Autonomous Cardio-Respiratory Stabilization System

UNIVERSITÀ DEGLI STUDI DELL'AQUILA

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Course: Software Engineering for Autonomous System

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1. Goals of the System

1.1 Introduction

The goal of the proposed system is to design and implement a **self-adaptive healthcare monitoring and therapy management system** for simulated patients.

The system continuously monitors vital parameters through distributed sensors, analyzes their trends and clinical relevance, and automatically adapts therapeutic actions in order to maintain the patient's physiological stability.

The system follows an autonomic computing paradigm and implements a distributed MAPE-K (Monitor–Analyze–Plan–Execute over a shared Knowledge base) loop. It integrates multiple microservices communicating via MQTT and relies on a knowledge base to support reasoning and decision-making.

The primary objective is to maintain vital parameters within safe clinical ranges while reacting promptly to deteriorating conditions, minimizing risks and enabling timely interventions.

1.2 Functional Requirements

The system shall satisfy the following functional requirements:

FR1 – Continuous Monitoring

The system shall continuously acquire physiological data from distributed sensors, including:

- Heart Rate (HR)
- Respiratory Rate (RR)
- Oxygen Saturation (SpO_2)
- Systolic Blood Pressure (SBP)
- Diastolic Blood Pressure (DBP)

FR2 – Data Aggregation and Storage

The system shall collect and store monitored data in a knowledge base to support temporal analysis and reasoning.

FR3 – Trend Analysis

The system shall analyze both instantaneous values and trends of physiological parameters in order to detect potentially critical evolutions over time.

FR4 – Therapy Planning

The system shall determine an appropriate therapy plan based on:

- Current physiological measurements
- Derived metrics (e.g., MAP)
- Observed trends and intensity

FR5 – Automatic Execution of Therapy

The system shall automatically translate the therapy plan into actuator commands, including:

- Adjustment of oxygen flow
- Activation or deactivation of fluid infusion
- Adjustment of beta-blocking infusion rate
- Triggering of alert notifications

FR6 – Multi-Patient Support

The system shall support the simultaneous management of multiple patients in a scalable and isolated manner.

FR7 – Event-Driven Operation

The system shall react to new data events in real time without requiring manual intervention.

FR8 – Monitoring Interface

The system must offer an interface for each patient that displays data, symptoms and therapies in a user-friendly way.

FR9 – Dynamic configuration

The system must provide a way to change the thresholds related to the creation of statuses dynamically.

1.3 Non-Functional Requirements

NFR1 – Scalability

The system shall support horizontal scalability, allowing the addition of new patients.

NFR2 – Modularity

The system shall be composed of loosely coupled microservices communicating through a message broker, enabling independent deployment and evolution of components.

NFR3 – Reliability

The system shall ensure reliable message delivery between components using appropriate Quality of Service (QoS) levels.

NFR4 – Responsiveness

The system shall react to clinically relevant changes within a short time interval (near real-time processing).

NFR5 – Security

The system shall guarantee secure communication between components.
Security mechanisms include:

- MQTT authentication through username and password credentials
- Credential management via environment variables
- Token-based authentication for access to the knowledge base (InfluxDB) and telegram

These measures ensure that only authorized components can publish or subscribe to sensitive clinical data and therapy commands.

NFR6 – Portability

The system shall be portable across different deployment environments.
Containerization using Docker enables the system to run consistently on different operating systems and infrastructures (local machines, cloud environments, or virtualized systems) without requiring configuration changes.

2. Managed Resources

2.1 Oxygen Delivery System

The oxygen delivery system regulates the oxygen flow administered to the patient.

Controlled Parameter:

- Oxygen flow rate (e.g., L/min)

Purpose:

To compensate for reduced oxygen saturation (SpO_2) levels and prevent hypoxemia.

Managed Effect:

By increasing oxygen flow, the system aims to stabilize or improve blood oxygen saturation levels.

2.2 Intravenous Fluid Administration System

The intravenous fluid system controls the release of fluids into the patient's bloodstream.

Controlled Parameter:

- Fluid infusion activation (open/close)
- Type of administered fluid (if applicable)

Purpose:

To support blood pressure regulation and compensate for hypotensive states.

Managed Effect:

Fluid administration influences systolic blood pressure (SBP), diastolic blood pressure (DBP), and mean arterial pressure (MAP).

