CORBYS
Cognitive Control Framework for Robotic Systems

University of Reading

Modular Situation Assessment Architecture for Cognitive Robot Control through Multi-Modal Sensing of Dynamic Environments

Intelligent Systems Research Laboratory
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SEVENTH FRAMEWORK PROGRAMME

Outline

- The CORBYS Architecture
- Cognitive modules integration
  - Human Sensory System,
  - Situation Awareness Black Board SWABB,
  - BCI (Intention to start walking)
- Muscle Activity, Gait Analysis
- User Responsive Training & Orthosis Actuation Adaptation
- FPGA based Reflexive Layer for Safety Management
- In-FPGA Complex Event Processing

CORBYS

www.Corbys.eu

- Cognitive Control Architecture for Robotic Systems
- Human Sensory System for the Situation Assessment

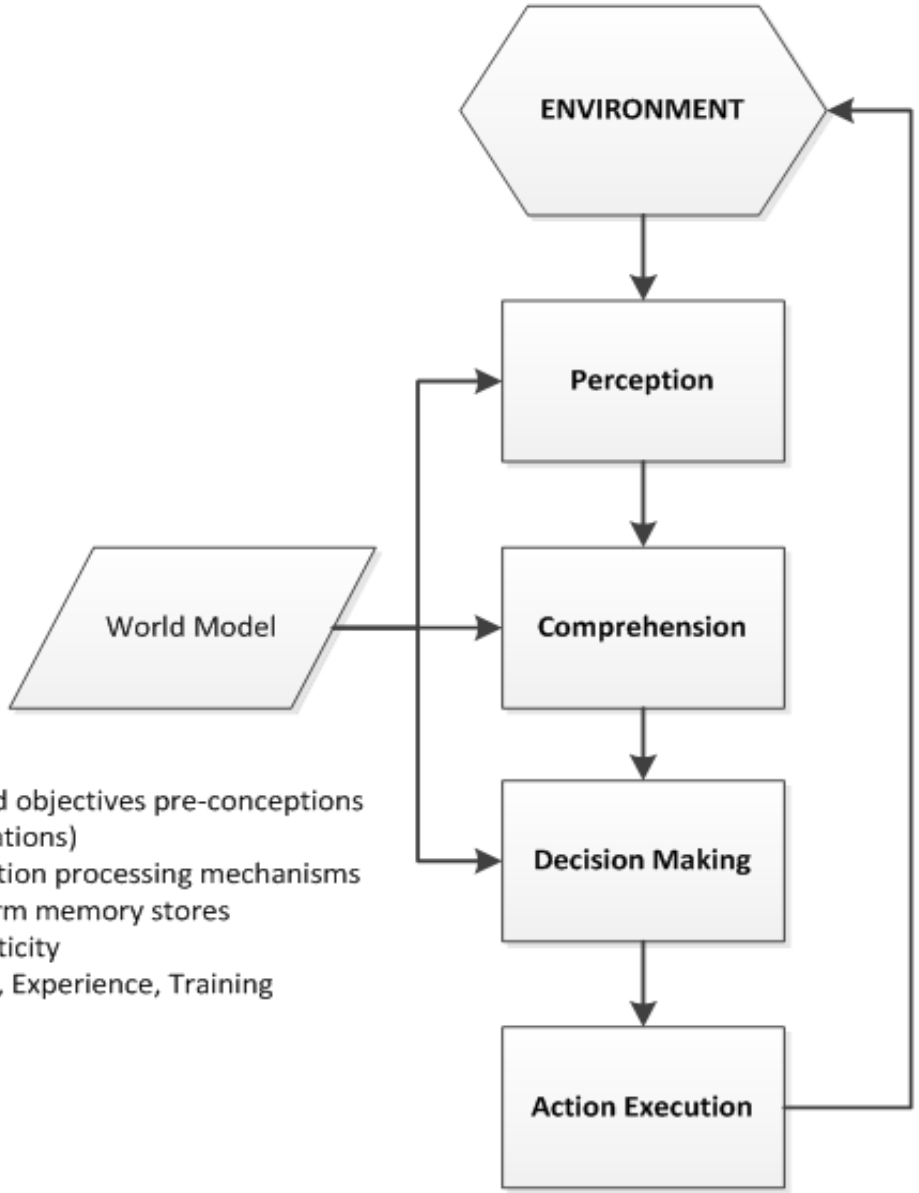
with two Demonstrators

- I) Gait Rehabilitation Assistant
- 2) Human Follower/Co-worker

Robo-Humatics

- In a dynamic operational environment of human-robot interaction, need awareness of the interacting human state and activity for robotic decision making
- **Human-robot co-working is** supported by our Human Sensory System, for measuring physiological data during robot-assisted gait rehabilitation, which provides sensors and infrastructure to measure the physiological data.
- **The HSS Data is for Situation Assessment Architecture in monitoring the human state, operational environment states & demand, responsive activity and performance states to aid the process of gait rehabilitation**

CORBYS Demonstrator II: The Human Robot Follower



- Perceive: Recognise patterns
- Perceive: Identify objects
- Perceive: Label/classify objects

- Comprehend: Relation between objects
- Comprehend: Inference regarding objects relations

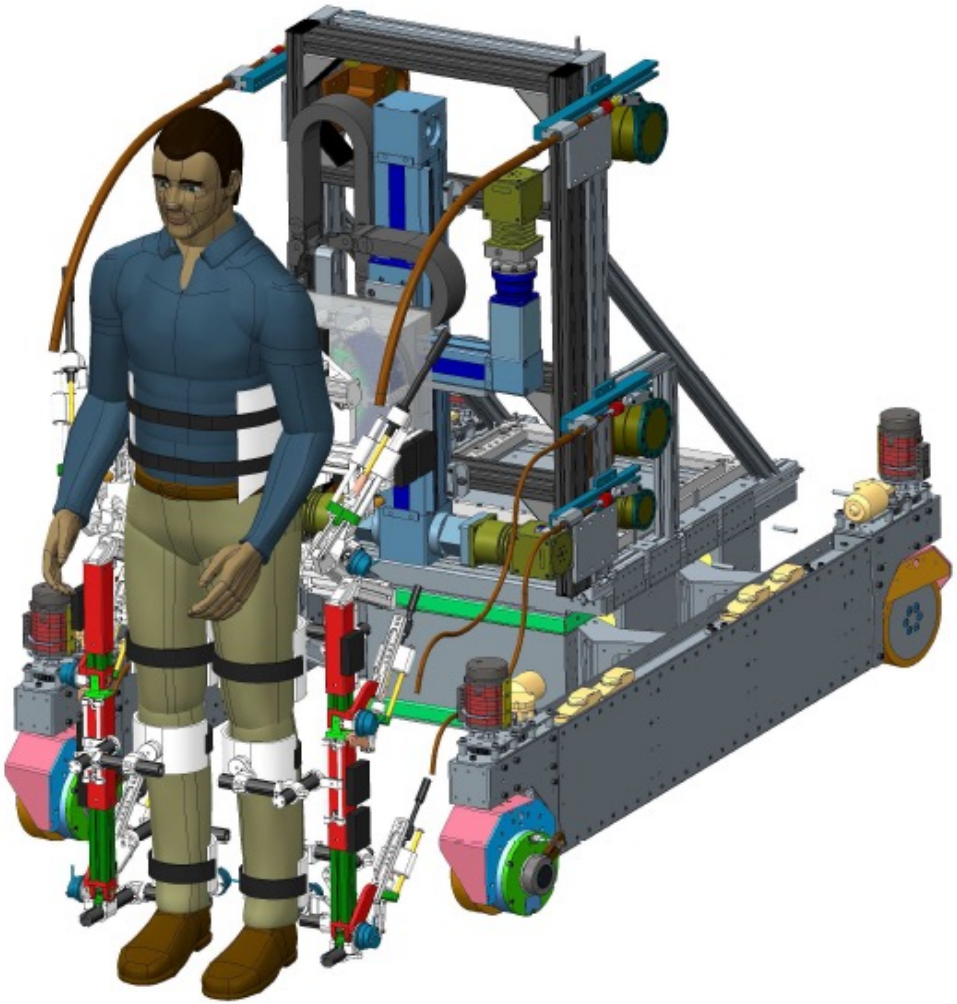
- Goal and objectives pre-conceptions (Expectations)
- Information processing mechanisms
- Long-term memory stores
- Automaticity
- Abilities, Experience, Training

Robotic Systems in Gait Rehabilitation has to

- Provide safe, intensive and task-oriented rehabilitation.
- Support structured, precise & controllable training sessions.
- Support objective measurement for therapy evaluation.
- Support routinisable therapy session prescription & motivation.
- Reduce the need for human intervention in training sessions.
- Gait recovery robotic systems vary from simple electromechanical walking aids - treadmill with body weight support to electro-mechanical exoskeletons.

Gait rehabilitation robotic systems have to be in truly symbiotic relationships with human users.

