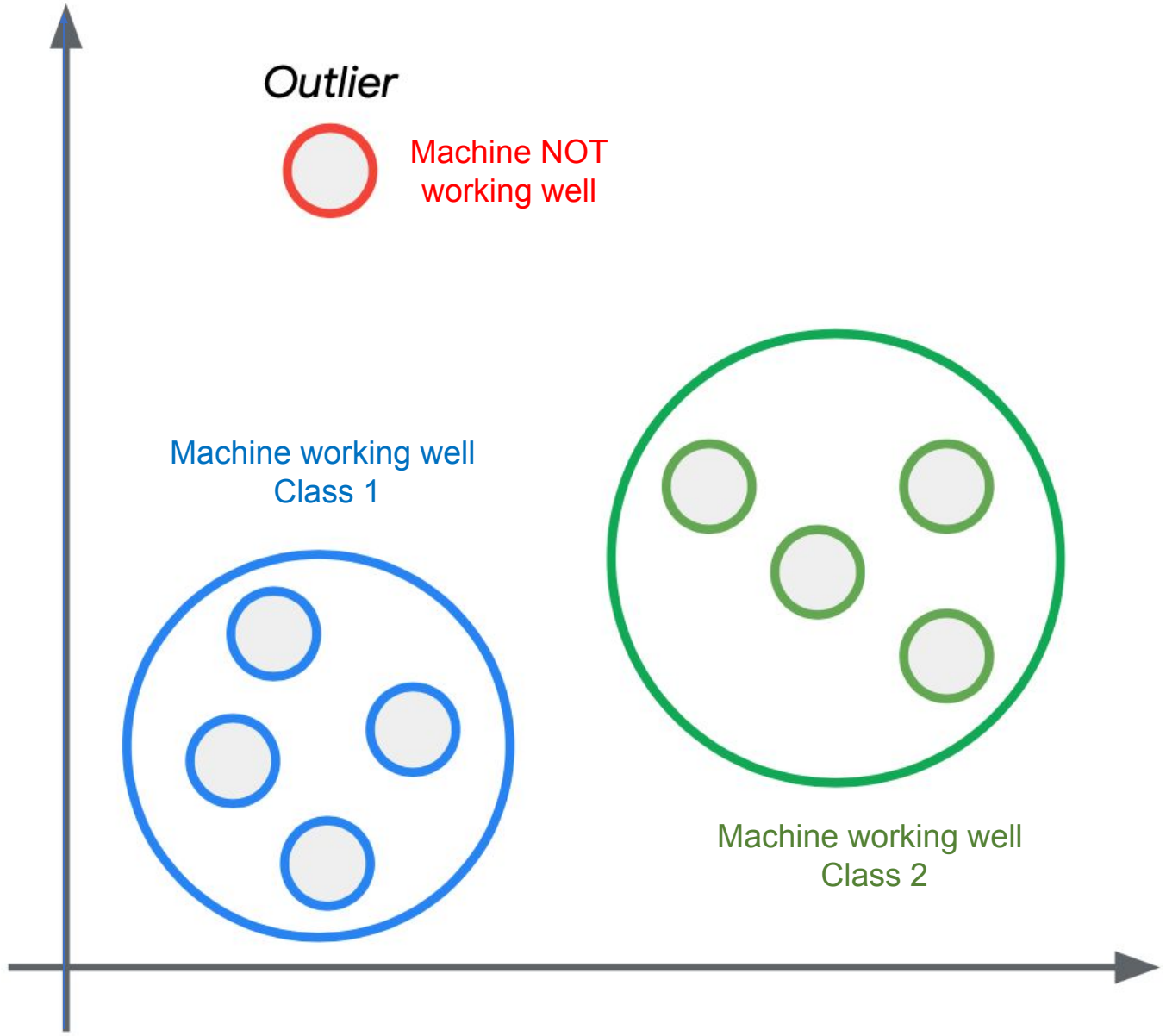
Sleeping

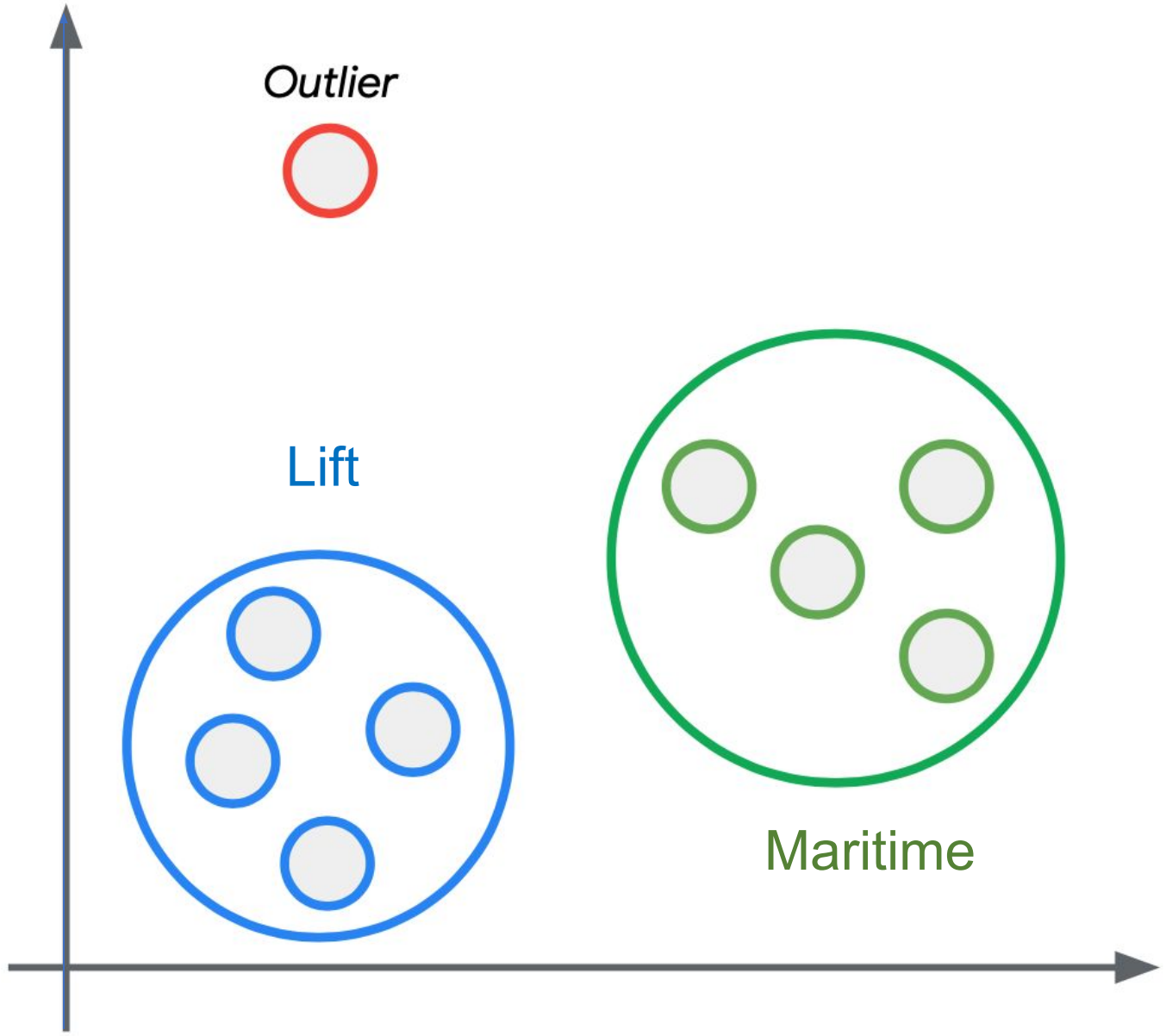


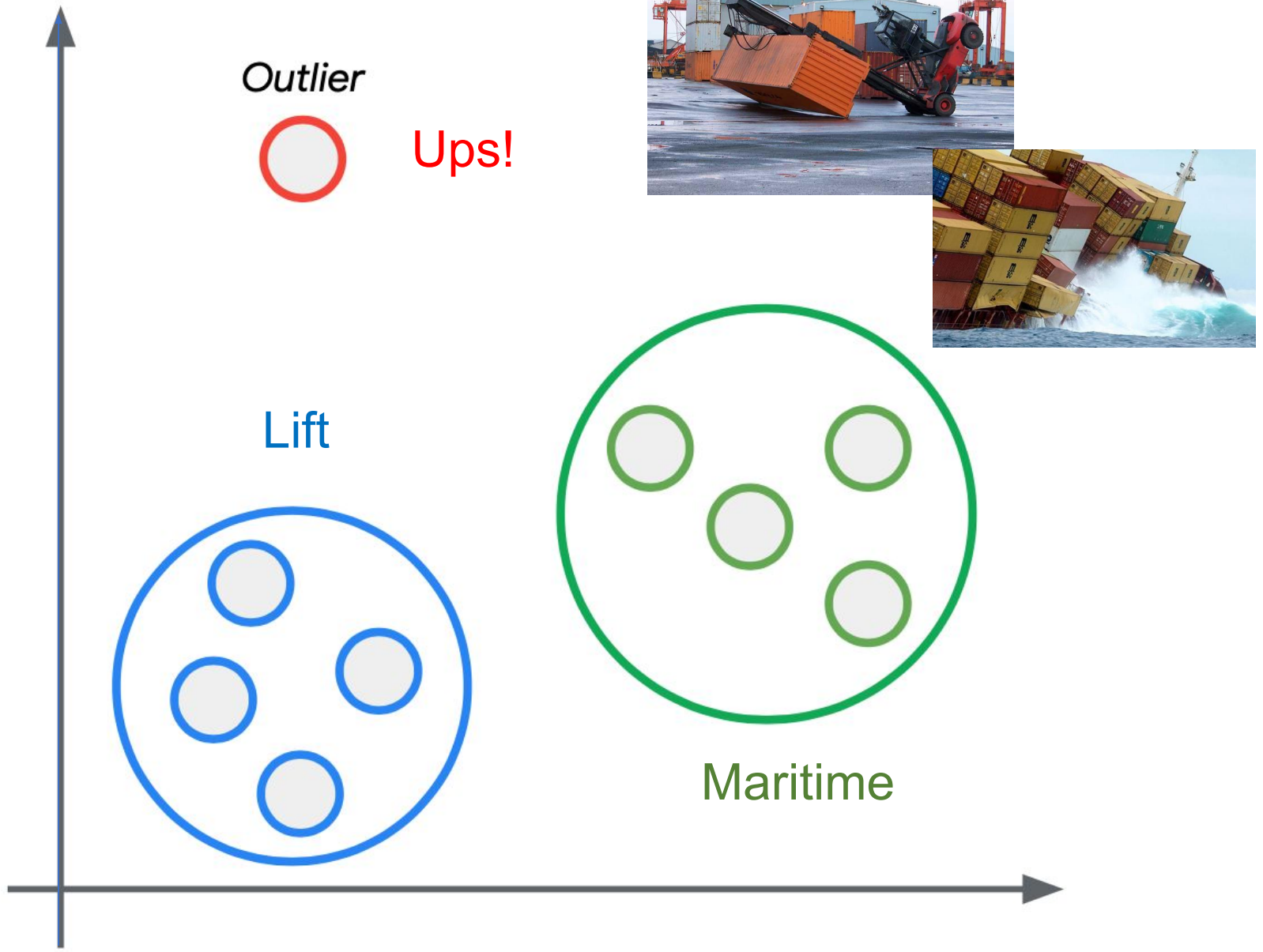