2.3 Beta-Blocking Infusion System

The beta-blocking infusion pump regulates the administration of beta-blocking agents.

Controlled Parameter:

- Infusion flow rate (e.g., μg/min)

Purpose:

To control excessive heart rate (tachycardia) and reduce cardiovascular stress.

Managed Effect:

Beta-blocking therapy influences heart rate (HR) and indirectly affects blood pressure.

2.4 Emergency Alert System

The alert system is responsible for notifying medical personnel in critical situations.

Controlled Parameter:

- Alert activation with contextual information

Purpose:

To ensure human intervention in emergency scenarios where automated therapy alone is insufficient.

Managed Effect:

While it does not directly modify physiological parameters, it increases system safety by escalating critical conditions to medical staff.

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3. Sensors and Effectors

3.1 Overview

The system relies on distributed sensors to monitor the physiological state of each patient and on effectors (actuators) to apply therapeutic actions.

Sensors are responsible for acquiring and publishing physiological data, while effectors execute adaptation decisions determined by the autonomic manager.

Communication between sensors, analyzer, planner, executor, and actuators is performed using the MQTT publish/subscribe protocol in an event-driven architecture.

3.2 Sensors

Each patient is associated with a set of simulated medical sensors that continuously generate physiological measurements.

3.2.1 Heart Rate Sensor (HR)

- **Measured Parameter:** Heart Rate (beats per minute)
- **Purpose:** Monitor cardiovascular activity
- **Published Topic:** acrss/sensors/{patient_id}
- **Impact on System:** Used to detect tachycardia or bradycardia conditions

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3.2.2 Respiratory Rate Sensor (RR)

- **Measured Parameter:** Respiratory Rate (breaths per minute)
- **Purpose:** Monitor respiratory stability
- **Published Topic:** acrss/sensors/{patient_id}
- **Impact on System:** Contributes to detection of respiratory distress

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3.2.3 Oxygen Saturation Sensor (SpO_2)

- **Measured Parameter:** Blood Oxygen Saturation (%)
- **Purpose:** Detect hypoxemia
- **Published Topic:** acrss/sensors/{patient_id}
- **Impact on System:** Drives oxygen flow adaptation decisions

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3.2.4 Blood Pressure Sensor (SBP / DBP)

- **Measured Parameters:**
    - Systolic Blood Pressure (SBP)
    - Diastolic Blood Pressure (DBP)
- **Derived Parameter:**
    - Mean Arterial Pressure (MAP)
- **Purpose:** Monitor hemodynamic stability
- **Published Topic:** acrss/sensors/{patient_id}
- **Impact on System:** Influences fluid therapy and cardiovascular regulation

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3.3 Effectors (Actuators)

Effectors are responsible for executing the therapy plan generated by the autonomic manager. Each actuator subscribes to patient-specific action topics and reacts to commands published by the executor.

3.3.1 Oxygen Flow Regulator

- **Subscribed Topic:** acrss/actions/{patient_id}/oxygen_flow_regulator
- **Controlled Parameter:** Oxygen flow rate (L/min)
- **Effect:** Adjusts oxygen delivery to stabilize SpO_2 levels

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3.3.2 Fluid Infusion Actuator (Drip Valve)

- **Subscribed Topic:** acrss/actions/{patient_id}/drip_valve
- **Controlled Parameter:** Fluid administration (open/close)
- **Effect:** Modifies blood pressure by adjusting intravenous fluids

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3.3.3 Beta-Blocking Infusion Pump

- **Subscribed Topic:** acrss/actions/{patient_id}/beta_blocking_infusion_pump
- **Controlled Parameter:** Infusion flow rate (µg/min)
- **Effect:** Reduces heart rate and cardiovascular stress

3.3.4 Alert System

- **Subscribed Topic:** acrss/actions/{patient_id}/alert_server
- **Controlled Parameter:** Alert activation message
- **Effect:** Notifies medical staff in critical scenarios

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4. Architectural Pattern of the Autonomic Manager

4.1 Mapping of Components to the MAPE-K Loop

The system components can be mapped to the MAPE-K model as follows:

Monitor

The **Monitor** component is implemented as an independent microservice responsible for collecting raw sensor data and standardizing their publication within the system.

