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Enhancing Humanoid Robot Autonomy:

An ISPU-Based Approach to Fall Detection and Prevention

Giuseppe Messina

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Introduction

- This experiment is part of a complete ISPU (Intelligent Sensor Processing Unit) project in collaboration with University of Catania.
- The main objective is to improve the stability of a **humanoid robot, decreasing Microcontroller processing effort.**
- The ISPU is used to collect real-time data on the robot's movements.
- These data are used to detect any imbalances in the robot and to take corrective actions in real-time.

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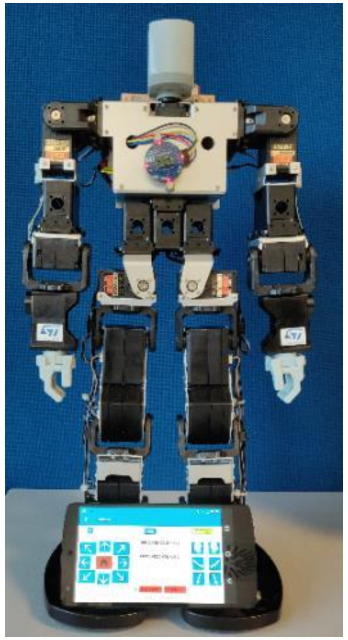
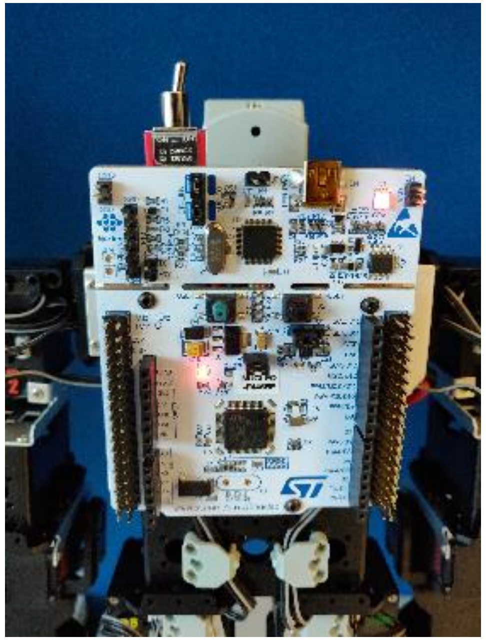
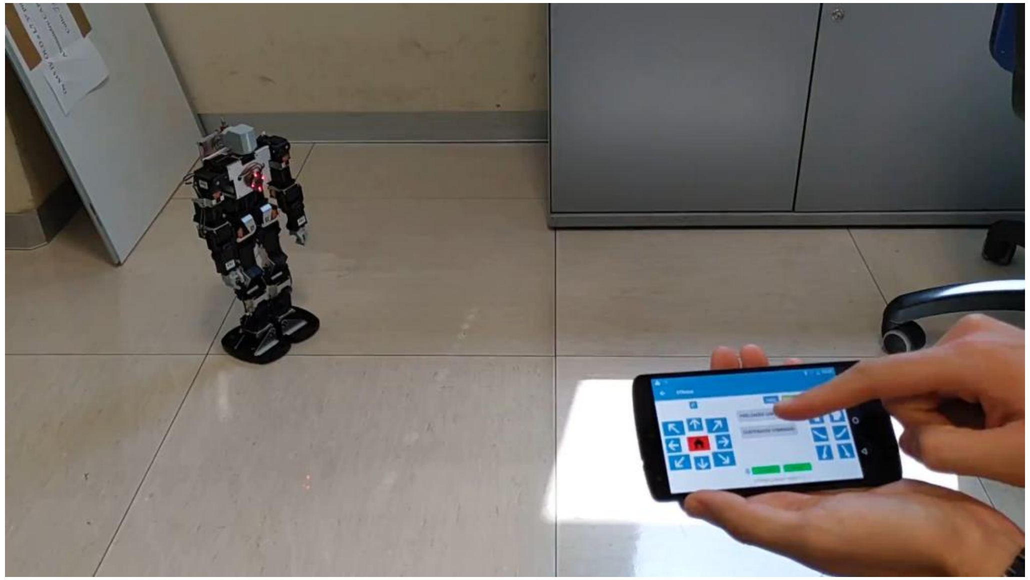
Kondo Robot with ST-Nucleo

- Kondo KHR-3HV
  - Replaced the Renesas-based main board for motor control with the Core STM32F44RE board.
  - Added BlueCoin board for BLE communication
  - STM32-Kondo-Bot is paired with an ad-hoc Android app.