Modular Situation Assessment Architecture for Cognitive Robot Control through Multi-Modal Sensing of Dynamic Environments



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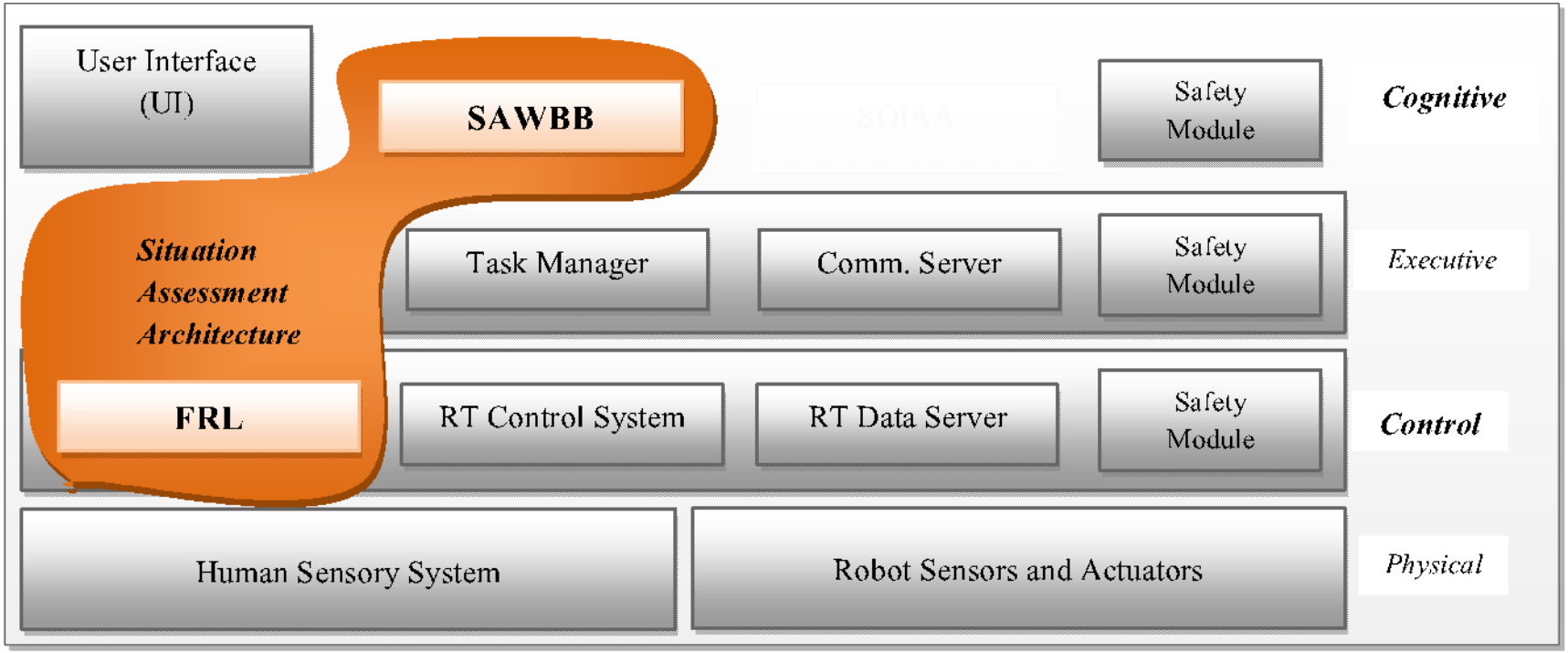
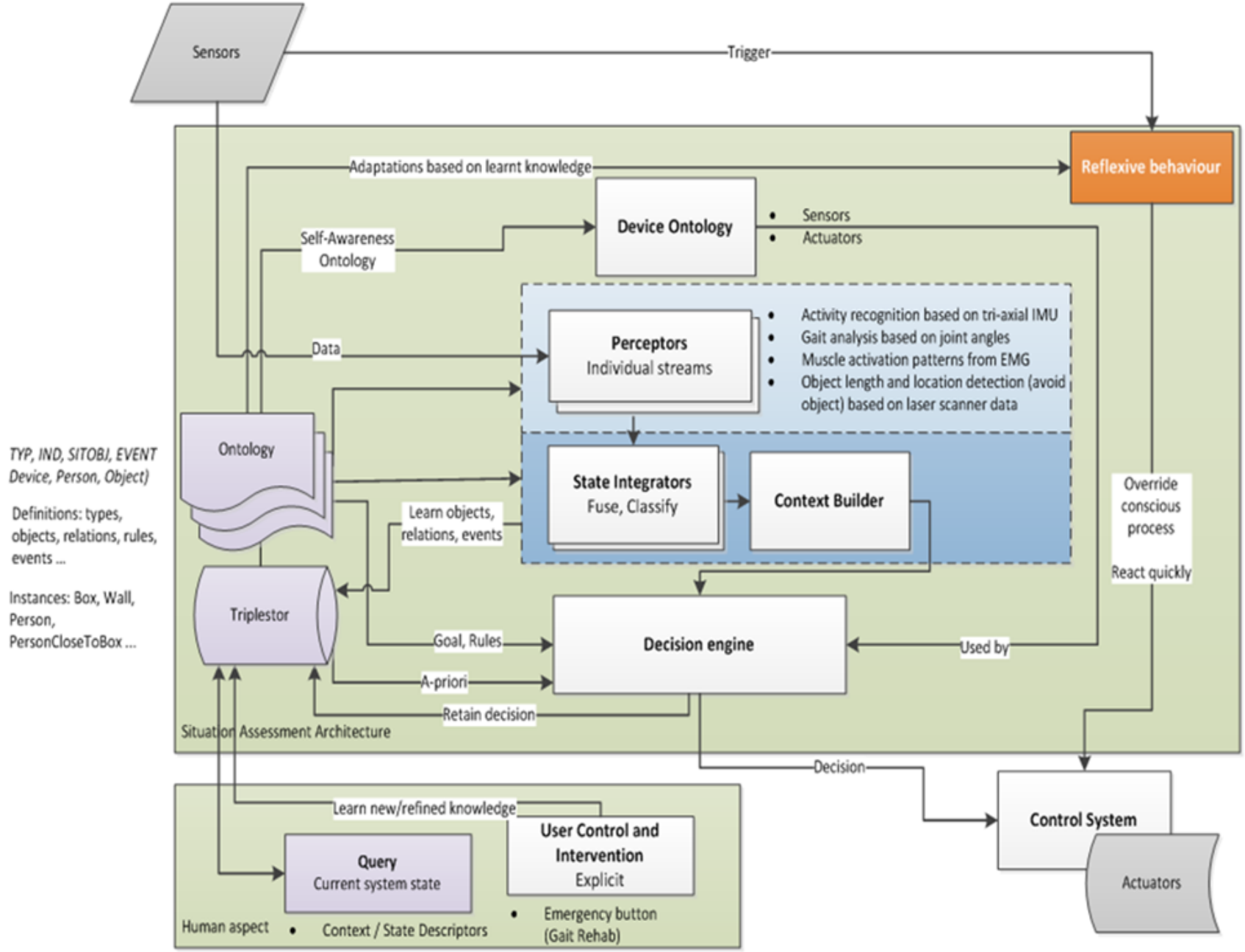
Situation Assessment Architecture

- ***Situation Awareness (SAWBB)***
  - Activity Recognition
  - Person state monitoring
  - Gait segmentation, extraction and analysis
  - Muscle activity analysis
  - BCI intention processing
  - Synchronisation
  - ***FPGA Reflexive Layer (FRL)***