The Monitor subscribes to sensor topics structured as: acrss/sensors/{patient_id}/{sensor}.

Upon receiving a message, it republishes the same payload to: acrss/states/{patient_id}/{sensor}.

Analyze

The **Analyzer** performs trend computation and statistical aggregation.

It derives:

- Mean values
- Trends over time
- Potential deviations from normal ranges

This phase extracts higher-level information from raw sensor data, enabling meaningful clinical interpretation.

Plan

The **Planner** is responsible for decision-making.

Based on:

- Current physiological values
- Derived metrics
- Observed trends

The Planner generates a **therapy plan** that aims to maintain physiological stability and prevent critical deterioration.

This phase implements the decision function of the autonomic manager.

Execute

The **Executor** translates the therapy plan into actuator-specific commands.

It publishes:

- Oxygen flow adjustments
- Fluid administration commands
- Beta-blocking infusion rates
- Alert notifications

Actuators subscribe to patient-specific action topics and perform the required adaptations.

Knowledge

The **Knowledge base** consists of:

- Historical physiological data (InfluxDB)
- Derived metrics
- Configuration parameters
- Clinical thresholds

The knowledge base supports both analysis and planning decisions by providing historical context and aggregated information.

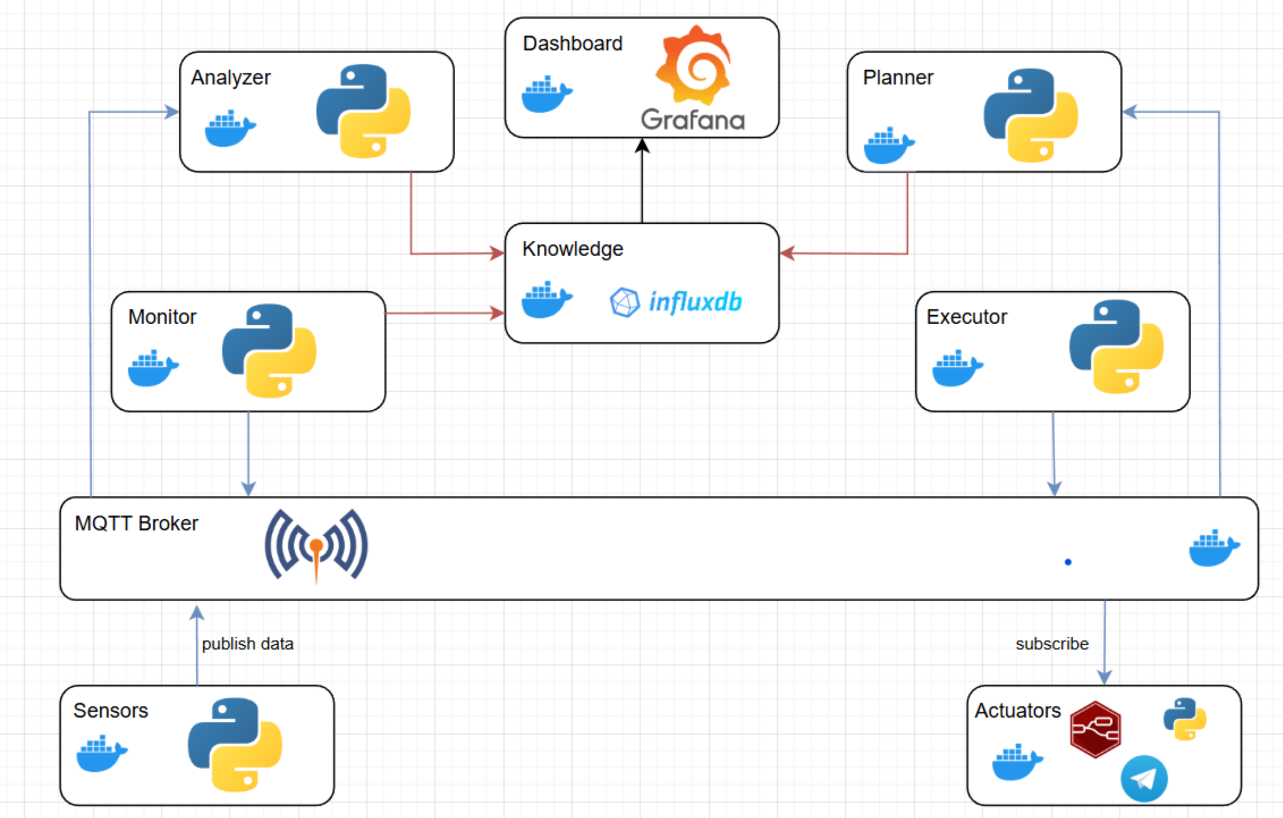
4.2 Architectural Style

The system adopts:

- A **logically centralized autonomic manager**,

- Implemented as a **physically distributed microservice architecture**.