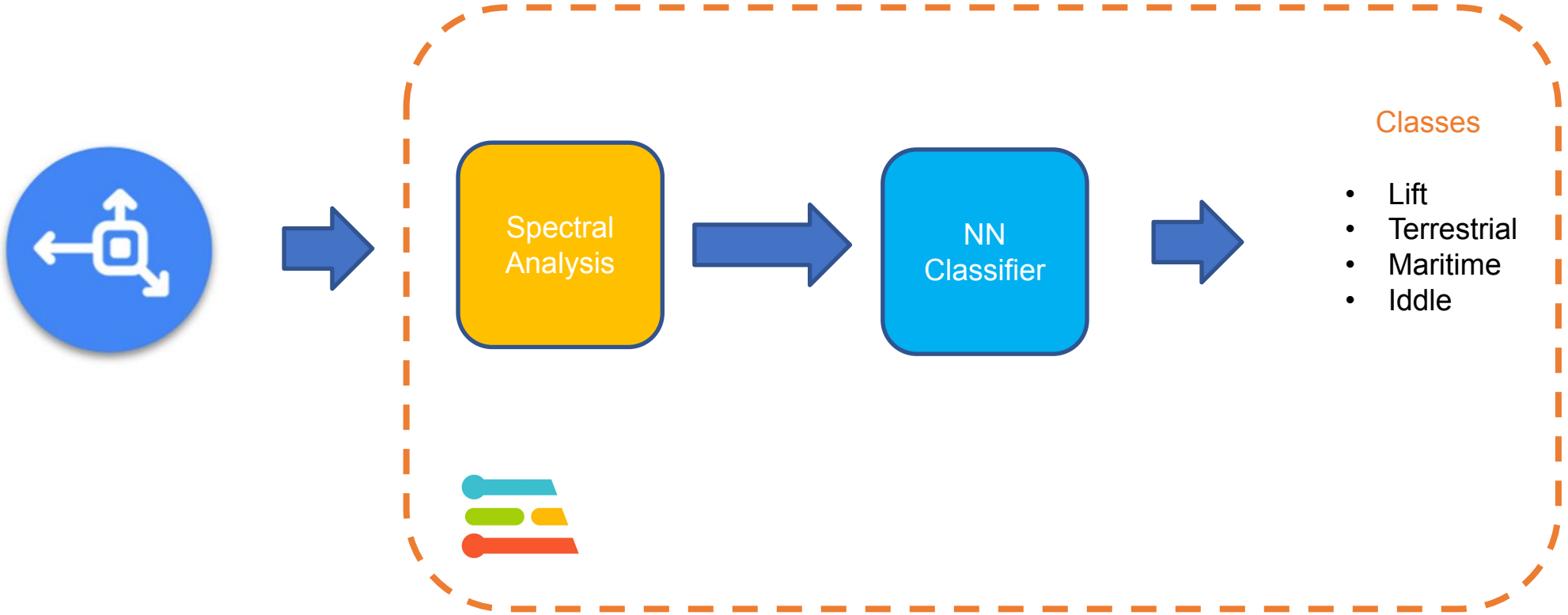
https://www.hackster.io/dhruvsheth_/eletect-tinyml-and-iot-based-smart-wildlife-tracker-c03e5a