Kondo KHR-3HV

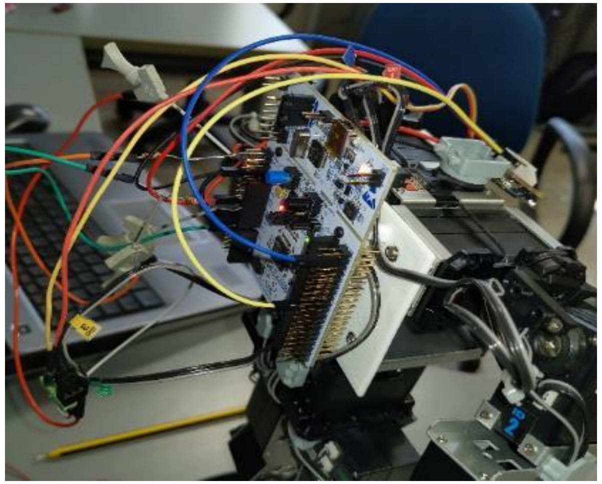




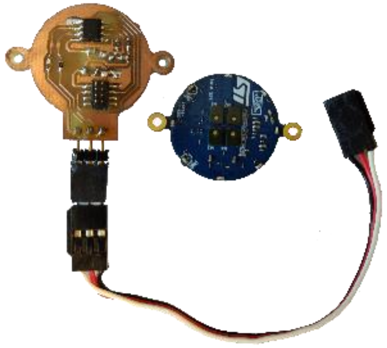


Customizations

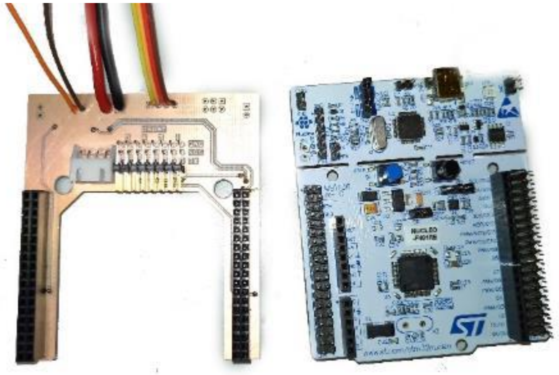
- Two expansion boards have been developed to connect the BlueCoin card and the Nucleo STM32
  - For the BlueCoin, we used an expansion that allows to connect data and power from the Nucleo.
  - For the Nucleo board we have developed an expansion that allows the connection of 6 data channels, power supply and battery control.
- We could have done that without these expansions, but it would have been a lot less tidy.



