Alternative Approach for Solar Panel Monitoring and Maintenance using Multi-Agent Systems and Robotics

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***Abstract*—With the increasing usage of renewable energy sources such as solar panels and wind turbines as a means to fight against climate change and rising energy prices, their optimal performance and efficiency is ever more necessary. Robotics can be used for this task, aiding humans in achieving this goal in a fast and efficient way. To tackle the issue of the complexity existing in solar panel monitoring and maintenance, the proposed solution presents a system that combines robotics with multi agents systems, simplifying solar panel monitoring and maintenance by splitting it into different tasks tackled by different kinds of agents.**

***Index Terms*—Multi Agent System, Solar Energy, Robotics**

I. Introduction

Solar energy has emerged as a promising and sustainable alternative to conventional sources of electricity generation, owing to its environmental friendliness and potential for long-term cost savings. As solar panel installations continue to expand rapidly worldwide, ensuring their optimal performance and efficient maintenance has become crucial.

Robots are, nowadays, widely used to help humans in daily tasks increasing the performance to achieve goal of the task [1]. That means, doing it correctly in the shortest time possible, spending the least resources possible, while taking decisions autonomous. Reminding that all this process has to be supervised by a human.

In real world, that are lots the tasks that must be done before a major task be requested, or a major task depends on the management of little tasks that can show that something unusual or predictable is happening. These actions can triggering the robot to take an action. All these tasks, can be performed in small systems capable of handle a specific task, to contribute to the major goal of the all system. Those are called multi-agent systems (MAS) [2]. [2] shows a application of MAS with multi-robots systems. The case study was reproducing a team of rescuers in a disaster, given that sometimes some disasters can't be handle by humans, due the high risk of human losses. So, several robots were set, each one with they own task. The major goal was to distribute the tasks between the robots, maximizing the profit and minimizing or preventing possible collisions or competitions. In our project we aim to use a robot to help cleaning solar panels that are producing less that they should due some dirtiness. To address this challenge, the integration of MAS and robotics presents a compelling approach, offering advanced monitoring and maintenance capabilities that can enhance the reliability and lifespan of solar panels [3].

Effective monitoring of solar panels is essential for maximizing their energy output and detecting any performance issues promptly. Traditional monitoring techniques often rely on inspections performed through manual means, which takes lots of time that are needed in other important tasks, costly, and susceptible to mistakes made by humans. In contrast, multi-agent systems provide an intelligent and autonomous framework for monitoring solar panel arrays.The integration of infrared monitoring in photovoltaic modules presents a non-intrusive inspection methodology, facilitating the identification of potential failures through analysis of the modules' thermal characteristics. This approach yields valuable insights into the operational status of solar panels while avoiding invasive procedures [4].

Multi-agent systems comprise a network of autonomous agents that collaborate and communicate with each other to achieve a common goal. In the context of solar panel monitoring, these agents can be equipped with sensors and actuators to collect real-time data on panel performance, including temperature, voltage, current, and radiance levels. By employing data fusion techniques, the multi-agent system can analyze the collected data, identify anomalies, and make informed decisions regarding maintenance actions [3], [5].

An agent refers to a computer system operating within a given context that is capable of self-governing action within this context to achieve its intended goals. They determined that defining autonomy is a challenging task; however, in the context of this paper, it signifies the system's capacity to act independently without direct human or any other entity or agent intervention while exerting self-regulation over its actions and internal mechanisms [5].

Regular maintenance is crucial to ensure the longevity and optimal performance of solar panels. However, traditional maintenance practices often involve labor-intensive procedures, such as manual cleaning and visual inspections, which can be time-consuming and expensive, especially for large-scale solar installations. Robotics, integrated with multi-agent systems, offer a promising solution to automate and optimize solar panel maintenance processes [5].

Robotic agents, equipped with cameras, cleaning mechanisms, and navigational capabilities, can be deployed to inspect, clean, and perform minor repairs on solar panels. These robotic systems can navigate autonomously across the solar array, detecting dirt accumulation, physical damage, or faulty connections. The data collected by these agents can be shared and analyzed within the multi-agent system, enabling proactive maintenance scheduling and efficient resource allocation [6].

II. State of the Art

A. Multi Agent Systems applied to Energy fields

Multi agent systems can also be used in the Energy area. Because agents are distinguished from each other, they are able to adequately model the various entities in a Power and Energy System (PES). Likewise, complex entities and interactions can be handled by decomposing the problem into simpler blocks [7]. Thus, many examples in the literature are found where MAS were applied to decentralized energy architectures, namely Smart Grids (SG) [8] and microgrids (MG) [9]. [10] presents a MAS used to control the optimization and market distribution of the MG. The authors propose four types of agents, a Microgrid Central Controller (MGCC) agent to coordinate tasks with local controllers and manage energy exchanging periods between agents. Generation and consumption agents bid on the market to both sell and buy energy. Finally, the power systems agent is the middleman between the two previous agents. The authors of [11] model an Energy Control Center (ECC) in combination with MAS. The agents are responsible for representing the smart grid, users, control, database and Distributed Energy Resources (DER). The DER consisted of solar and wind power generators via MATLAB/SIMULINK. The authors in [12] merge Multi-Agent Systems (MAS) with Machine Learning (ML) models to construct a case-based reasoning recommender system that exhibits intelligent energy management capabilities for buildings. The system provides recommendations on the optimal level of energy reduction to be implemented in a building. Subsequently, the Case-Based Reasoning (CBR) agent seamlessly integrates into a collective of MAS, so that the building it is managing is connected to an external system. This integration enriches the recommender system's decision-making process by incorporating additional contextual information. Logenthiran et al. [13] presented a MAS developed to work in a distributed energy resource management in a micro grid. The micro grid was characterized as a distributed power network with low voltage power, composed by several generators, loads and storage that shares the grid power between them,while maintaining stability in the main grid. Each element in the micro grid, such as the generators and the loads, was designed as an autonomous intelligent agent. To do that, the JADE framework was the tool to developed the MAS system. The agents were designed to be capable of communicating with each other, of modifying the the world around them, of knowing and sharing its knowledge about the world around, also having some autonomy and behaviors to achieve the individual goals.