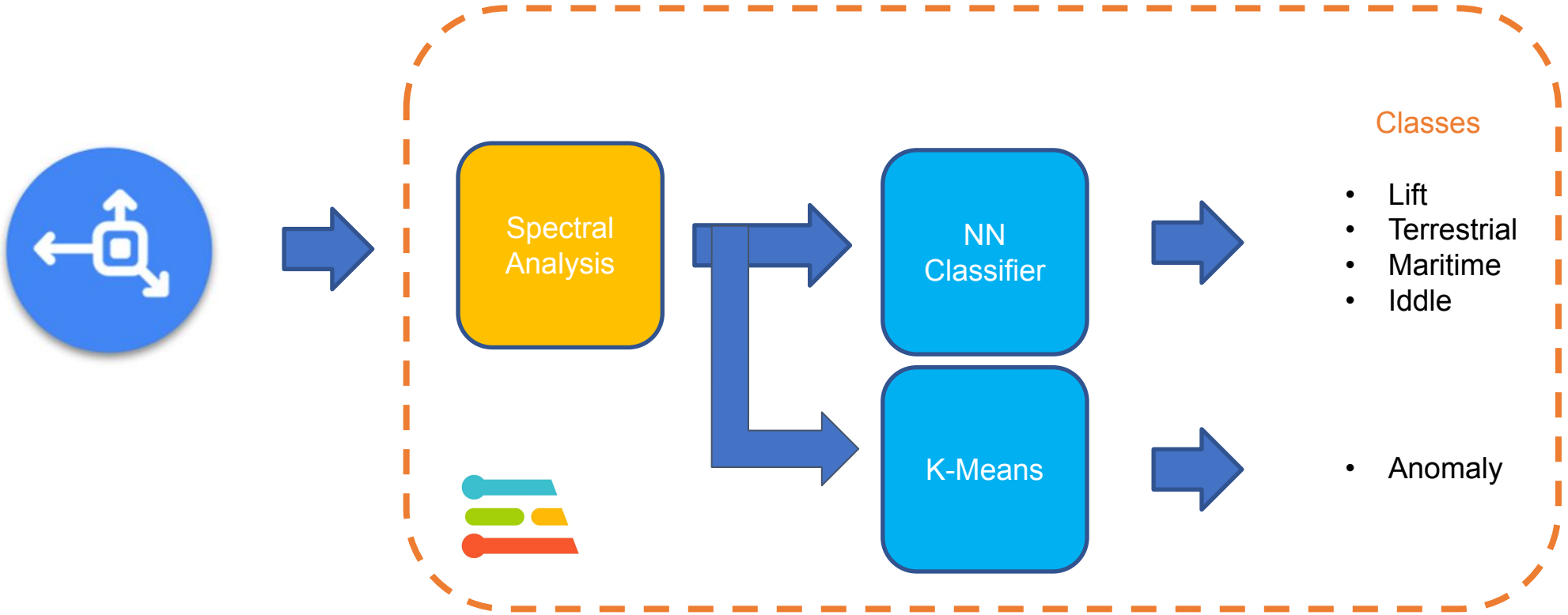
Anomaly Detection Hands-On

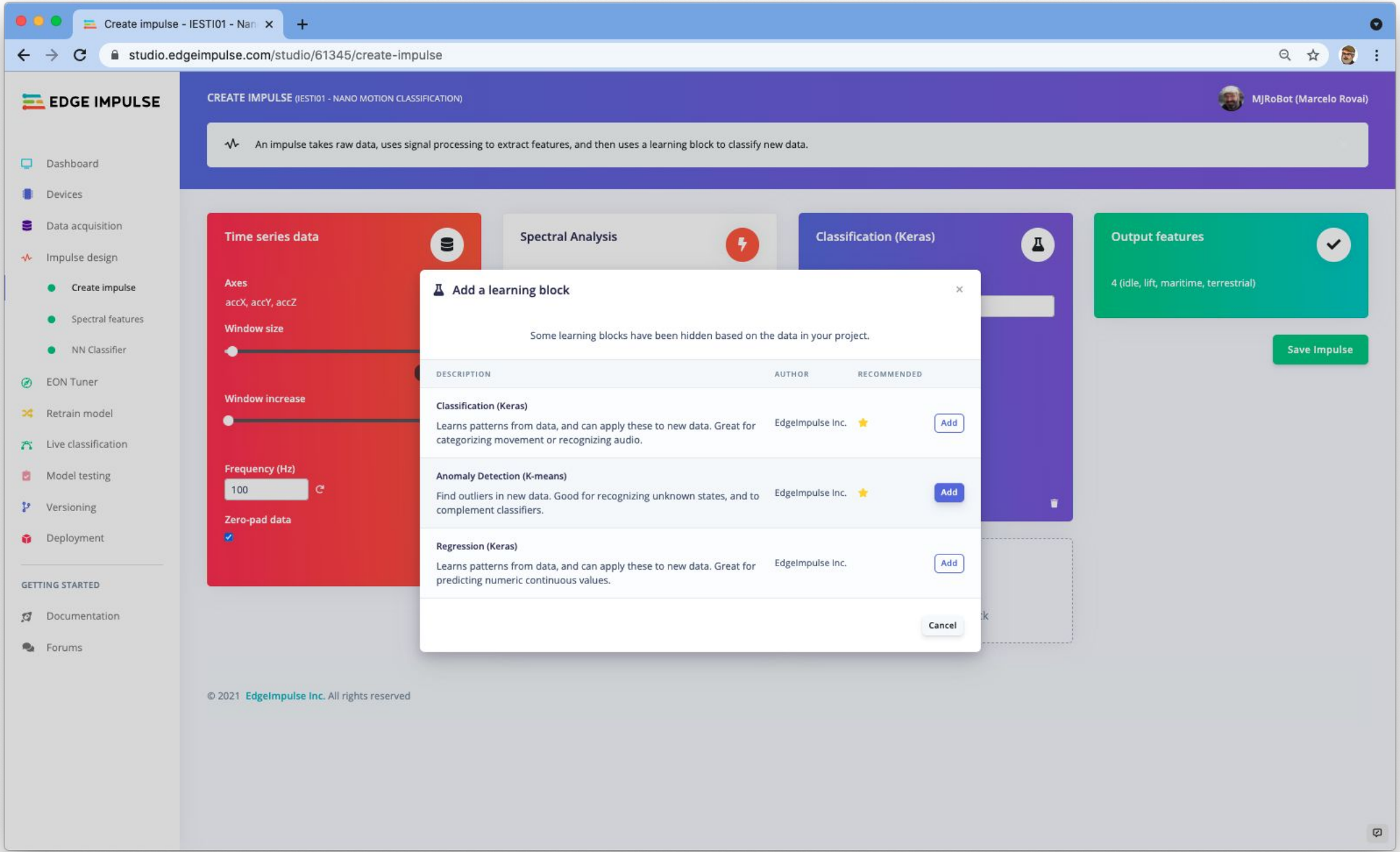

Outlier
Machine NOT working well
Machine working well Class 1
Machine working well Class 2


Outlier
Lift
Maritime


Outlier
Ups!
Lift
Maritime


Spectral Analysis
NN Classifier
Classes
Lift
Terrestrial
Maritime
Iddle


Spectral Analysis
NN Classifier
K-Means
Classes
• Lift
• Terrestrial
• Maritime
• Iddle
• Anomaly