No custom expansion boards



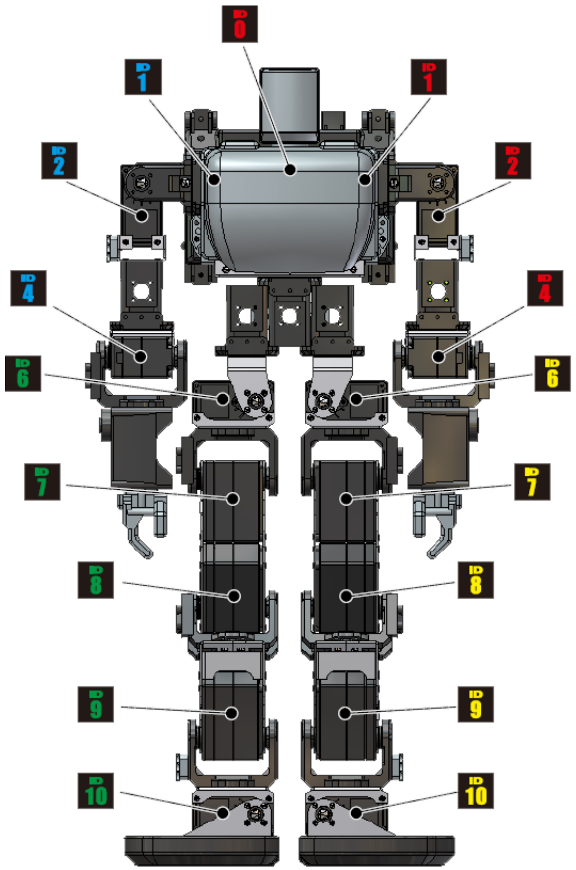
Bluecoin and transceiver

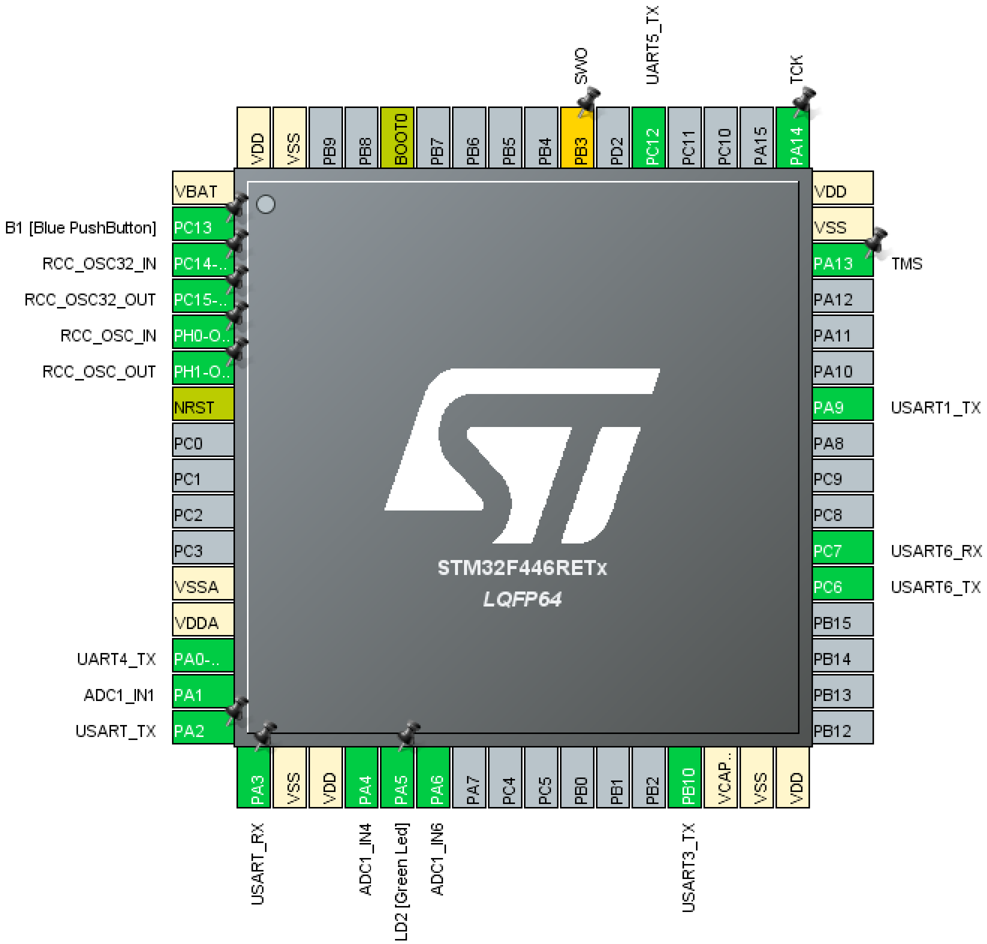


Nucleo and Motors Connector

STM32CubeMx

- Peripherals:
  - USART1 → Red Line
  - USART3 → Blue Line
  - UART4 → Yellow Line
  - UART5 → Green Line
  - USART2 → Debug USB
  - USART6 → Communication with Bluecoin
- ADC1 → Battery Management





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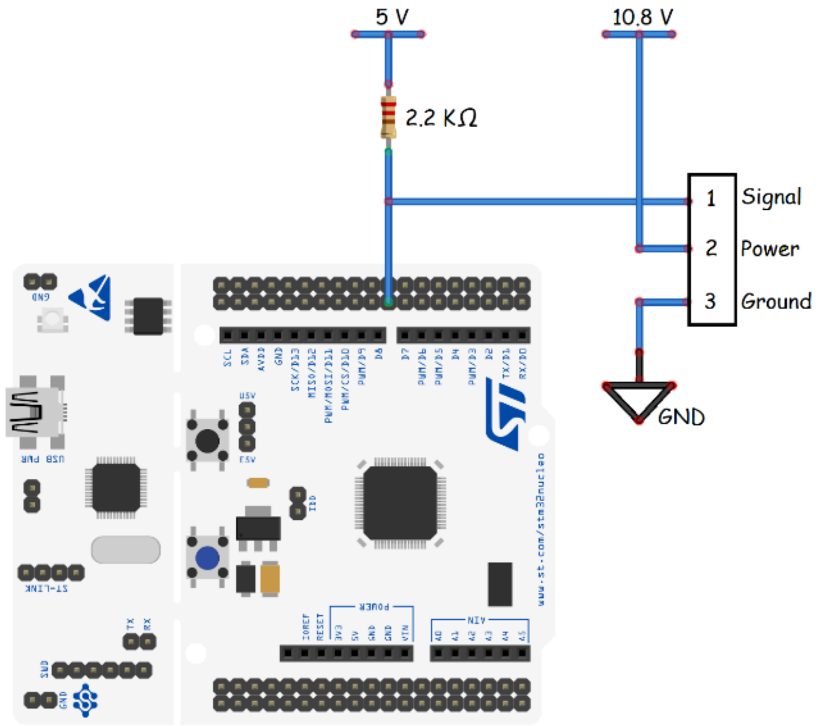
ICS3.5 Communication Standard

- High-speed communication of up to 1.25 Mbps
- Max 32 servo motors connected on the same line
- Single data line used for serial communication (Half-Duplex)
- Multi-drop connection
- Signal level 5 V TTL
- ID Setting
- Read and Write Parameters
- Setting the Location



CMD	SC	DATA
Command Header+ ID	Sub-control	Data

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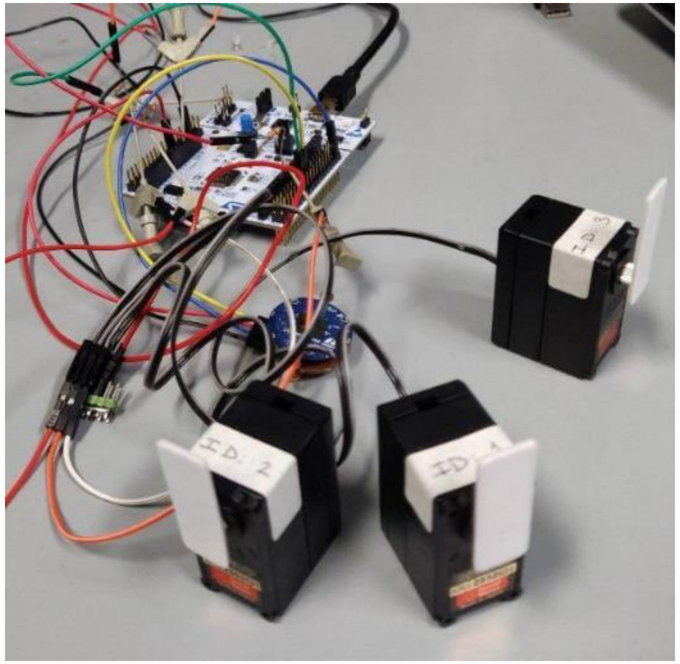
Firmware Implementation