4.3 System Architecture



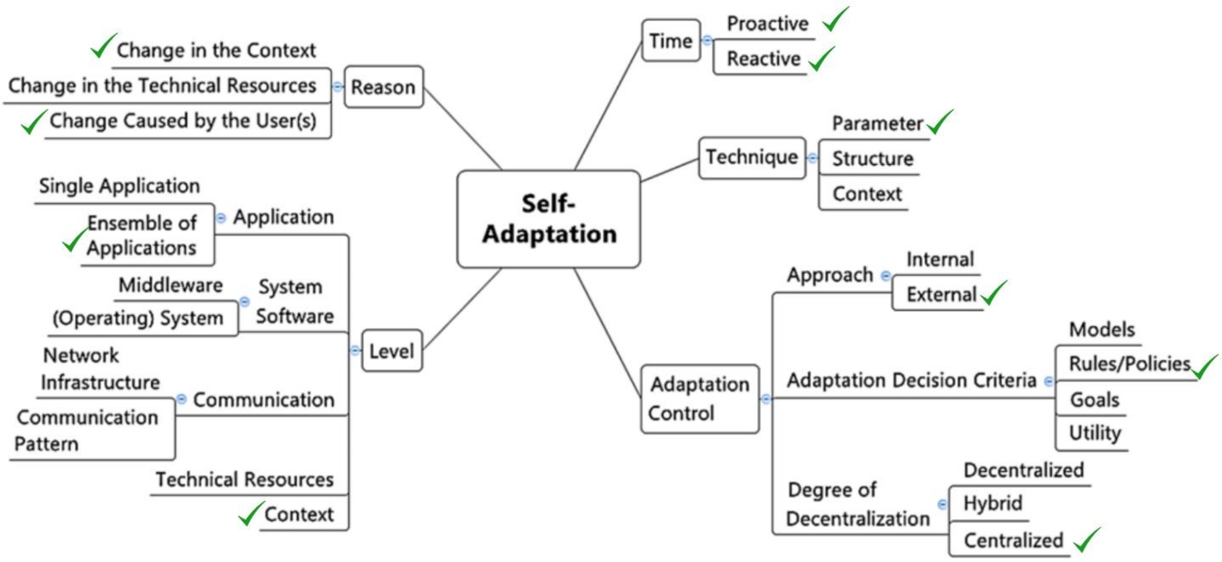
In the diagram the communication between each component its represented by arrows with different color coording to their scope:

Communicatio to/from DB

Communication performed thanks to MQTT broker

Communication with external service

4.4 Autonomic Manager



Self-Adaptation

Reason

The system adapts due to:

- **Change in Context**
    - Variations in patient physiological parameters (HR, RR, SpO_2, BP)
    - Detection of clinical deterioration or stabilization
- **Change Caused by Users**
    - Indirectly through simulated sensor inputs (patient behavior/environment)

Level

Adaptation occurs at multiple levels

Application

- **Ensemble of application**: The system is based on containerized microservices that communicate through a message broker and access a database server, meaning the system could easily be scaled to run on different machines.
- **Context**: The system adapts to changes according to vitals parameters.

Time

The adaptation is primarily:

- **Reactive**
  - Triggered by detected clinical state changes
  - Based on trend, slope, and threshold evaluation

However, it also has:

- **Limited proactive** behavior
  - EWMA filtering anticipates deterioration
  - Trend-based therapy escalation prevents critical states

Technique

The adaptation technique is based on:

Parameter Adaptation

- Adjusting:
  - Oxygen flow (L/min)
  - Fluid infusion
  - Beta-blocker dosage

Adaptation Control

Approach

Your adaptation control is:

- **External**
  - The Planner makes decisions based on Analyzer output
  - Separation between monitoring, analysis, and execution

Adaptation Decision Criteria

The system is driven by:

- **Rules / Policies** (decision tables)
- Threshold-based logic (clinical rules file)
- Arbitration safety overrides

It does not optimize a utility function or goal maximization.