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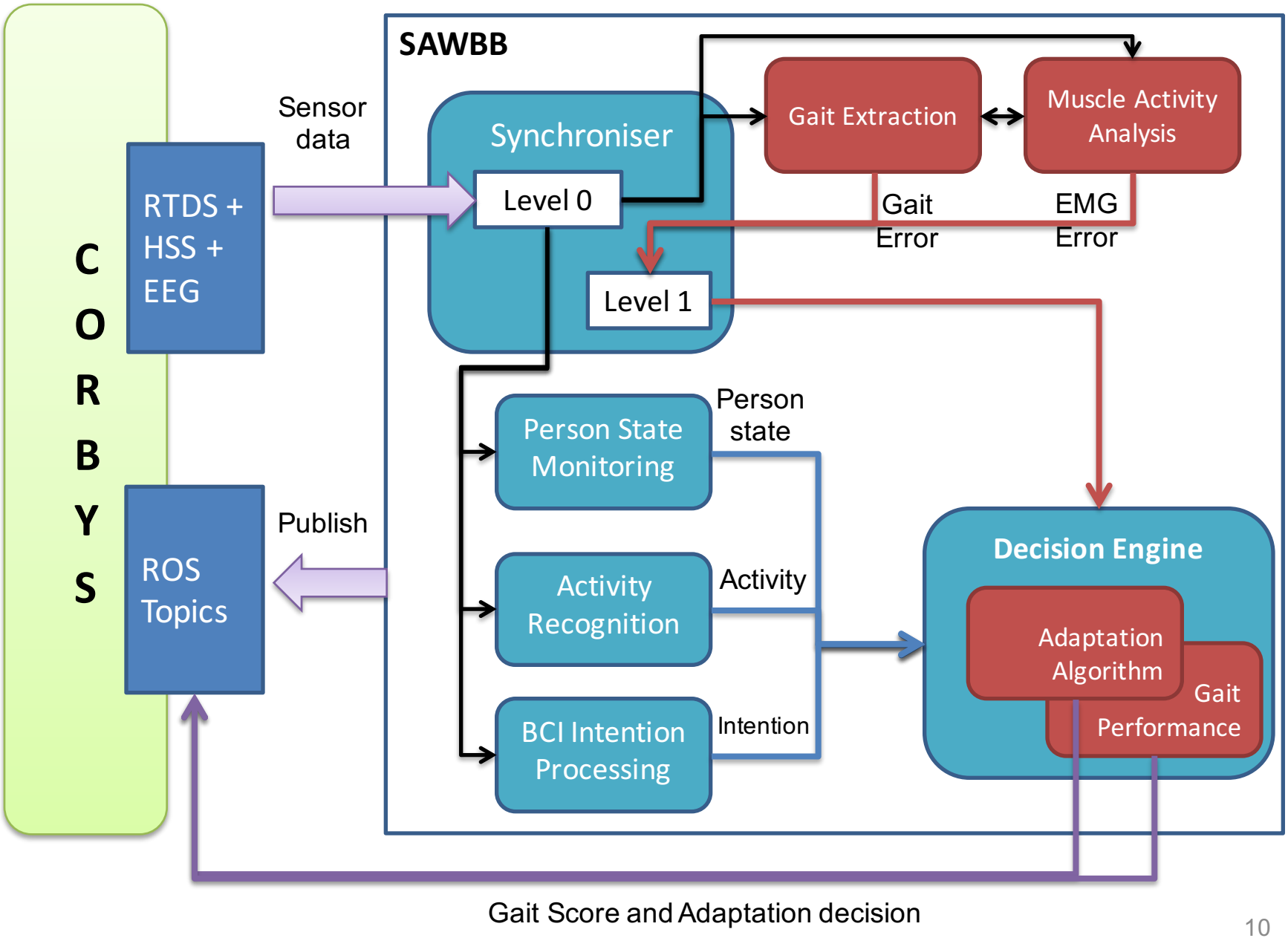
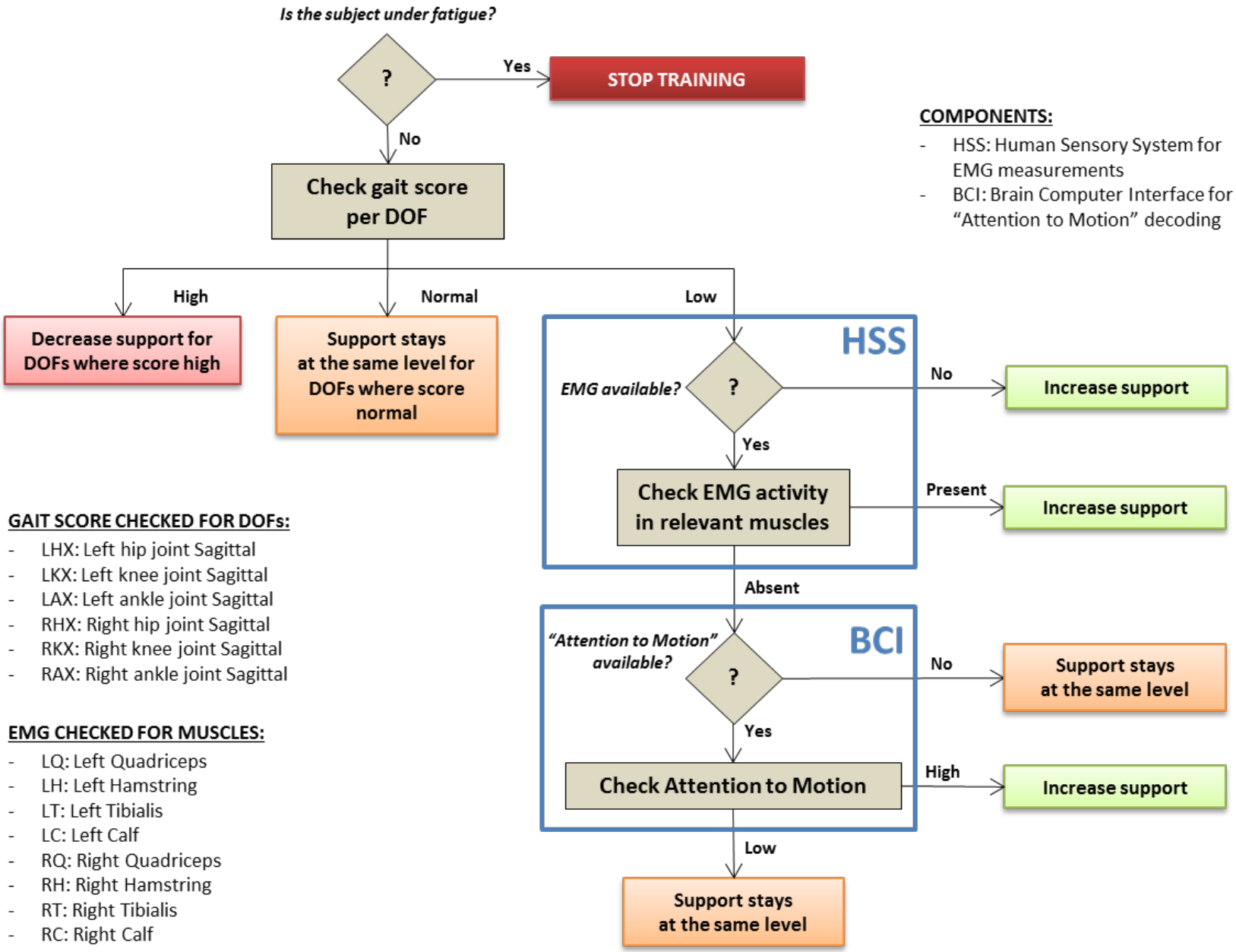
Data flow in the CORBYS Situation Assessment Architecture





CORBYS adaptation algorithm as implemented in the Situation Assessment Architecture

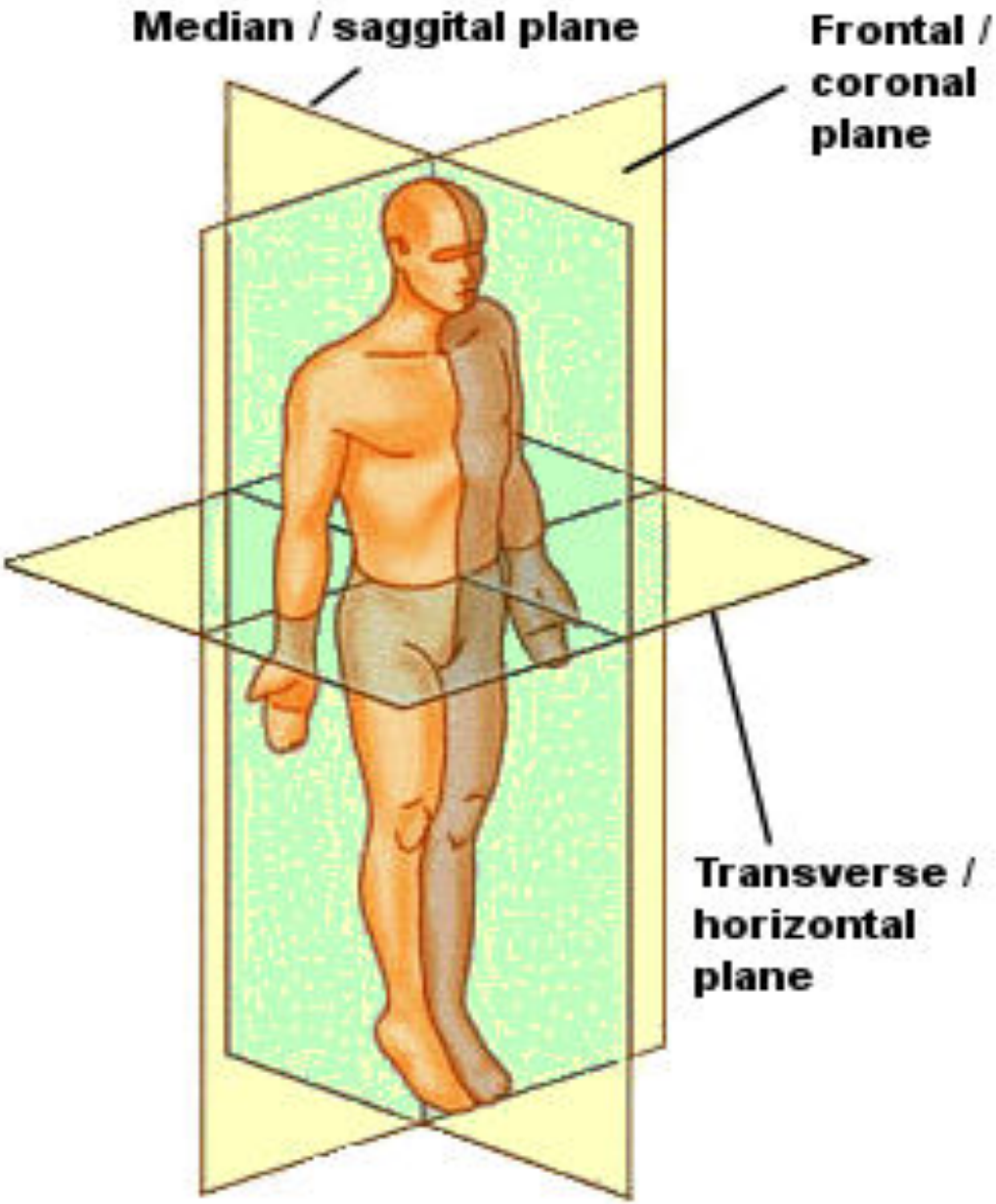
Gait Reference Planes

Biomechanics, movements are generally described and measured with respect to 3 Reference Planes, comprising 3 axes:

Saggital

Frontal

Tranversal



Human Walk System-of-Systems

- Movements made by certain body parts, specifically:
- **The Controller**: Neuromotor & Balance Control
- **The Controlled:**
  - Upper body (arms and pelvic girdle);
  - The pelvis;
  - The hips;
  - Knees;
  - The ankles and feet

Human Walk Cycles of (sub)Phases

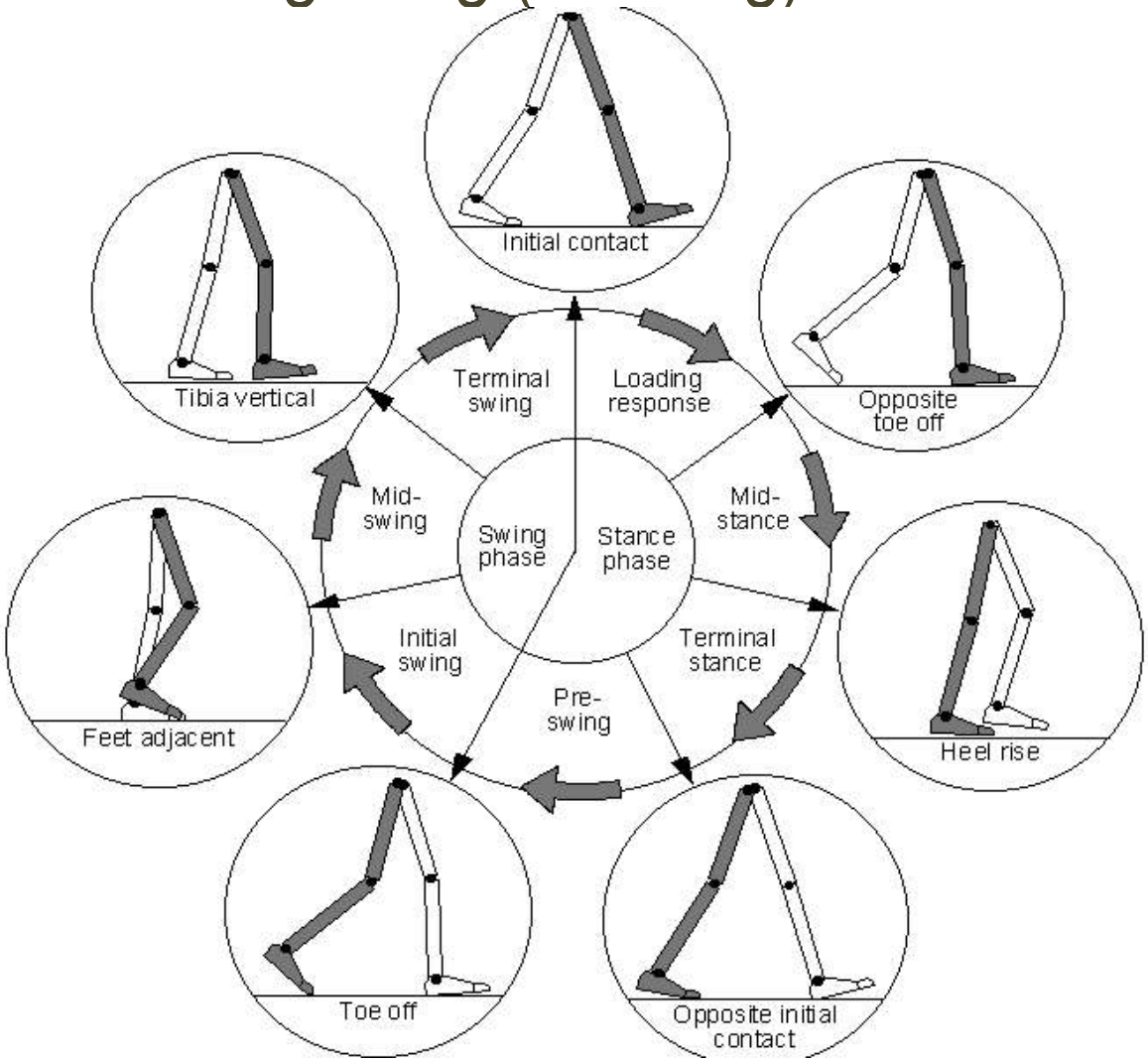
Each phase starts and ends with an instantaneous reference state of the position of the body.

the “Loading response” phase starts with Initial Contact (IC) and ends with Opposite Toe off (OT).

Stance Phase	Swing Phase
Loading Stance	Initial Swing
Mid Stance	Mid Swing
Terminal Stance	Terminal Swing
Pre Swing Phase	

Positions of the legs during a gait cycle

– reference is the right leg (dark leg).



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Sensing & Mining Muscle Activation Demand-Response Patterns

- Requirements **Non –cumbersome, Non-disruptive, Non-obstructive**, compact, easy to set up/remove (typical therapy session 30 minutes approx).
- Data to be **adapted to standardised robotics S/W interfaces**.
- **Facilitating device** within an overall robotic system such as CORBYS to **allow physiological understanding of the interacting patient and enable real-time safety control.**
- Physiological sensors should integrate with robotic control to provide data to build an **understanding of the patient state and to check muscle activation pattern in gait cycles against patterns found in normal and healthy locomotion.**

Human Sensory System

- Must enable cognitively controlled supportive **orthosis actuation responsive to intention** to stop, walk turn L/R.
- Making smooth and **fluent & graceful interaction** possible.
- Low level control of the gait rehabilitation system, not to use the live physiological sensor data directly.
- Training adaptation readily informed by Gait D-R session analytics
- Patients will be fastened to an orthosis with cuffs and straps, hence physiological **sensor units should be wireless to avoid cables influencing leg/orthosis movement.**

Interaction design based on

Impatient Patient expectations

HSS Inventory

- Biomechanical effort can be quantified by **torque and force sensors i**ntegrated in the robotic system
- Measure corresponding physiological effort e.g. **ECG or heart rate, breathing rate and muscular activation** (EMG, Electromyography).
- **Mental engagement**: psychological states measured based on physiological recordings during robot-assisted gait rehabilitation e.g. **heart rate, skin conductance responses, and skin temperature** could be used

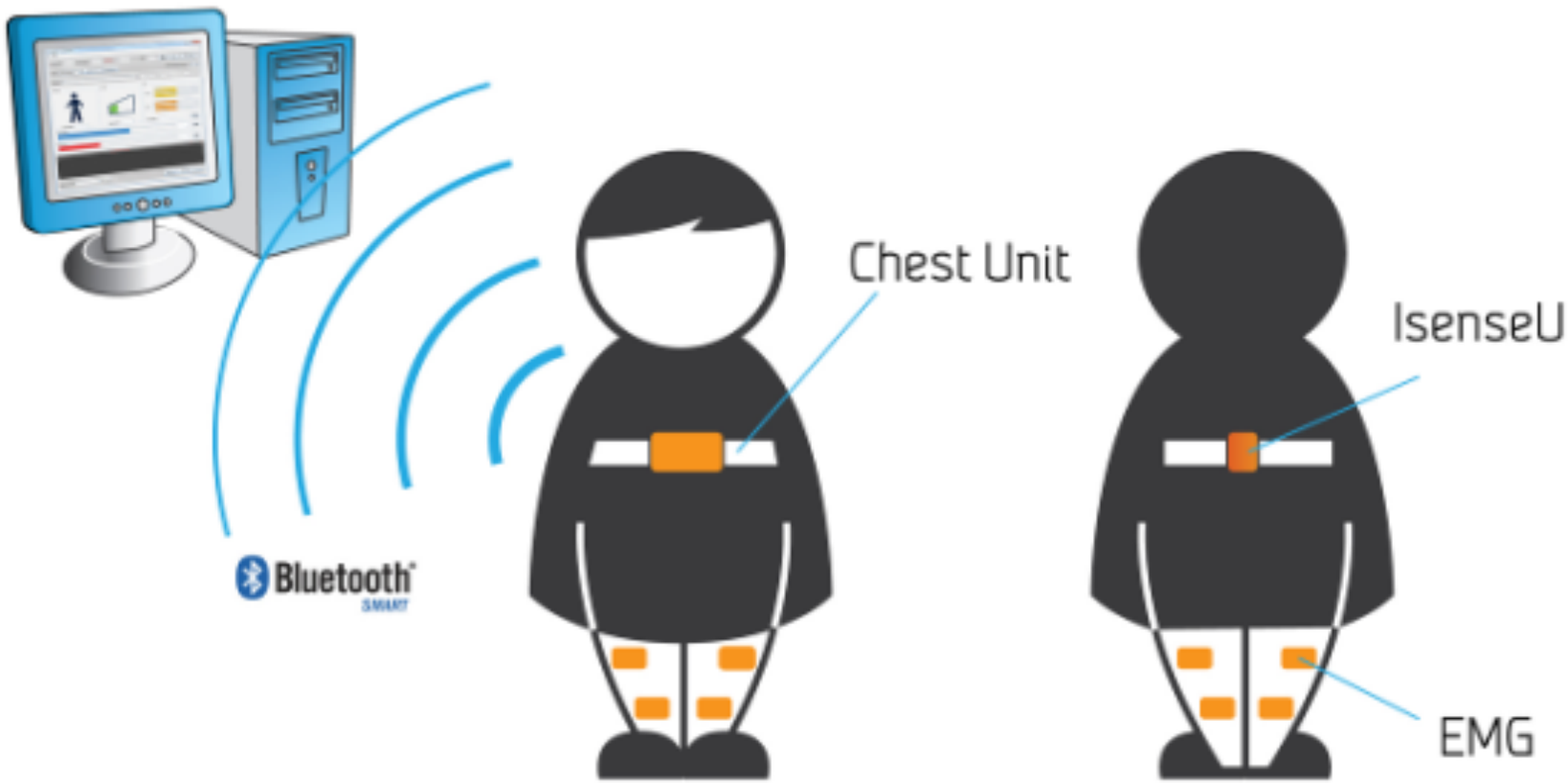
Human Sensory System consists of 3 sensor module types;