- ICS.h:
  - ics_get_id()
  - ics_set_id()
  - ics_get_speed()
  - ics_set_speed()
  - ics_get_stretch()
  - ics_set_stretch()
  - ics_get_current()
  - ics_pos()
  - ics_free()

```c
uint16_t ics_pos(ICSData *r, uint16_t id, uint16_t pos, UART_HandleTypeDef *huart)
{
    uint16_t byte_in = 3;
    uint16_t byte_out = 4;

    if(id>31)
    {
        snprintf(r->error,128,"ERROR: Invalid servo ID (0-31)");
        return -1;
    }

    if(pos>16383)
    {
        snprintf(r->error,128,"ERROR: Invalid servo position (0-16383)");
        return -1;
    }

    //build command
    r->swap[0] = id | ICS_CMD_POS;    //Command
    r->swap[1] = (pos >> 7) & 0x7F;    //POS_H: high 7 bits of pos
    r->swap[2] = pos & 0x7F;    //POS_L: low 7 bits of pos

    //send command
    HAL_UART_Transmit(huart, r->swap, byte_in, ICS_POS_TIMEOUT);

    for(int i=0; i < byte_in; i++)
        r->swap[i] = 0;

    //wait for the the response
    HAL_UART_Receive(huart, r->swap, byte_out, ICS_POS_TIMEOUT);

    //return the position
    return (((r->swap[2] & 0x7F) << 7) | (r->swap[3] & 0x7F));
}
```



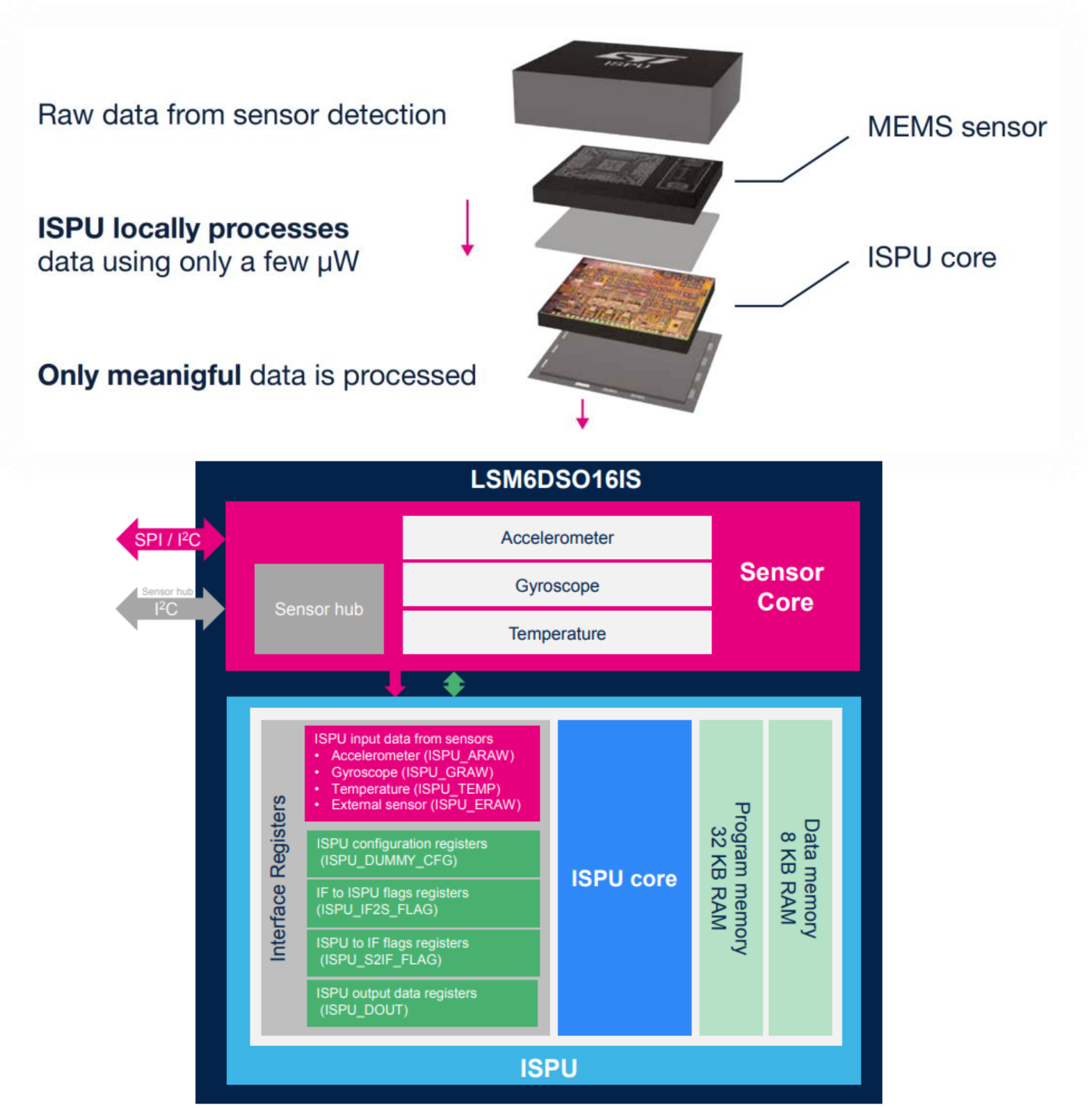
Intelligent Sensor Processing Units

ISPUs introduce artificial intelligence into the world of sensors, within a compact and low-power device:

- The core reads the values generated by the sensors.
- It processes them using pre-processing algorithms or artificial intelligence.
- It provides the result via I2C or SPI interface.

Used sensor: LSM6DSO16IS

- 3-axes Accelerometer and Gyroscope.
- **32KB of programmable RAM**.
- **8KB of data RAM**.