Create impulse - IESTI01 - Nan
studio.edgeimpulse.com/studio/61345/create-impulse
EDGE IMPULSE
CREATE IMPULSE (IESTI01 - NANO MOTION CLASSIFICATION)
MJRoBot (Marcelo Rovai)
An impulse takes raw data, uses signal processing to extract features, and then uses a learning block to classify new data.
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
Spectral features
NN Classifier
EON Tuner
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Time series data
Axes
accX, accY, accZ
Window size
Window increase
Frequency (Hz)
100
Zero-pad data
Spectral Analysis
Classification (Keras)
Output features
4 (idle, lift, maritime, terrestrial)
Save Impulse
Add a learning block
Some learning blocks have been hidden based on the data in your project.
DESCRIPTION
AUTHOR
RECOMMENDED
Classification (Keras)
Learns patterns from data, and can apply these to new data. Great for categorizing movement or recognizing audio.
EdgeImpulse Inc.
Add
Anomaly Detection (K-means)
Find outliers in new data. Good for recognizing unknown states, and to complement classifiers.
EdgeImpulse Inc.
Add
Regression (Keras)
Learns patterns from data, and can apply these to new data. Great for predicting numeric continuous values.
EdgeImpulse Inc.
Add
Cancel
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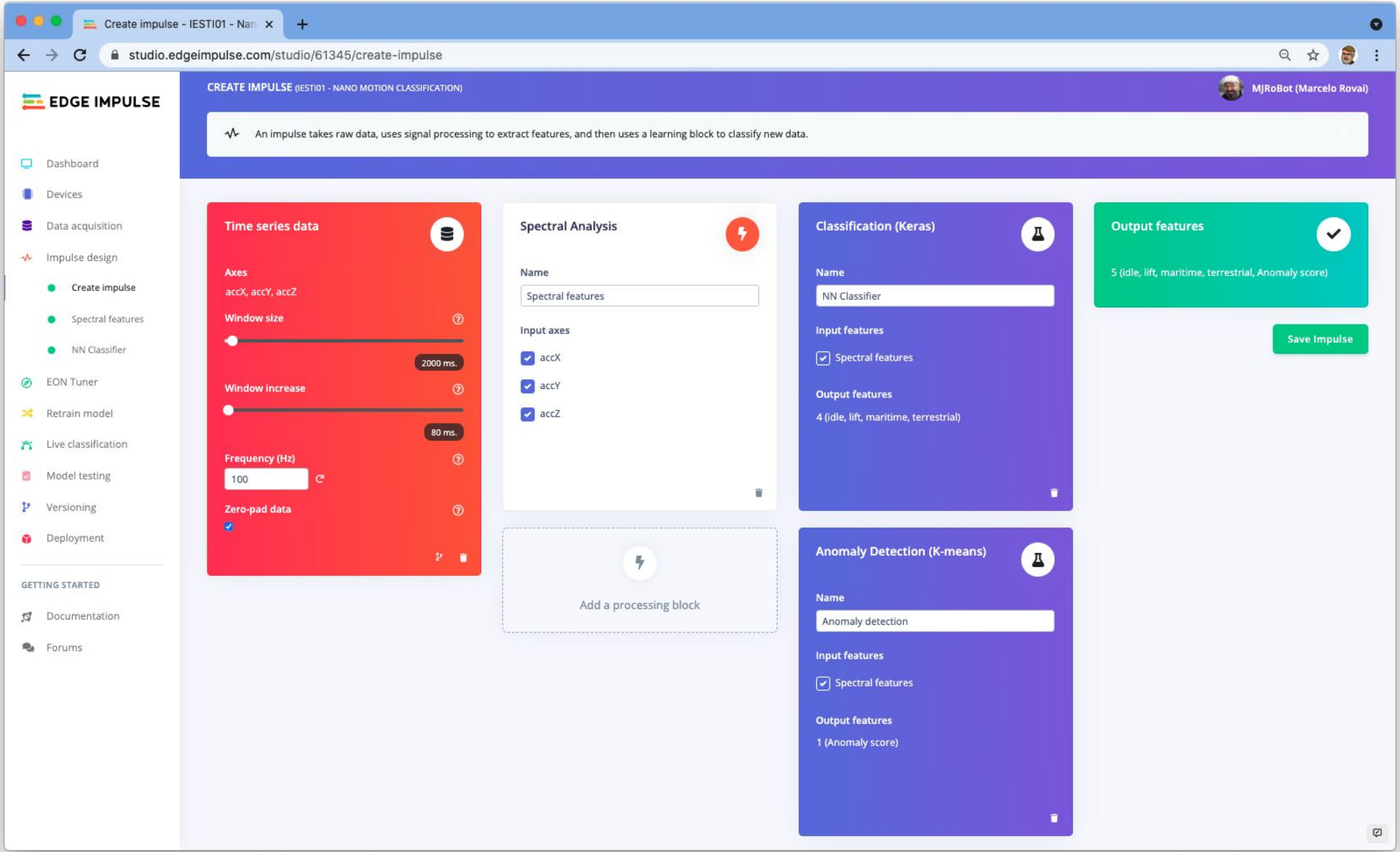
Create impulse - IESTI01 - Nan
studio.edgeimpulse.com/studio/61345/create-impulse
EDGE IMPULSE
CREATE IMPULSE (IESTI01 - NANO MOTION CLASSIFICATION)
MJRoBot (Marcelo Rovai)
An impulse takes raw data, uses signal processing to extract features, and then uses a learning block to classify new data.
Dashboard
Devices
Data acquisition
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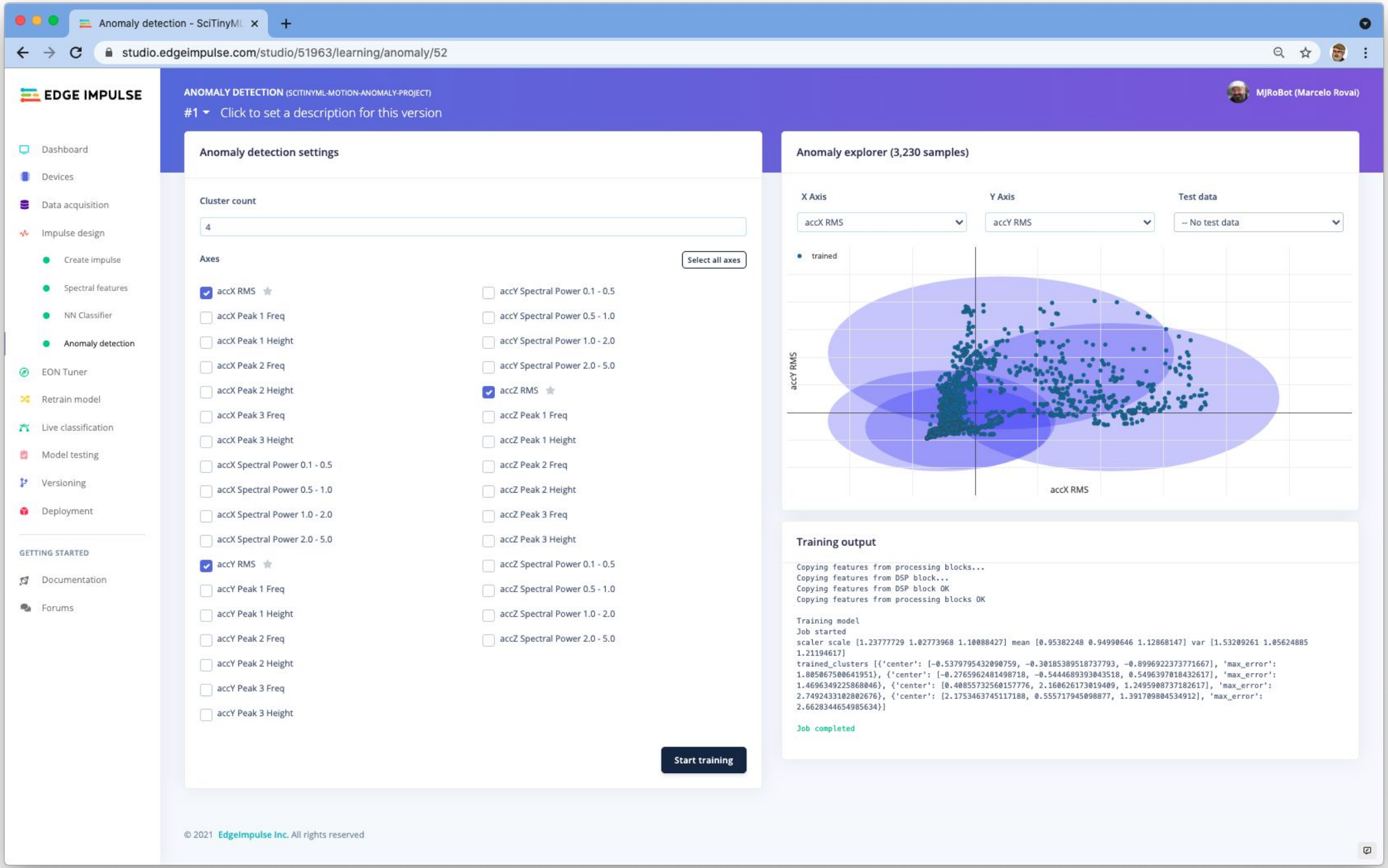
Spectral features
NN Classifier
EON Tuner
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Time series data
Axes
accX, accY, accZ
Window size
2000 ms.
Window increase
80 ms.
Frequency (Hz)
100
Zero-pad data
Spectral Analysis
Name
Spectral features
Input axes
accX
accY
accZ
Add a processing block
Classification (Keras)
Name
NN Classifier
Input features
Spectral features
Output features
4 (idle, lift, maritime, terrestrial)
Anomaly Detection (K-means)
Name
Anomaly detection
Input features
Spectral features
Output features
1 (Anomaly score)
Output features
5 (idle, lift, maritime, terrestrial, Anomaly score)
Save Impulse