Degree of Decentralization

The architecture is:

- Distributed in execution (microservices)
- But logically centralized at decision level (Planner per patient)

Each patient has:

- Independent planner instance
- Independent therapy state

However, decision logic is **centralized** per patient.

5. Adaptation Goals of the Autonomic Manager

The autonomic manager aims at maintaining physiological stability of each patient by enforcing safety constraints (hard goals) and optimizing clinical conditions (soft goals).

5.1 Hard Adaptation Goals

Goal	Description	Evaluation Metric
Oxygen Safety	The patient shall not remain in severe hypoxia conditions.	$SpO_2 \geq SpO_2$_critical_threshold
Hemodynamic Stability	The patient shall not enter shock conditions.	MAP ≥ MAP_critical_threshold
Cardiovascular Safety	Excessive tachycardia shall be prevented.	HR ≤ HR_critical_threshold

Goal	Description	Evaluation Metric
Therapy Safety Constraints	Unsafe combinations of therapies shall be avoided (e.g., beta-blockers during shock, fluids during overload).	Logical safety constraints satisfied

These goals represent **safety invariants**.
If violated, the system must immediately trigger corrective actions or alerts.

6. Decision Function – Rule Tables

6.1 Oxygenation Control Rules

Status	SpO_2 Trend	SpO_2 Intensity	Action
STABLE_SATURATION/RESPIRATION	Any	Any	No action
LIGHT_HYPOXIA	IMPROVING	Any	+1 L/min O_2
LIGHT_HYPOXIA	STABLE	MODERATE/STRONG_DECREASE	+2 L/min O_2
LIGHT_HYPOXIA	DETERIORATING	Any	+2 L/min O_2
GRAVE_HYPOXIA	Any	Any	O_2 Boost ≥ 6 L/min
FAILURE_OXYGEN_THERAPY	Any	Any	Alert + Stop fluids

6.2 Respiration Control Rules

Status	RR Trend	RR Intensity	Action
STABLE_RESPIRATION	Any	Any	No action
MODERATE_TACHYPNEA	IMPROVING	Any	No action

Status	RR Trend	RR Intensity	Action
MODERATE_TACHYPNEA	STABLE	Any	+1 L/min O_2
MODERATE_TACHYPNEA	DETERIORATING	MODERATE/STRONG_DECREASE	+2 L/min O_2
RESPIRATORY_DISTRESS	Any	Any	Alert + Stop fluids
BRADYPNEA	Any	Any	Alert

6.3 Heart Rate Control Rules

Status	HR Trend	HR Intensity	Action
STABLE_HR	Any	Any	No action
COMPENSED_TACHYCARDIA	IMPROVING	Any	No action
COMPENSED_TACHYCARDIA	STABLE	Any	+1 L/min O_2
COMPENSED_TACHYCARDIA	DETERIORATING	STRONG_DECREASE	+1 L/min O_2
PRIMARY_TACHYCARDIA	IMPROVING	MODERATE_INCREASE	Keep monitoring
PRIMARY_TACHYCARDIA	STABLE	Any	Beta-blocker (standard dose)
PRIMARY_TACHYCARDIA	DETERIORATING	STRONG_INCREASE	Beta-blocker (increased dose)

6.4 Blood Pressure Control Rules

Status	MAP Trend	MAP Intensity	Action
NORMAL_PERFUSION	Any	Any	No action
MODERATE_HYPOTENSION	IMPROVING	Any	Monitor
MODERATE_HYPOTENSION	STABLE	Any	Fluid bolus

Status	MAP Trend	MAP Intensity	Action
MODERATE_HYPOTENSION	DETERIORATING	MODERATE/STRONG_DECREASE	Fluid bolus + Alert
SHOCK	IMPROVING	MODERATE/STRONG_INCREASE	Maintain therapy
SHOCK	STABLE	Any	Alert
SHOCK	DETERIORATING	Any	Critical alert
DISTRESS_OVERLOAD	Any	Any	Stop fluids + Alert
CIRCULARITY_UNSTABILITY	IMPROVING	Any	Fluids
CIRCULARITY_UNSTABILITY	STABLE/DETERIORATING	Any	Fluids + Beta-blocker