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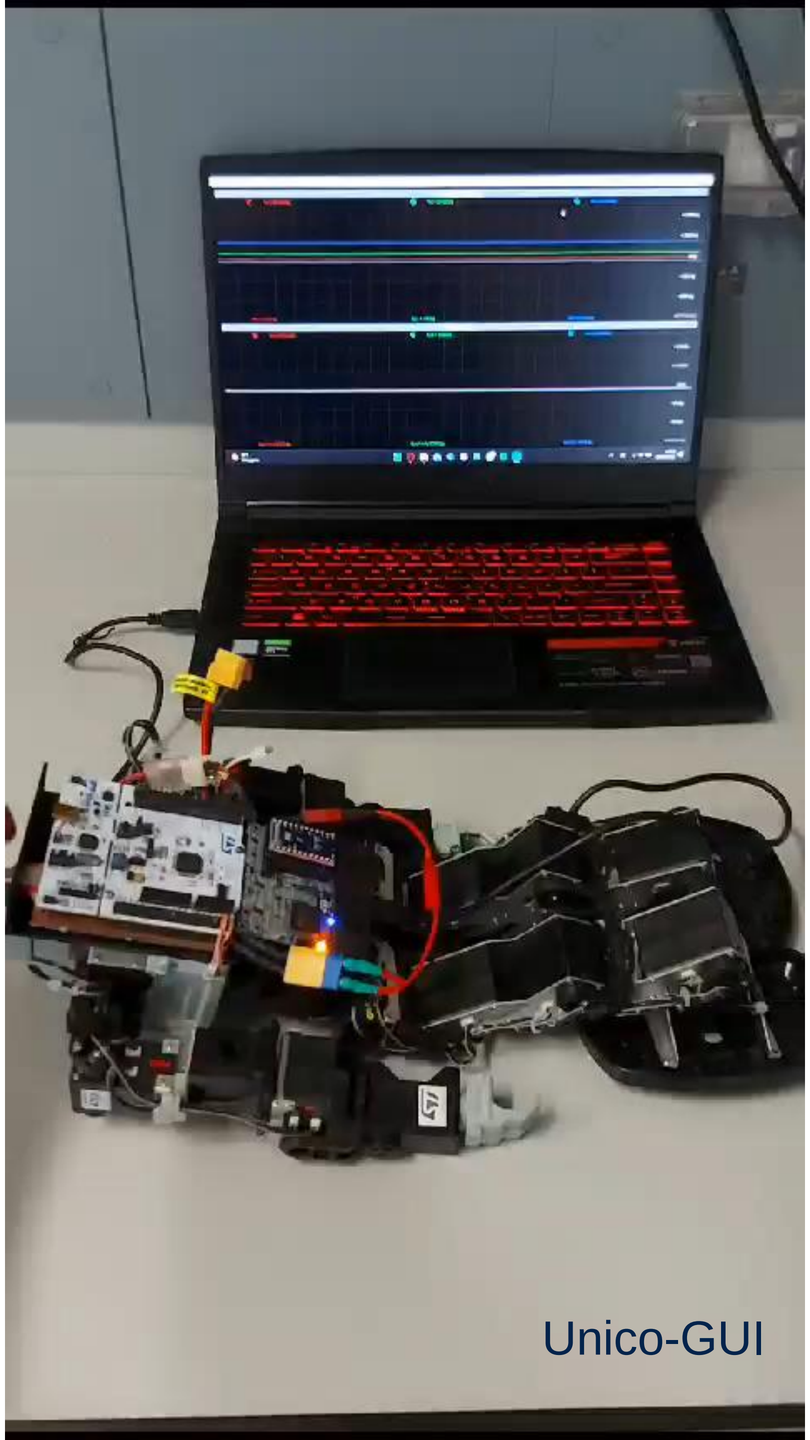
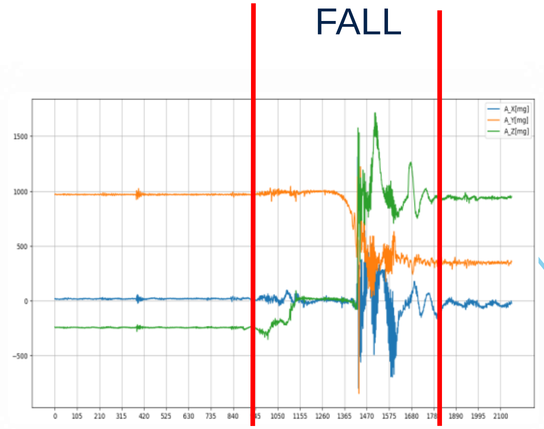
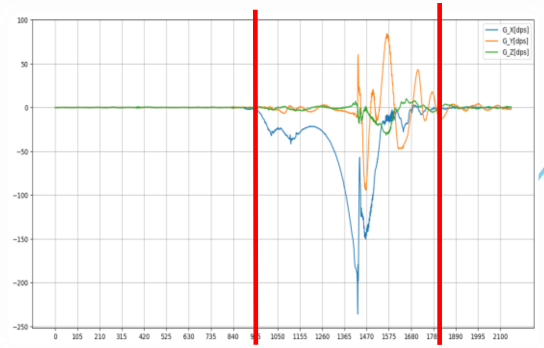
Sensor Fusion