- **Chest Unit** collecting one-lead ECG, heart rate and skin temperature measurements,
- **IsenseU Unit** equipped to measure humidity and inertial movements
- **EMG Measurement Unit.**
  - Synchronised sensor readings transmitted wirelessly, formatted as standardised Robot Operating System data from the Human Sensory System controller.
  - **Enables seamless sharing of physiological data with Situation Assessment Architecture, robotics control and end-user graphical interfaces.**

CORBYS HSS sensor units

a) Chest Unit with elastomer electrodes
(b) Dual channel EMG unit.(c) IsenseU sensor unit Vital signs-and-activity-monitoring unit

HSS Configuration



The *Chest Unit*

- Includes multiple sensors. **Heart Rate and Heart Rate Variability,** extracted from ECG measurement, indicates physical activity, Heart Response & Stress.
- **Skin temperature, activity level**, and a tri-axial accelerometer and gyroscope data are provided.
- Device strapped to the chest by an elastic belt with elastomer electrodes for one-lead ECG.
- Data can be immediately transferred via Bluetooth or stored on the unit.

IsenseU

- Multi-sensor device located on user's back
- Attached to the same belt as the chest unit.
- Providing environment temperature and robot IMU data.
- IMU includes a **Motion Processing Unit**, providing wide bandwidth motion data. An external humidity sensor is also connected via an I2C port.
- All sensor data transmitted on Bluetooth Smart as an attribute indication operation for efficient transmission

HSS Topics

The ***Surface EMG*** sensor modules are placed on the thigh and calf of both legs for measuring muscle activities

- A software framework, the ***Human Sensory System Controller*** (HSS controller): Data Acquisition from all HSS sensors and **integrating such data as input** to support the gait rehabilitation cognitive controllers through **standard Robot Operating System topics.**

Situation Awareness Functional Overview

Human States & Activities Classification

- SWAB Interprets the **state and effort of the human** (patient) including their psycho-physiological response.
- **Activity context classified using the Euclidean distance** from reference values for walking and standing activities and the **Average Rotation Angles** related to Gravity direction for the turning activities.
- Data Fusion & Interpretation enables **controlled adaptation of the mobile robotic gait rehabilitation**

Situation Assessment Architecture:

- **Processes EMG data** from Human Sensory System to assess **in-session performance** patient undergoing gait rehabilitation therapy
- **Processes inertial measurements** from the Human Sensory System to recognise **activity context standing, walking, turning**.
- **Gait analysis by muscle activation pattern detection + tracking** against expected activation **per normal locomotion.**
- **Muscle activity analysis verifies that muscle groups are activated consistent with gait motion re refernce expectations**

Decision Making:
Gait Context Classification
Gait Session Demand-Response Data Analytics
Supportive Actuations Adaptations

- A decision engine **closes the loop of situation assessment**, whereby decisions are taken according to the context.
- **Dempster-Shafer theory** of evidence combination to fuse the various data from the pre-processing modules to arrive at a context and situation classification.
- This implementation can be used to fuse any attributes or properties.

Gait Performance Situation Assessment

Learning mode:

- Activity Recognition and Person state monitoring act as 'meta' sensors

Corrective mode:

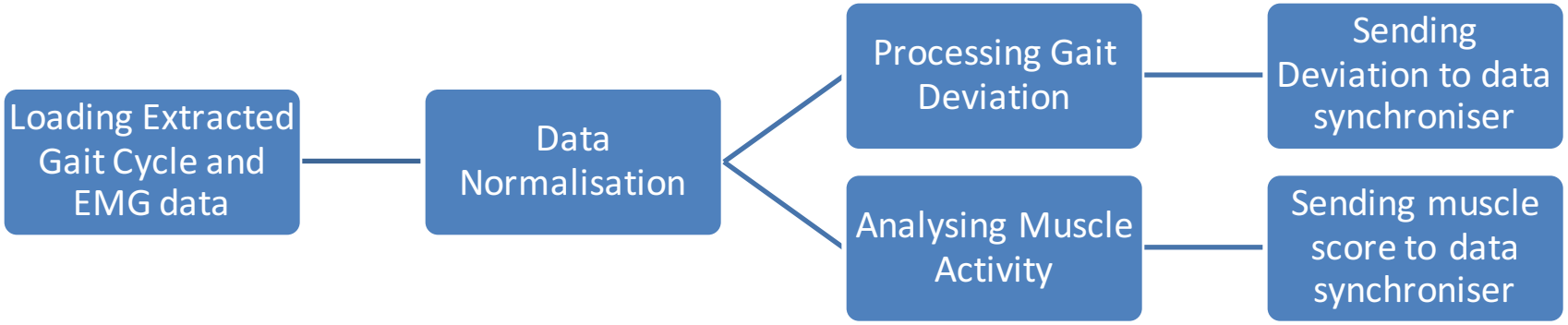
- ***Gait classification and analysis***: Segments phases in each gait cycle, Calculates deviations
- ***Muscle activity analysis***: Uses gait output to calculate muscle activation /phase/muscle/leg.
- ***Gait performance:*** calculates confidence score
- Determine ***actuation support*** trigger for session using BCI intention
- Adapt the actuation support level during the session based on the patient's state and performance

Sensors	SAWBB	Learning mode	Corrective mode
HSS IMU	Activity recognition	☑	☑
HSS Physio	Person state monitoring	☑	☑
BCI Intention	Intention processing		☑
Encoders (Joint angles)	Gait segmentation		☑
	Gait analysis		☑
HSS EMG	Muscle activity analysis		☑
	Decision Engine		☑

Gait Extraction Process

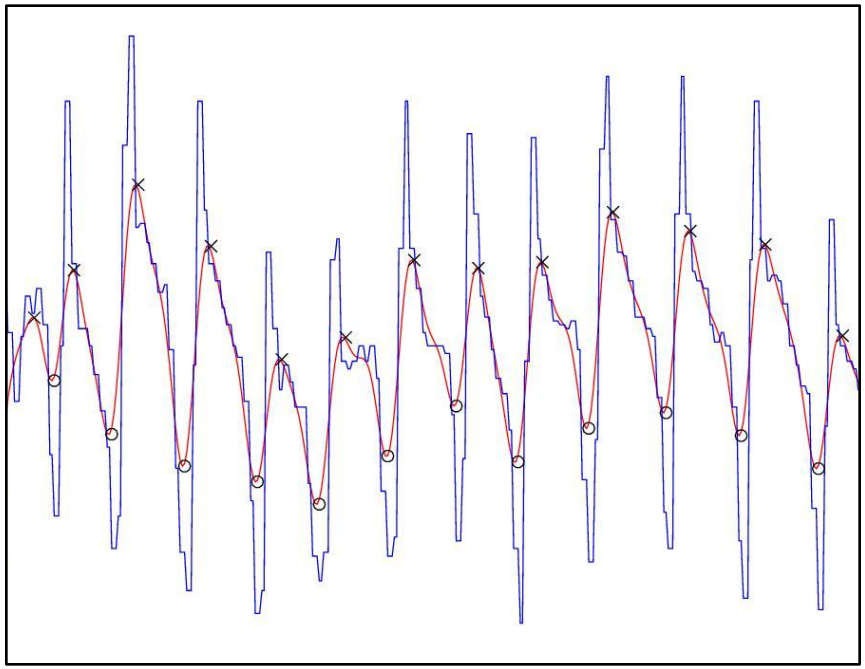
- EMG and Gait data synchronised
- Data filtered, smoothing signal
- Peak and trough identification
- Gait cycle segmentation (peak-to-peak)
- Result → Gait cycle + EMG data