Anomaly detection - SciTinyML
studio.edgeimpulse.com/studio/51963/learning/anomaly/52
EDGE IMPULSE
ANOMALY DETECTION (SCITINYML-MOTION-ANOMALY-PROJECT)
#1 Click to set a description for this version
MJRoBot (Marcelo Rovai)
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
Spectral features
NN Classifier
Anomaly detection
EON Tuner
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Anomaly detection settings
Cluster count
4
Axes
Select all axes
accX RMS
accX Peak 1 Freq
accX Peak 1 Height
accX Peak 2 Freq
accX Peak 2 Height
accX Peak 3 Freq
accX Peak 3 Height
accX Spectral Power 0.1 - 0.5
accX Spectral Power 0.5 - 1.0
accX Spectral Power 1.0 - 2.0
accX Spectral Power 2.0 - 5.0
accY RMS
accY Peak 1 Freq
accY Peak 1 Height
accY Peak 2 Freq
accY Peak 2 Height
accY Peak 3 Freq
accY Peak 3 Height
accY Spectral Power 0.1 - 0.5
accY Spectral Power 0.5 - 1.0
accY Spectral Power 1.0 - 2.0
accY Spectral Power 2.0 - 5.0
accZ RMS
accZ Peak 1 Freq
accZ Peak 1 Height
accZ Peak 2 Freq
accZ Peak 2 Height
accZ Peak 3 Freq
accZ Peak 3 Height
accZ Spectral Power 0.1 - 0.5
accZ Spectral Power 0.5 - 1.0
accZ Spectral Power 1.0 - 2.0
accZ Spectral Power 2.0 - 5.0
Start training
Anomaly explorer (3,230 samples)
X Axis
accX RMS
Y Axis
accY RMS
Test data
-- No test data
trained
accY RMS
accX RMS
Training output
Copying features from processing blocks...
Copying features from DSP block...
Copying features from DSP block OK
Copying features from processing blocks OK
Training model
Job started
scaler scale [1.23777729 1.02773968 1.10088427] mean [0.95382248 0.94990646 1.12868147] var [1.53209261 1.05624885 1.21194617]
trained_clusters [{'center': [-0.5379795432090759, -0.30185389518737793, -0.8996922373771667], 'max_error': 1.8050675006641951}, {'center': [-0.2765962481498718, -0.5444689393043518, 0.5496397018432617], 'max_error': 1.4696349225868046}, {'center': [0.40855732560157776, 2.160626173019409, 1.2495908737182617], 'max_error': 2.7492433102802676}, {'center': [2.1753463745117188, 0.555717945098877, 1.391709804534912], 'max_error': 2.6628344654985634}]
Job completed
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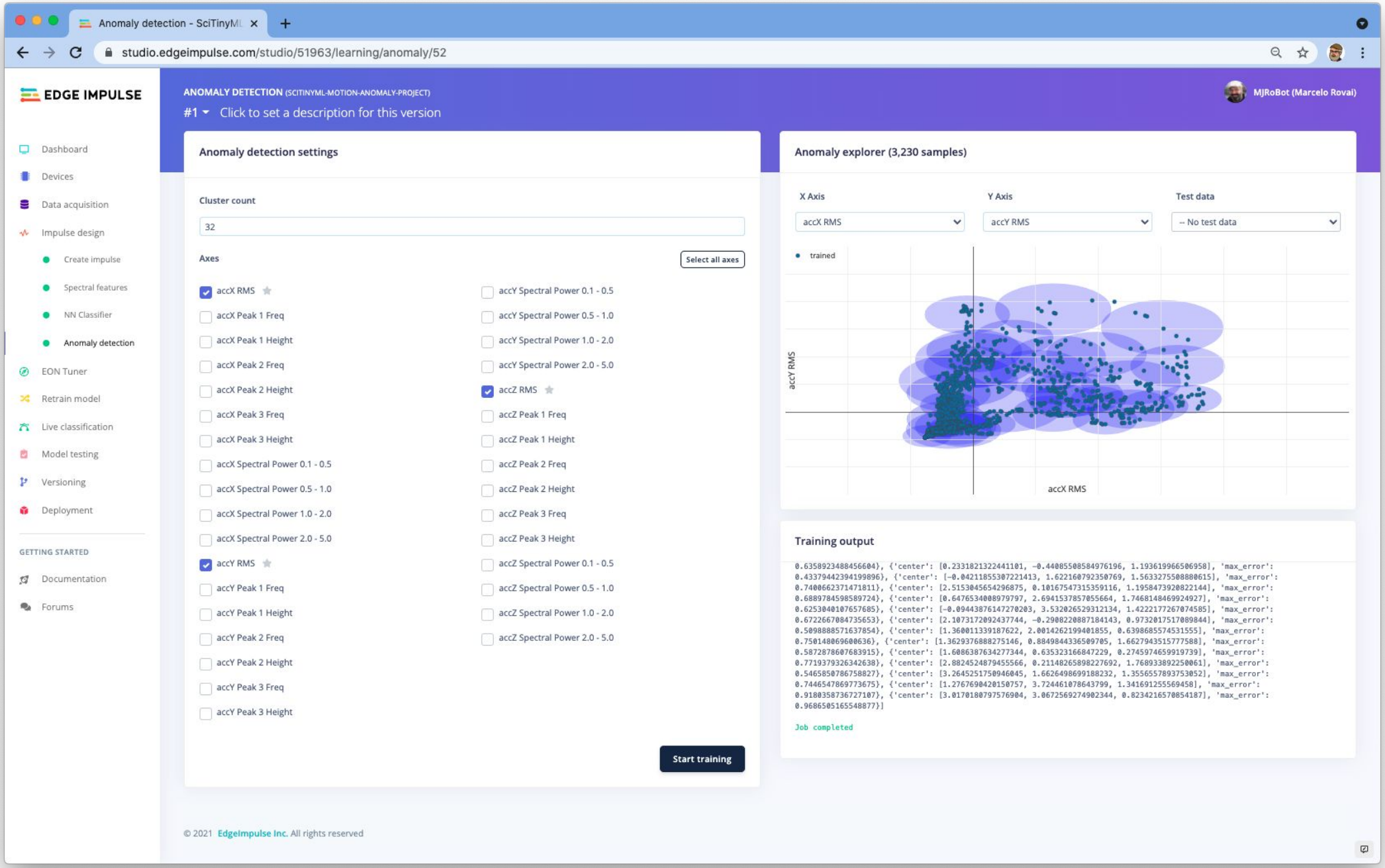
Anomaly detection - SciTinyML
studio.edgeimpulse.com/studio/51963/learning/anomaly/52
EDGE IMPULSE
ANOMALY DETECTION (SCITINYML-MOTION-ANOMALY-PROJECT)
#1 Click to set a description for this version
MJRoBot (Marcelo Rovai)
Dashboard
Devices
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Spectral features
NN Classifier
Anomaly detection
EON Tuner
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Anomaly detection settings
Cluster count
32
Axes
Select all axes
accX RMS
accX Peak 1 Freq
accX Peak 1 Height
accX Peak 2 Freq
accX Peak 2 Height
accX Peak 3 Freq
accX Peak 3 Height
accX Spectral Power 0.1 - 0.5
accX Spectral Power 0.5 - 1.0
accX Spectral Power 1.0 - 2.0
accX Spectral Power 2.0 - 5.0
accY RMS
accY Peak 1 Freq
accY Peak 1 Height
accY Peak 2 Freq
accY Peak 2 Height
accY Peak 3 Freq
accY Peak 3 Height
accY Spectral Power 0.1 - 0.5
accY Spectral Power 0.5 - 1.0
accY Spectral Power 1.0 - 2.0
accY Spectral Power 2.0 - 5.0
accZ RMS
accZ Peak 1 Freq
accZ Peak 1 Height
accZ Peak 2 Freq
accZ Peak 2 Height
accZ Peak 3 Freq
accZ Peak 3 Height
accZ Spectral Power 0.1 - 0.5
accZ Spectral Power 0.5 - 1.0
accZ Spectral Power 1.0 - 2.0
accZ Spectral Power 2.0 - 5.0
Start training
Anomaly explorer (3,230 samples)
X Axis
accX RMS
Y Axis
accY RMS
Test data
-- No test data
trained
accY RMS
accX RMS
Training output
0.6358923488456604}, {'center': [0.2331821322441101, -0.44085508584976196, 1.193619966506958], 'max_error':
0.43379442394199896}, {'center': [-0.04211855307221413, 1.622160792350769, 1.5633275508880615], 'max_error':
0.7400662371471811}, {'center': [2.5153045654296875, 0.10167547315359116, 1.1958473920822144], 'max_error':
0.6889784598589724}, {'center': [0.6476534008979797, 2.6941537857055664, 1.7468148469924927], 'max_error':
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0.7719379326342638}, {'center': [2.8824524879455566, 0.21148265898227692, 1.768933892250061], 'max_error':
0.5465850786758827}, {'center': [3.2645251750946045, 1.6626498699188232, 1.3556557893753052], 'max_error':
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0.9180358736727107}, {'center': [3.0170180797576904, 3.0672569274902344, 0.8234216570854187], 'max_error':
0.9686505165548877}]
Job completed
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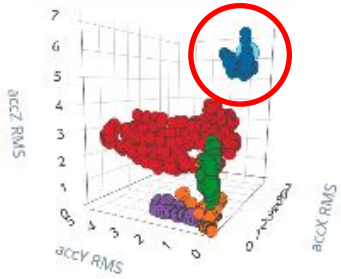
Spectral features (3,327 samples)