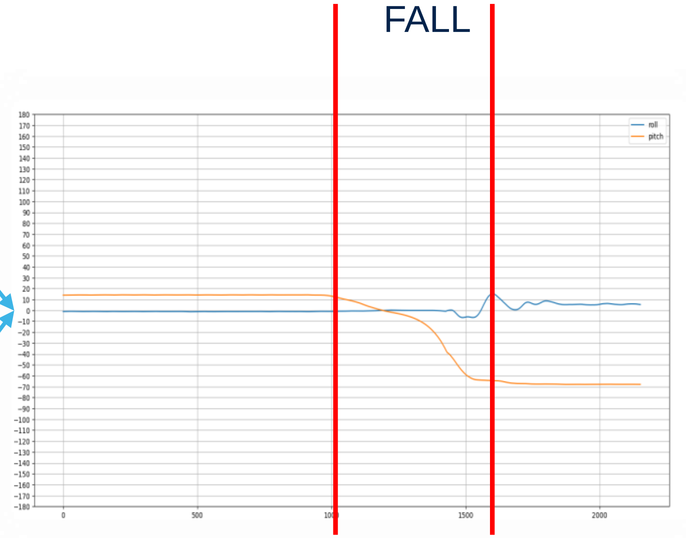
Unico-GUI



Data recorded by the accelerometer



Data recorded by the gyroscope



Roll and pitch data obtained after sensor fusion filter application (Madgwick filter)