Muscle Activity Analysis

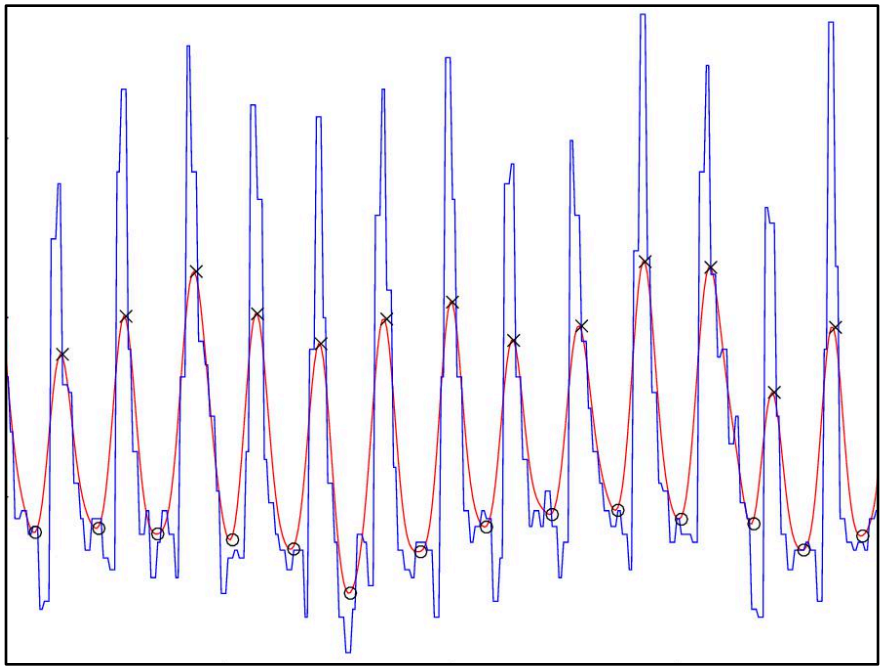


- **Gait and EMG** data for each cycle normalised
- **Gait deviation and muscle activity** (peak counts) are analysed per angle tolerance
- **Gait score** and **Muscle score** output

Gait Extraction Process – Filtering & Peak analysis



Patient A



Patient B

- Blue signal: Original signal
- Red signal: filtered signal
- (X) : peaks identified
- (O) : Troughs identified

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Cognitive Modules Integration

- BCI Intention of motion
  - Use intention level to start a corrective session

- Operating mode responsibilities
  - **BCI Intention** subscribed to by SAWBB
  - **BCI threshold** reached, trigger the start of a corrective session
  - **Initialise FRL** with updated thresholds (which are subject dependent)

Subject feedback

- To inform the subject of their performance

Average performance

High gait score

Low gait and muscle activity

FPGA Reflexive Layer (FRL)

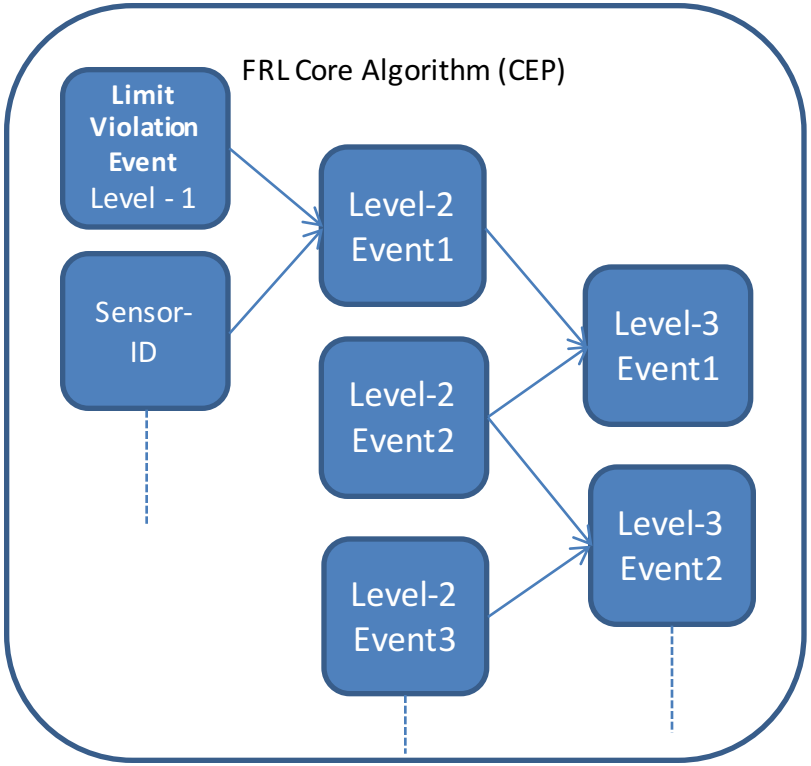
- Physically realises **real-time reflexive** responses of the robotic system.
- In the context of the two CORBYS demonstrators the following FRL functional objectives were identified:
  - **Safety Management & Alerting**
    - Demonstrator I – **Graceful shutdown of actuators when a trajectory is about to becomes unsafe**. Hard shutdown when necessary to make the system safe in a time-critical manner
  - **Collision Avoidance & Alerting**
    - Demonstrator II – **avoid dangerous situations / imminent collision with objects in the environment.**
    - For example, detection of obstacles in the path of the robotic platform which were not detected by the human operator and alerting the robotic platform controller.

FRL Architecture Requirements

- Specific HW/SW Co-Design Requirements
  - HW implementation of **real-time** performance
  - Management, house-keeping, self-state updates, **non-time-critical functionalities** to be implemented in embedded software (i.e. Embedded Linux & Applications)
- Generic Requirements
- Reconfigurable & Reprogrammable
- Modular & Plug-Play hardware architecture
  - Xilinx FPGA
  - With an embedded 32-bit microprocessor (MicroBlaze)

FRL Core Algorithm

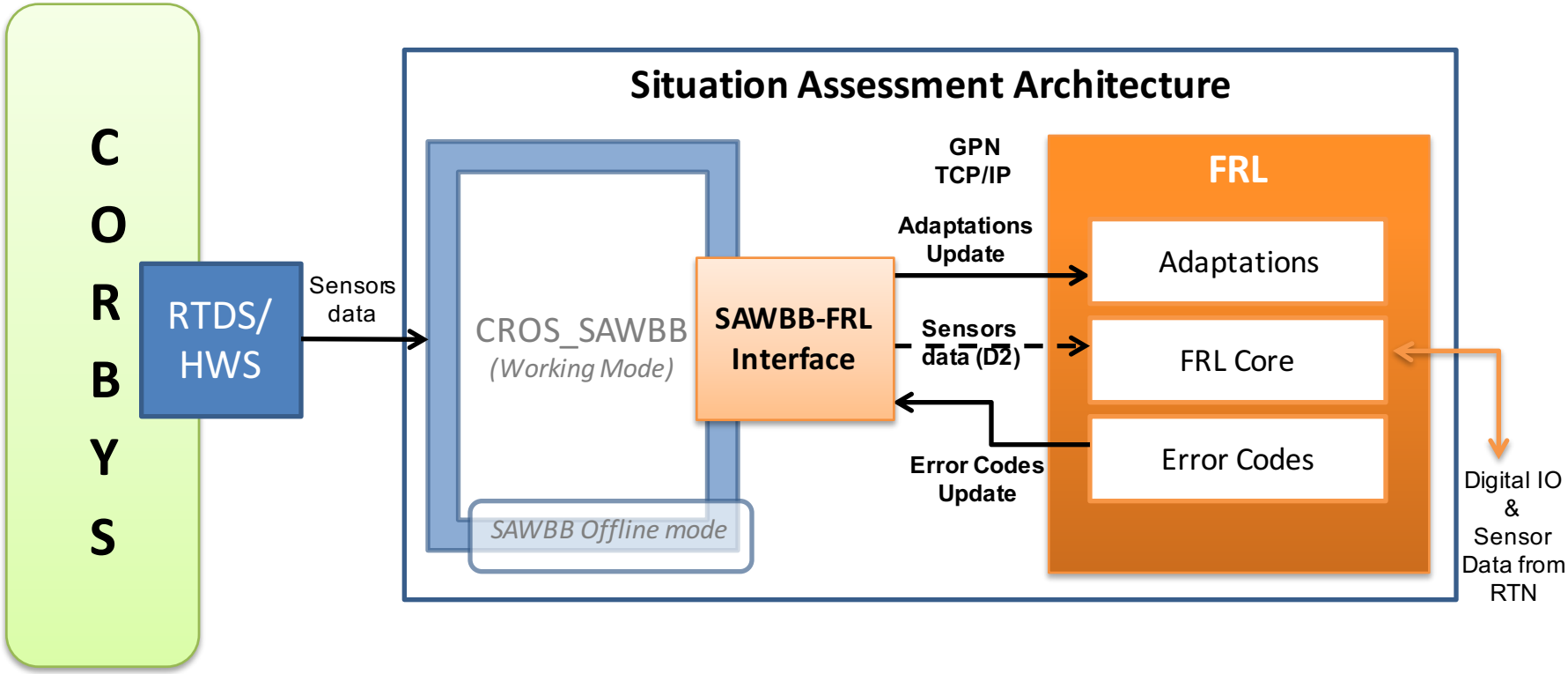
- The implementation of FRL Core Algorithm has three levels of events abstraction i.e.
  - Events at Level1 (**Detecting violation of sensor limits,** Paranoid Safety Level)
  - Events at Level2 (Detecting violation of sensor limits **together with sensor identification)**
  - Events at Level3 (**Detecting violation from multiple sensors** in a temporal sequence i.e. First violation of sensor1 limits then violation of sensor2 limits)