X Axis: accX RMS

Y Axis: accY RMS

Z Axis: accZ RMS

- classified
- idle
- lift
- maritime
- terrestrial
- classification 49



Processed features

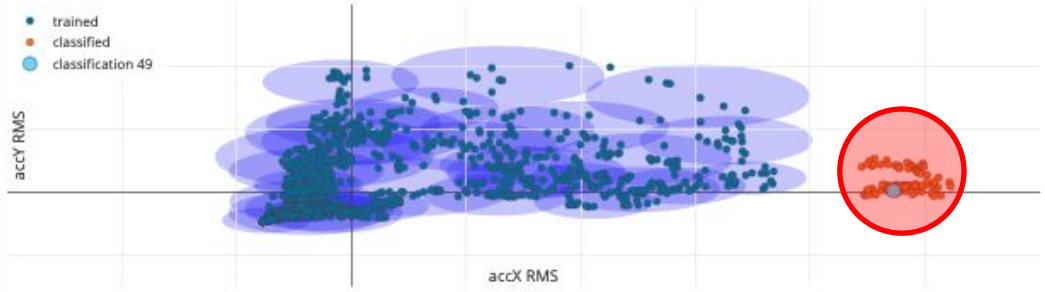
6.8037, 0.4960, 8.2240, 1.4881, 3.2398, 2.9762, 0.4911, 7.0271, 0.9133, 0.6076, 0.0159, 1.0079, 0.4960, 1.0556, 2.4802, 0.1…

Anomaly explorer (3,327 samples)