Dataset Construction

Step 1

Integration of the Madgwick filter within the ISPU

Step 2

Implementing Registration Firmware for the SensorTileBox.Pro

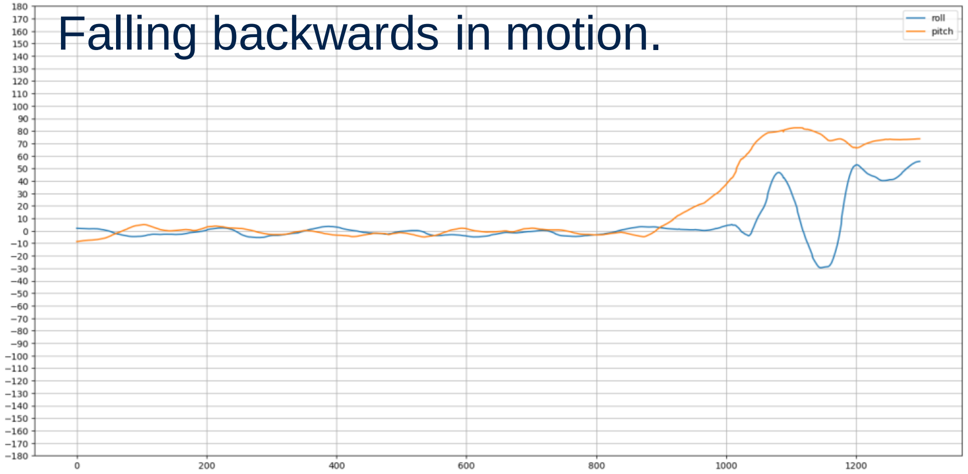
Step 3

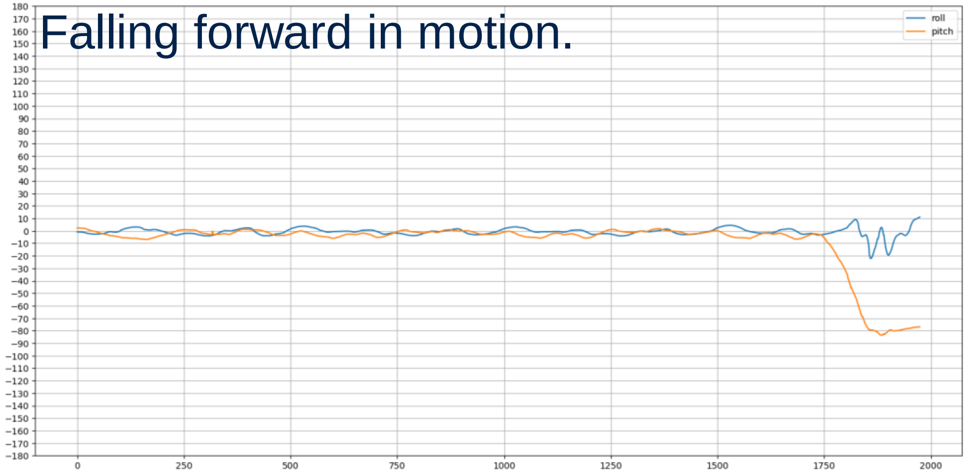
Capturing roll and pitch data

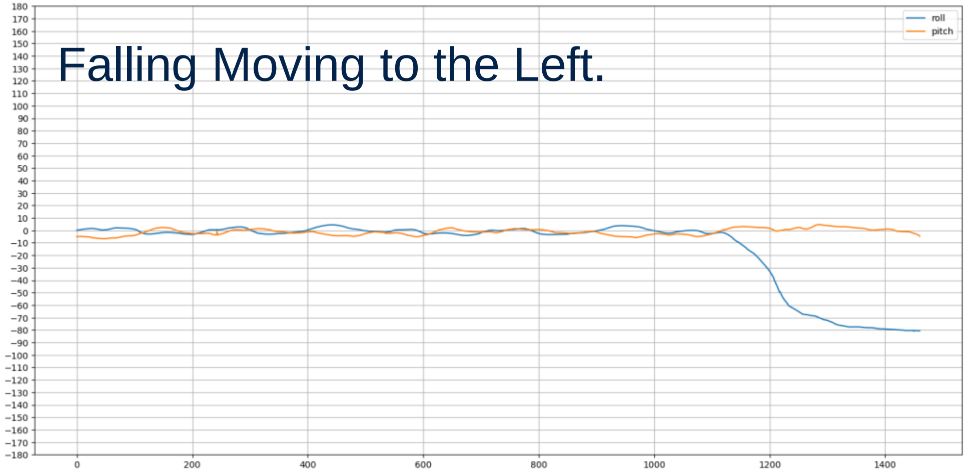
Step 4

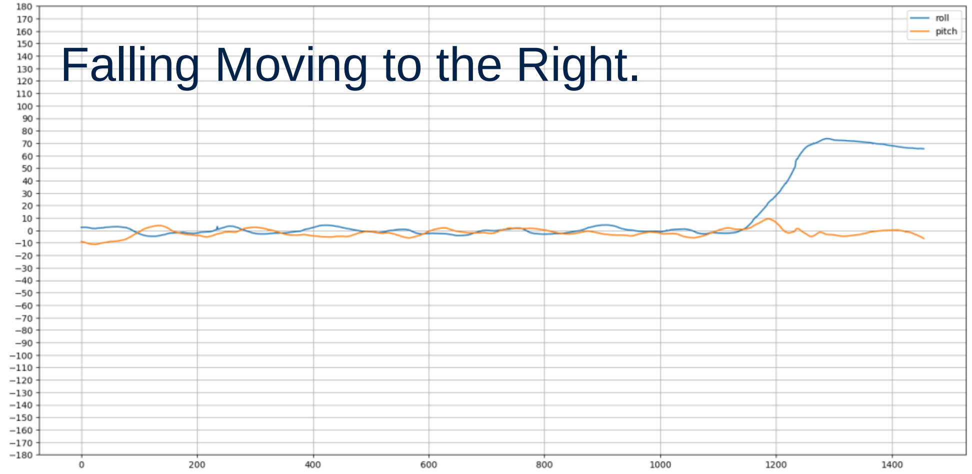
Dataset labeling

Falls with Moving Robots



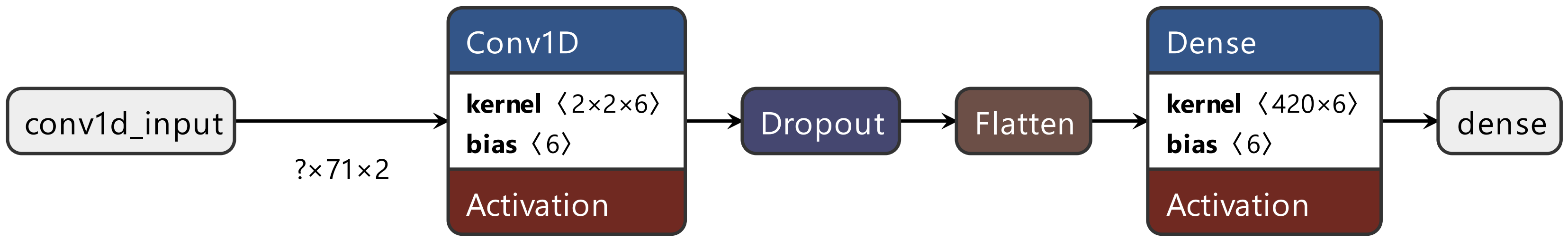






Dataset acquisition: 20 sequences for each classes (stationary, walking, front_falling, right_falling, back_falling, left_falling) of about 250 samples.

First Developed Model



- The model is inspired by a Human Activity Recognition network*
- The network has been significantly simplified to meet the ISPU's limited memory resource needs.
- The sampling rate used by the sensors is 416 Hz
- The network is structured as follows:
  - 6-filter convolutional layer with ReLU activation function and 71 × 2 input shape
  - Dropout layer with a factor of 0.5, to prevent overfitting
  - Flatten layer
  - Strongly connected output layer with Softmax activation function

*Human Activity Recognition: https://github.com/STMicroelectronics/stm32ai-wiki/blob/master/AI_resources/HAR/Human_Activity_Recognition.ipynb

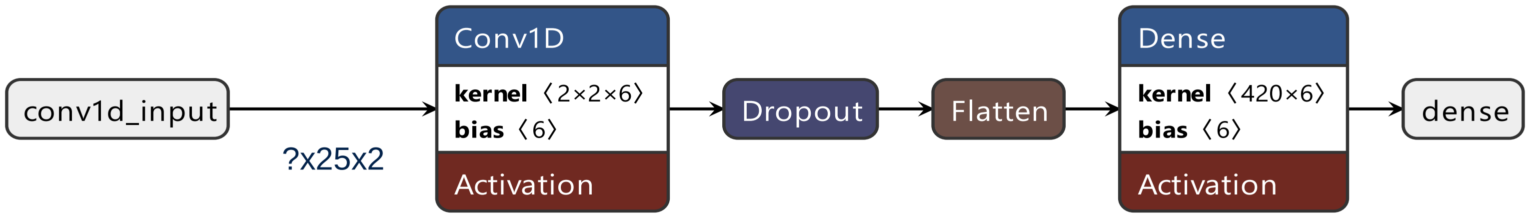
Results

Accuracy around 93%

True label \ Predicted label	stationary	walking	f_falling	r_falling	b_falling	l_falling
stationary	0.99	0.01	0.00	0.00	0.00	0.00
walking	0.03	0.96	0.00	0.00	0.01	0.00
f_falling	0.01	0.19	0.80	0.00	0.00	0.00
r_falling	0.00	0.04	0.00	0.96	0.00	0.00
b_falling	0.15	0.00	0.00	0.00	0.85	0.00
l_falling	0.00	0.00	0.00	0.00	0.00	1.00