FRL Architecture Integration

- Logical integration into the CORBYS Real Time Network (RTN, EtherCAT).
- Logical integration into the Situation Assessment Architecture
- Physical integration into the Demonstrator-1 (RTN, SAWBB-FRL, HeartBeat)
- Software based parser programs were developed in PERL
- System testing with SAWBB and CORBYS RTN
- Tested communication with full size 540 Byte CORBYS Process Data Object (PDO) i.e. Data from all devices on the RTN

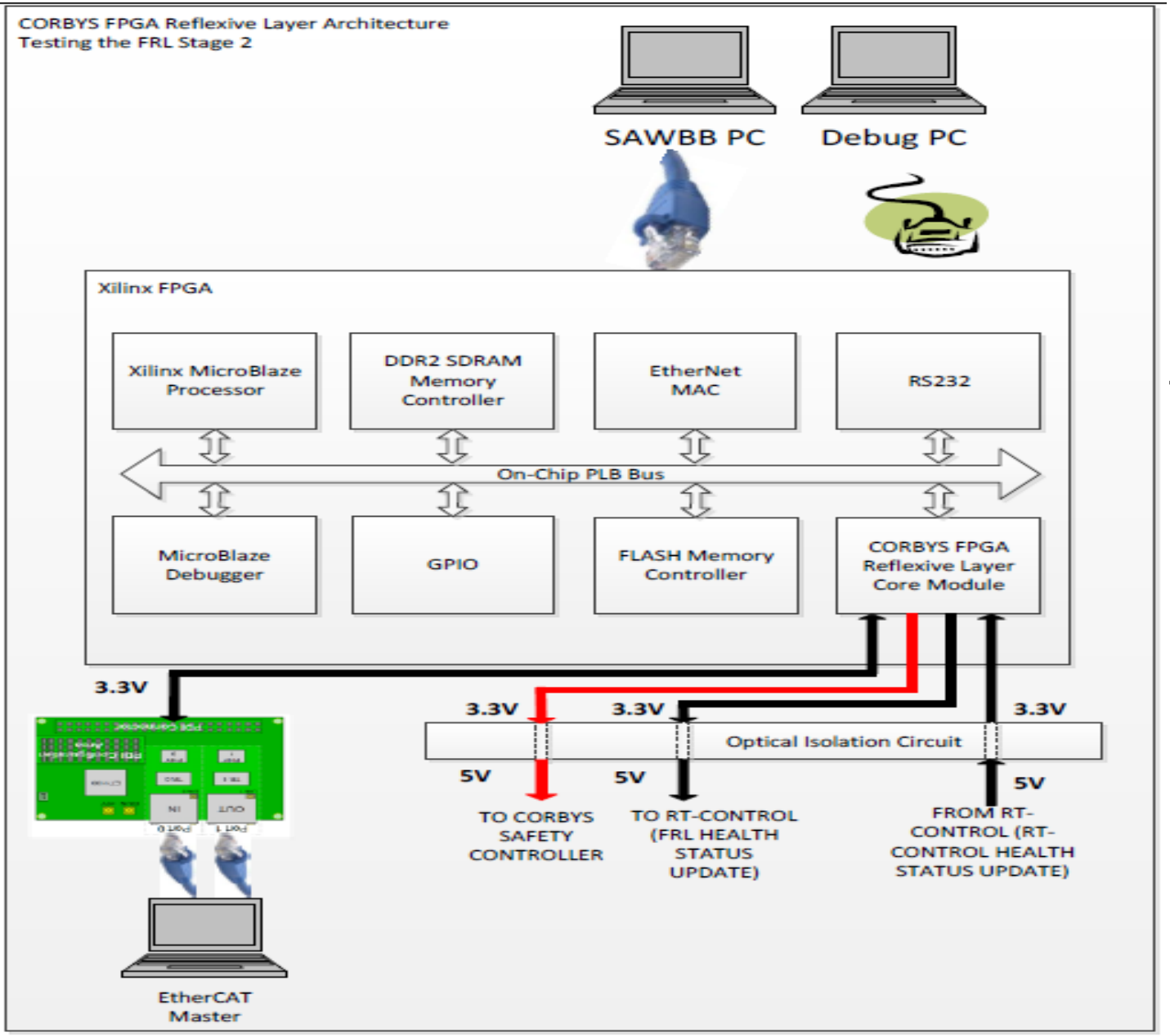
Integration: SAWBB-FRL Reflective/Reflexive



- SAWBB and FRL communicate over GPN (TCP/IP)
- FRL receives reflexive adaptations from SAWBB
- FRL provides detailed error code to SAWBB with a complete context of the detected unsafe situation

GPN ↔ RTN

FRL Hardware Architecture



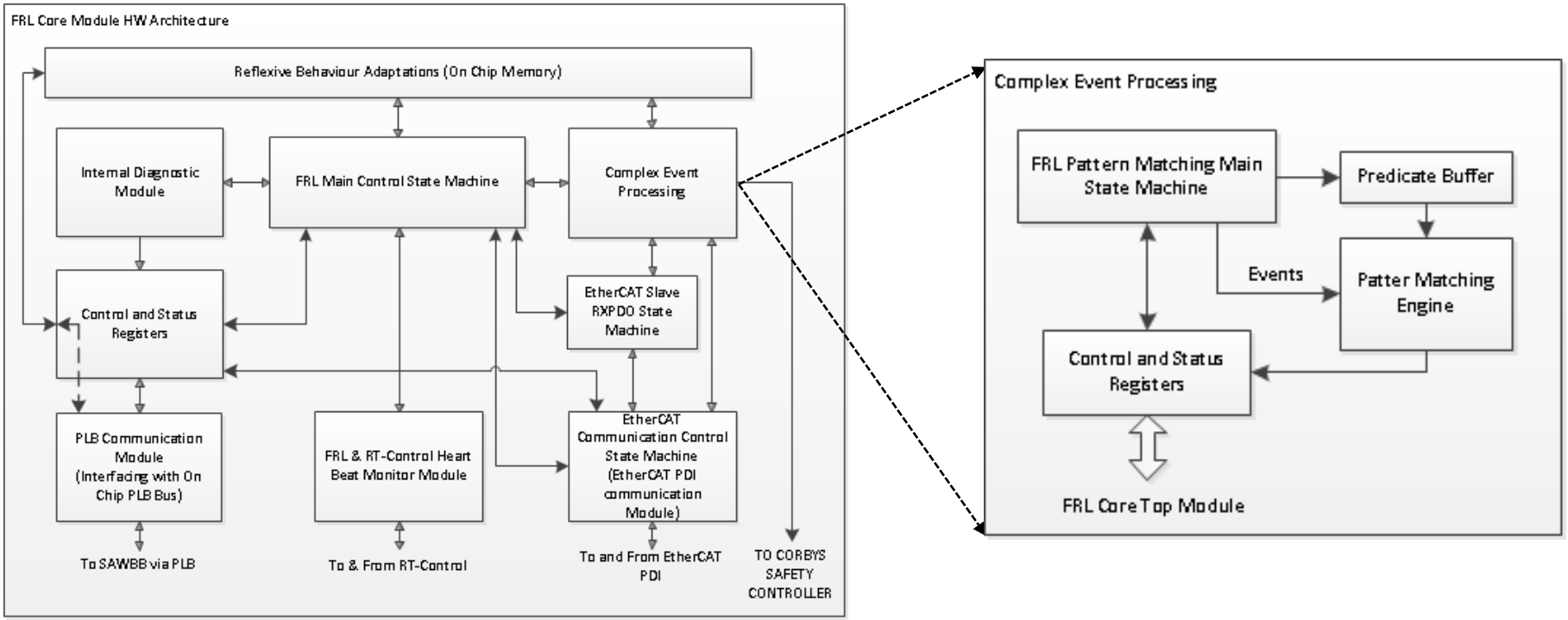
FRL hardware architecture

- Generic
- Modular
- Plug & Play

The figure shows FRL interfacing with

- RTN,
- Heart-Beat & Safety Relay (Optically Isolated)
- SAWBB on General Purpose Network (GPN) (TCP/IP)
- FRL Core Module implements the FRL Core Algorithm