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6.5 Arbitration Rules (Safety Overrides)

Condition	Overriding Action
RESPIRATORY_DISTRESS	Stop all fluids
FAILURE_OXYGEN_THERAPY	Stop fluids
SHOCK	Block beta-blockers
DISTRESS_OVERLOAD	Fluids forbidden
BRADYPNEA	Beta-blockers forbidden
GRAVE_HYPOXIA	Beta-blockers forbidden

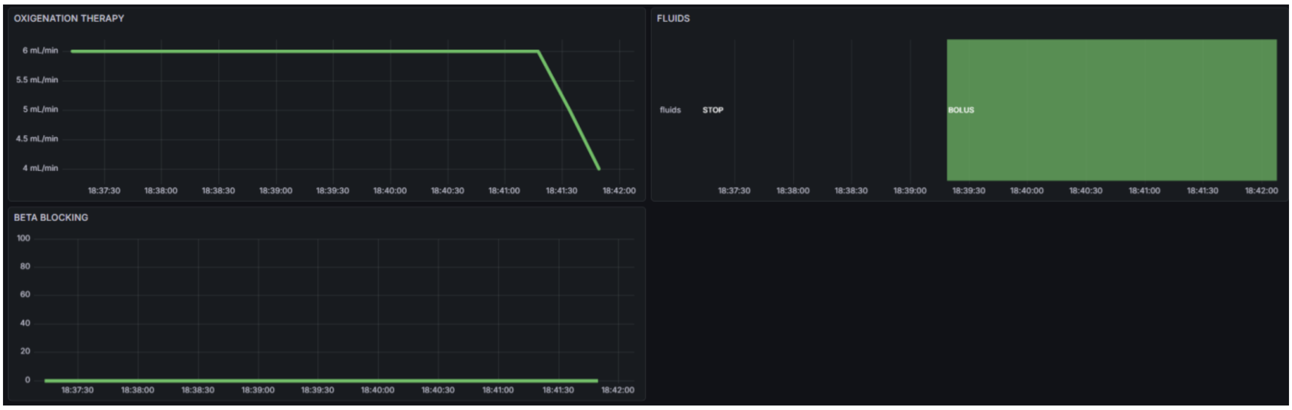
6. Dashboard

For each patient the dashboard show:

Vitals parameters

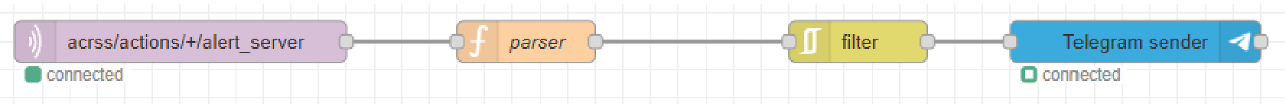
Symptoms with trends and instensity

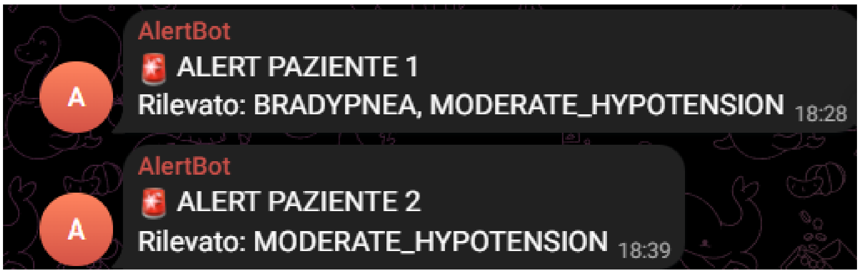
Therapies



7. Alert

Via a nodered stream that listens to a topic, mqtt parses the input and creates a telegram message that sends the alert to the chat via a telegram bot.


acrss/actions/+/alert_server
connected
parser
filter
Telegram sender
connected


AlertBot
ALERT PAZIENTE 1
Rilevato: BRADYPNEA, MODERATE_HYPOTENSION
18:28
AlertBot
ALERT PAZIENTE 2
Rilevato: MODERATE_HYPOTENSION
18:39