75% Training set, 25% Test set

Second Developed Model



- Final release size of the **first model**, after compression and quantization + Magdwick filter (15KB) was **33000 bytes over 32768 bytes** available on ISPU.
- The network has been further simplified to meet the ISPU's memory and processing time:
  - The sampling rate used by the sensors has been reduced to **52 Hz (comprise network reaction time)**
  - The network is structured as follows:
    - 6-filter convolutional layer with ReLU activation function and **25 × 2** input shape
    - Dropout layer with a factor of 0.5, to prevent overfitting
    - Flatten layer
    - Strongly connected output layer with Softmax activation function
    - Acquisition Dataset errors were removed
- Final release size of second model, after compression and quantization: **27828 bytes with an Accuracy of about 94%**

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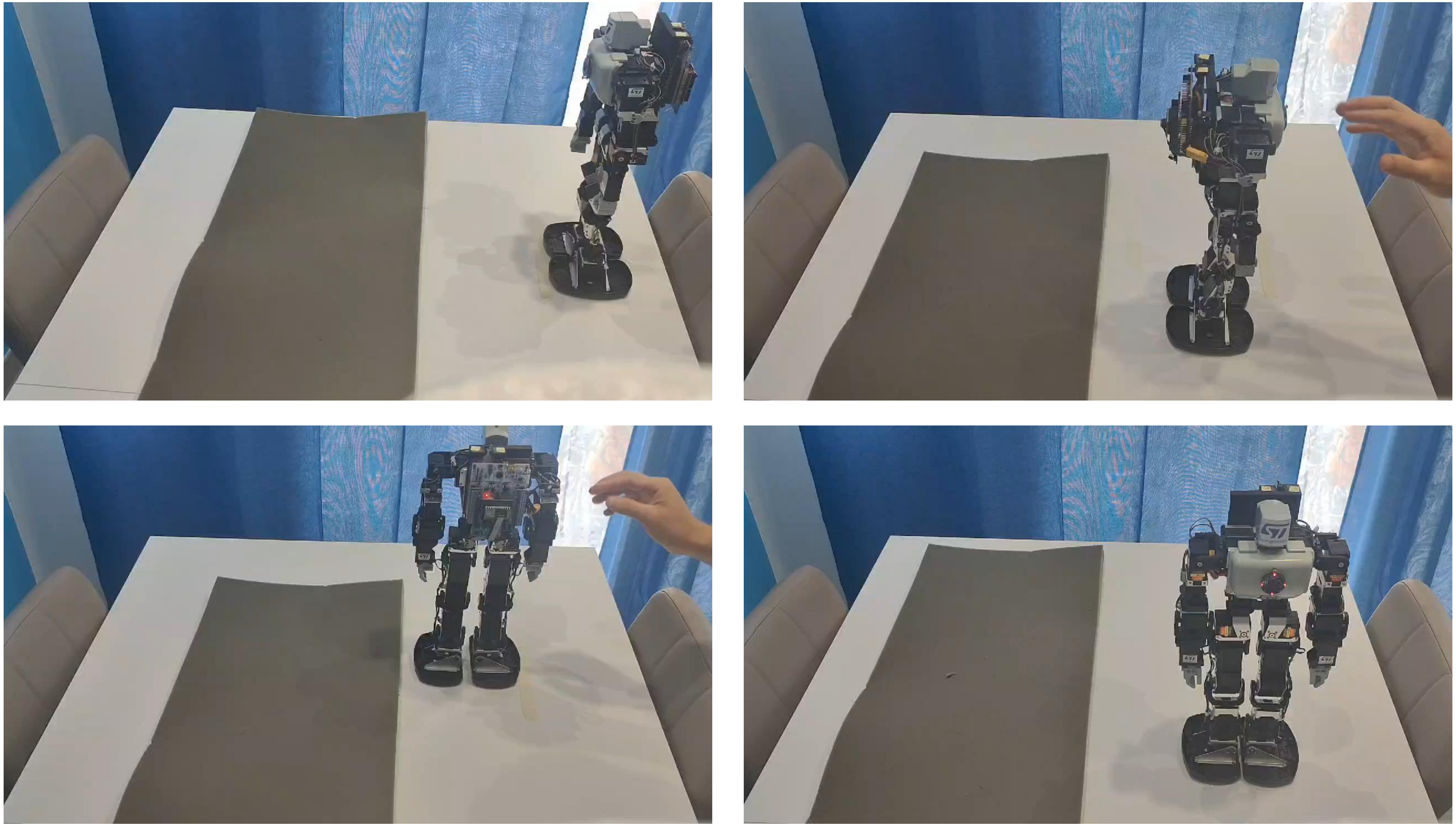
Final Accuracy

Accuracy around 94%

True label \ Predicted label	stationary	walking	f_falling	r_falling	b_falling	l_falling
stationary	1.00	0.00	0.00	0.00	0.00	0.00
walking	0.00	1.00	0.00	0.00	0.00	0.00
f_falling	0.00	0.07	0.93	0.00	0.00	0.00
r_falling	0.00	0.04	0.08	0.88	0.01	0.00
b_falling	0.01	0.00	0.00	0.01	0.98	0.00
l_falling	0.00	0.00	0.00	0.02	0.05	0.93

75% Training set, 25% Test set

Falling+Recover



Conclusion

- A complete Falling Detection system with Recover has been developed
- The system is based on an Intelligent Sensor Processing Unit, allowing real-time processing and decreasing Microcontroller computational effort.
- Future works:
  - Time of Flight and Camera integration
  - ROS integration, for real-time Avatar visualization

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