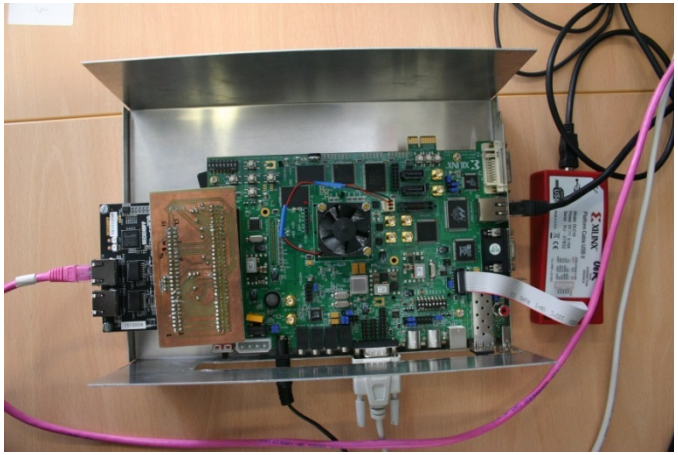
Hardware Architecture: FRL Core Module



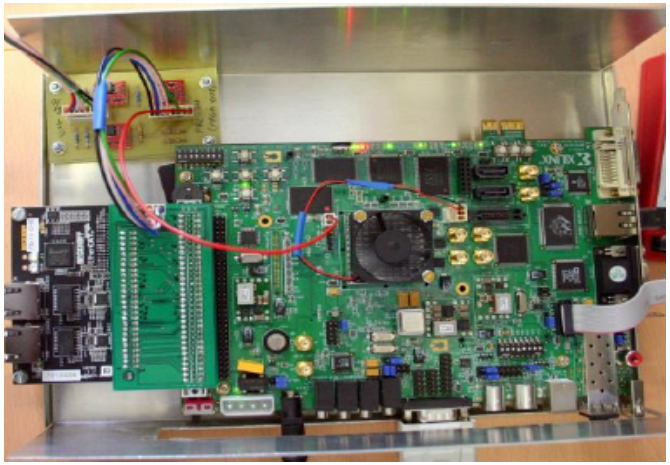
- The FRL Core algorithm has been implemented in the **Complex Event Processing** block within the FRL Core module
- **Event detection in hardware is carried out using Content Addressable Memory based pattern matching engine**
- **Event predicates are used for event filtering** and to identify the event of interest
- Level-1 limits, Level-2 and Level-3 predicates can be dynamically loaded at run time

FRL Iterative Design

FRL stage 1



FRL Stage 2

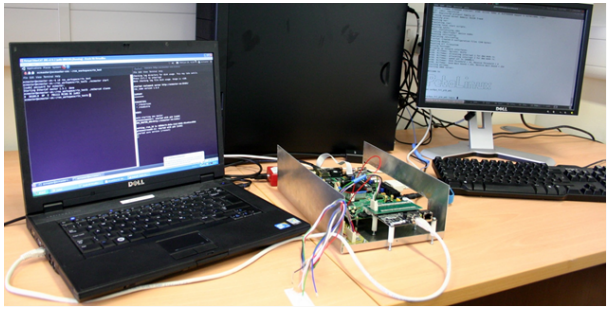


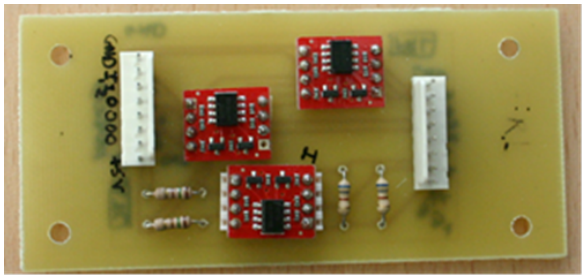
FRL Stage 3

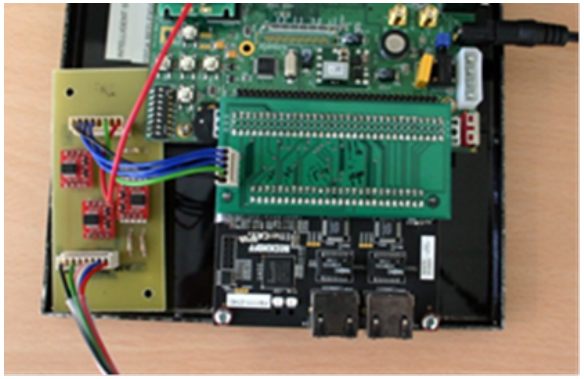
FRL final stage as
Installed in GRS

FRL Integration & Testing

- **FRL integration with the Safety Controller**
  - Dedicated digital line 5V DC Output for shutting the power to the demonstrator
- **FRL<->RTC Heartbeat Interface**
  - Dedicated two digital Line 5V DC switching (4Hz) signals to monitor the heath status
- Carried out full system testing in-house and on the demonstrator







FRL Results

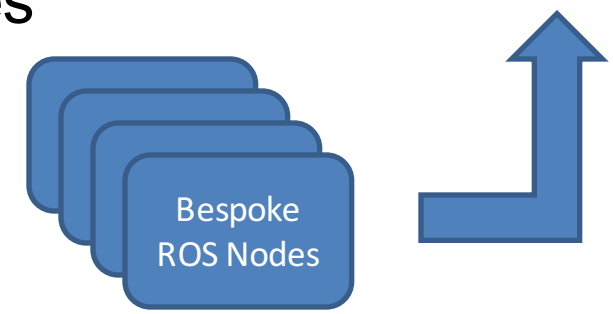
- FRL fetches & processes the entire 540 Byte Process Data Object (PDO) in hardware
  - ~216 Microsecond (@Process Data Interface clock rate of 10MHz)
  - FRL could fetch the entire PDO in ~86.4 Microsecond (@Process Data Interface clock rate of 25MHz)
- FRL Core runs at 100MHz
  - Processes the Level-1 decisions in ~50 ns (5 clock cycles).
  - Level-2 and Level-3 decisions in ~10ns (1 clock cycle).
  - Level 3 decision is made in 50+10+10 = 70ns, Level-2 in 60ns.
- FRL currently supports:
  - Variable width sensor data (8bit, 16bit, 32bit)
  - 256 sensors at Level-1 (Supports 11 condition types for each sensor i.e. <, >, =, <|>, <&>,… can be dynamically programmed for each sensor)
  - 256 predicates at Level-2 ({Sensor1, <|>}, {Sensor2, <&>}, {Sensor3, <|=}…)
  - 256 predicates at Level-3 ({Level-2 event1, Level-2 event2}….)

Conclusions

- Situation Assessment Architecture
  - Perceptor modules
  - Raw sensor data (level 0) synched
  - Semantic (level 1) synched
  - Decision Engine
  - FRL

Situation Assessment Architecture in **ROS**

- Bespoke demonstrator specific nodes
  - Gait extraction and performance
  - Muscle activity analysis
  - Adaptation algorithm
  - BCI integration modules



Conclusions

- Gait classification using signal processing and ML
- HSS datasets IMU measurements for activity recognition analysed (Naïve Bayes, K-Means, Clustering, C4.5 decision tree, Boosting)
- Monitoring the person states (heart rate, skin temperature)
- Sub-phase classification (~80% accuracy for healthy, ~70% for pathological gait)
- Refinement of the offline training by determining the best classifier configuration in terms of classification accuracy.

Thank you

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Gait Analysis

- Makes use of **joint angles** data to perform gait deviation analysis which is then used to make a decision re the change in actuation

- Machine learning and classification techniques was carried out for classifying the phases in a gait cycle from joint angles data

- ANNs, Naïve Bayes, SVMs plus unsupervised methods including Expectation Maximisation and K Means using a joint angles dataset that comprised of gait trajectories for the hip, knee and ankle joints of both legs.

Gait Analysis

- Trained classifiers used to classify optimal gait provided by therapist
- Sub phase classification used time domain for spectral analysis.
- Deviation was calculated from the optimal reference gait pattern.
- Gait Phase classification based on number of domain features of joint-angular gait cycle motion data
- Tested with normal and pathological data demonstrating suitability in classifying phases of the gait regardless of type

Muscle Activity Analysis

- Muscle activation checked in comparison with the analysed gait motion and with literature.
- EMG signal enables detection of muscle activity orchestration per gait cycle which allows the determination of expected muscle activation pattern as exhibited in normal locomotion.
- Determination is provided with a confidence measure and as such is made accessible to the Therapist through an appropriate UI space.

Muscle Activity Analysis

CORBYS project senses four muscles groups by placing the electrodes on the

- Vastus Medialis (quadriceps),
- Biceps Femoris (hamstrings),
- Tibialis Anterior (anterior shank) and
- Gastrocnemius (calf).

The muscle activity analysis verifies that the muscle groups are activated in line with gait motion; this is of interest to the therapist from rehabilitation point of view.

Gait cycle segmentation and analysis

- Segmented TAG cycle in all 6 DOFs acts as the optimal gait cycle or reference pattern
- SAWBB analyses gait deviation and performance in Corrective Mode
- Joint angle data from the orthosis encoders
- Running gait phase-wise analysis
  Gait error calculation per active DOF (and subsequent gait score assignment)

SAWBB Operation

- Initially, single decision to actuate all DOFs
- Modified to support each joint individually

- Modified decision making in adaptation algorithm to switch off analysis and actuation support for one leg

- Output interval specification (e.g., 10 seconds)

- Saving training data to perform several corrective sessions without training

Thank you

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