X Axis: accX RMS

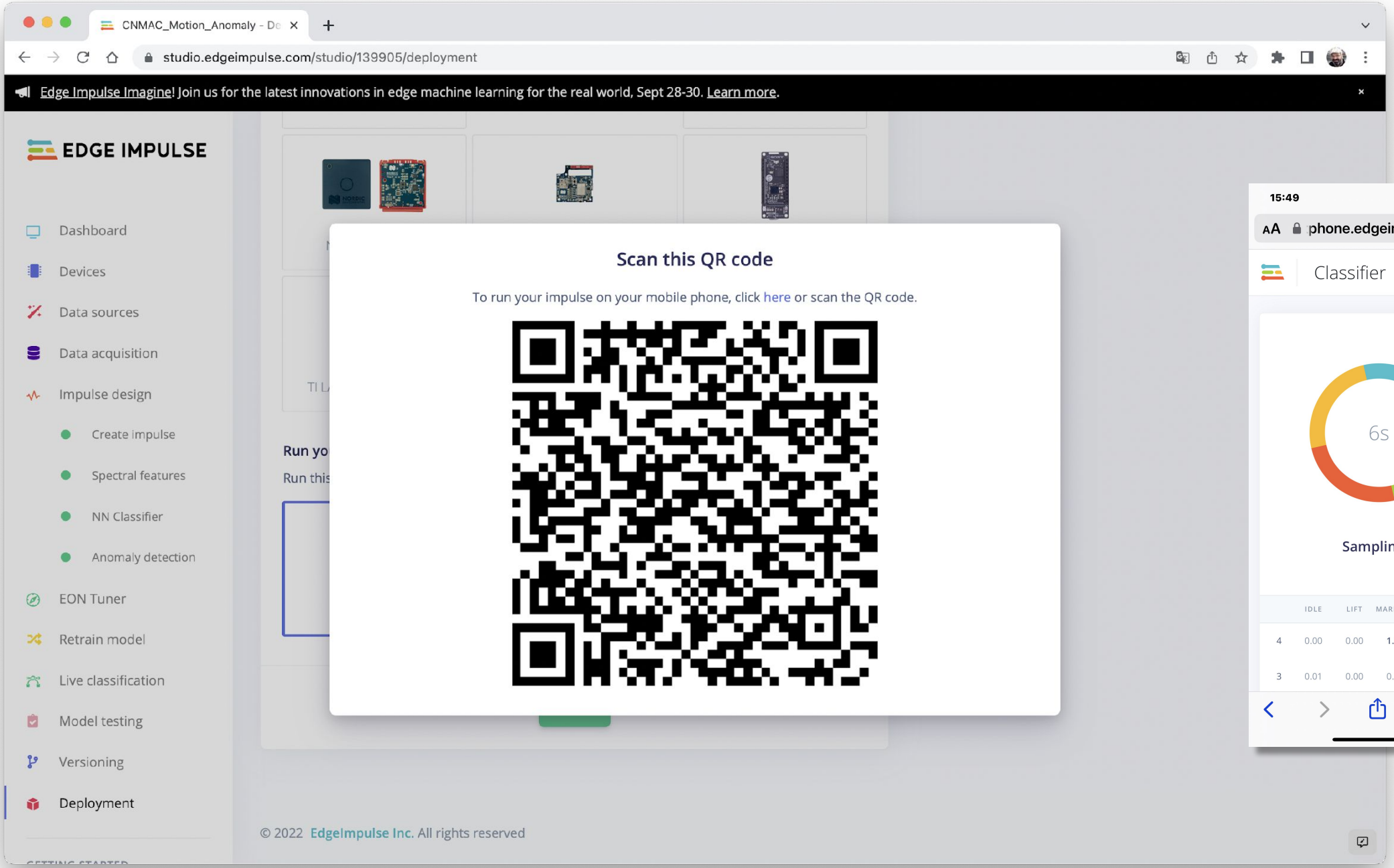
Y Axis: accY RMS

- trained
- classified
- classification 49



Distance from closest cluster

accX RMS: 1.2592, accY RMS: 0.4069, accZ RMS: 2.8992


CNMAC_Motion_Anomaly - De
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Model testing
Versioning
Deployment
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15:49
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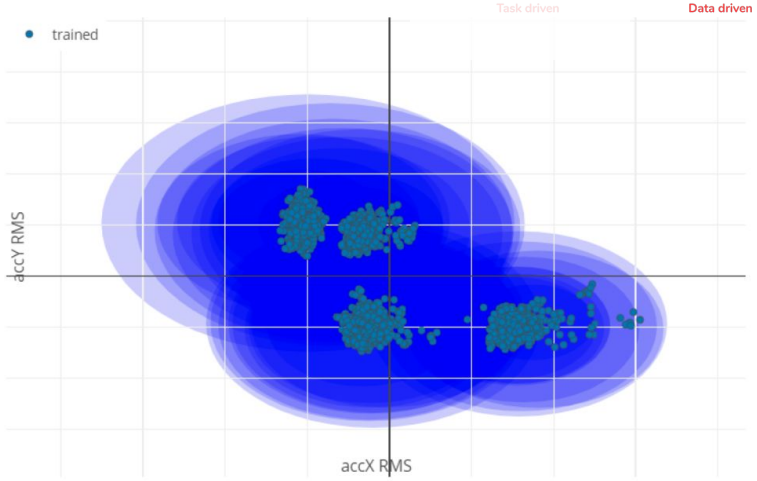
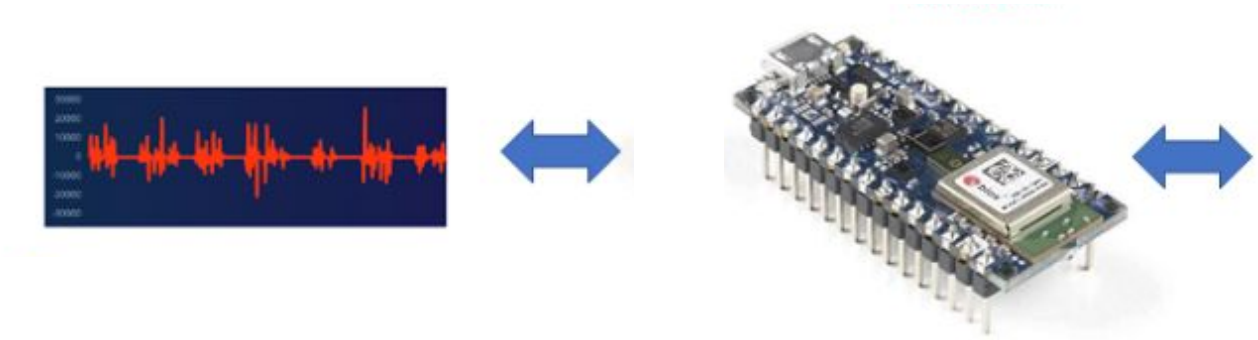
Classifier
6s
Sampling...
IDLE
LIFT
MARITIME
TERREST...
ANO...
4
0.00
0.00
1.00
0.00
2.00
3
0.01
0.00
0.16
0.83
-0.10

Industrial – Anomaly Detection





[IESTI01 2021.2 - Final Group Project: Bearing Failure Detection]

To learn more about Edge AI

- UNIFEI - IESTI01 TinyML - Machine Learning for Embedding Devices
- Professional Certificate in Tiny Machine Learning (TinyML) – edX/Harvard
- Introduction to Embedded Machine Learning - Coursera/Edge Impulse
- Computer Vision with Embedded Machine Learning - Coursera/Edge Impulse
- "Deep Learning with Python" book by François Chollet
- "TinyML" book by Pete Warden, Daniel Situnayake
- "TinyML Cookbook" by Gian Marco Iodice
- "AI at the Edge" book by Daniel Situnayake, Jenny Plunkett

Thanks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