[14] presented a MAS applied to buildings, for energy management. They combine the energy management, forecast methods and MAS to implement the concept of smart homes, i.e. homes that has the ability of make transactions (buy/sell) with the local energy market using the power grid, also dealing with electrical power control in the house. The system was designed with six(6) types of agents: the Main agent with the task of implementing the others agents, the Distributed Energy Resources agent with the task of manage the renewable energy resources, the Electrical Loads agent with the task of spend the energy produced, the Energy Storage Systems agent, representing batteries and EVs, with the task of saving the energy produced, the Information Provider agent with the task of communicate the agents and environment real-time and stored data, the Local Electricity Market set of agents, they are external agents representing the energy supplier and a Demand Response aggregator, and the Energy Scheduler agent with the task of join all elements presents in the system, lineup all the agents for generation and consumption, assay the data, make predictions and control the energy flow. To implement the MAS they used JADE framework. The proposed system proved to be very promising, achieving results more accurate when worst scenarios were considered, the demand response program showed to help saving electricity on the smart home tested.

After reviewing all these articles and each proposed solution, it can be concluded that the decomposition of a robust problem into multiple smaller one results in better system performance. The robust problem is better solved using multiple entities rather than just one, due to the complexity and number of procedures it possess. Usually, energy problems have a lot of aspects and particuliarities to be considered, so it's benefitial to split the tasks and assign each task to an agent, having its own goals and responsibilities, while still working towards the major goal of the whole system. With this architecture, it is more likely that the system is able to keep functioning even if an agent fails, diminishing how badly the overall objective is affected. In additions, some agents can be experts at a particular task, and eceive and share information to other agents without knowing their specifics. This allows the agent to focus on improving his tasks, and can result in an increased overall system performance.

B. Multi-Agent Systems in Solar Panel Plant Monitoring

Related to solar power generation, [15] proposes the usage of multi-agent systems to monitor power, current,voltage and position of solar panels belonging to a solar farm. By monitoring the panels, it is possible to perform early fault detection and actions to be taken to increase the performance of the solar farm. The proposed solution considers an agent to monitor solar power values and perform actions or raise alarms, an agent to measure environmental data and, an agent to manage the system alarms raised in case of a malfunction. Similarly, [16] proposes a system that utilizes micro inverters, Internet of Things (IoT) and MAS to monitor and control the condition of photovoltaic systems. The system combines smart micro inverters and IoT technology to not only transfer the generated energy to grid or loads, but also to gather and analyze the inverter data, allowing for better control of the solar farm, but also enabling the detection of faults in order to improve efficiency. The authors considered a MAS approach to combat the increased complexity of the task caused by the existence of several micro inverters. In addition, the proposed system is also comprised of a web page where monitored values that stray from the ideal conditions will be displayed.

Khan et al. [17], presented a system that uses MAS to perform a optimal management and control on a distributed micro grid, that contains elements such as Wind Energy, Solar Energy and EV/Direct Current Load, also using optimization approaches, such as PSO, for hybrid energy system. Some agents in the distributed micro grid, control and management agents, were able to check the status of the distributed generators presented in the micro grid. Based on the those values a decision of store or transmission the energy produced is taken. Each agent established for checking the distributed generators status were inspected to be sure that the optimal management was always achieved. Some others business rules, such as handling surplus, energy distributions constraints, were also handled by the smart agents. These smart agent were also endowed with the capacity of obtain the values of the energy power generated, because, as said above, they had to decide about load or transfer the energy produced. Others agents were stipulated to obtain the energy consumption, others the energy generation, and pass those to the central agent, and this central agent passes those values to the control and management agents. The PSO proved to be very effective for reducing interruption and load costs, also for determine the best lineup and proportion for the micro grid in a MAS.

In the area of solar panel monitoring, agents can be used to monitor the sensors of each panel or panel section. The agent will be responsible for detecting anomalies that happen in the panel or panel section. So, this monitoring doesn't interfere with other agents's monitoring, and the anomaly doesn't propagate or cause consequences in other panels or sections. Allowing each agent to handle a specific sensor also prevents information from being mixed up or lost.

C. Robotics in Solar Panel Plant Maintenance

When it comes to solar panel cleaning, many approaches have already been developed and/or documented. In [18], it is provided an extended review on this topic where cleaning techniques range from:

- Natural Cleaning due to specific weather conditions (rain, wind, etc.);
- Manual Cleaning such as brushing and washing;
- Automated Cleaning with robots or sprinklers via remote access;
- Preventing Cleaning with protective coatings;
- Electrostatic Cleaning.

In [19], [20] it is showcased a system of vibrating brushes over photovoltaic modules where, in [20], with a novelty cleaning system, was able to improve the generated power relative to a photovoltaic module with no cleaning strategy by up to 30%. However, automated irrigation systems employing abundant quantities and reduced force of water, along with cleansing agents, exhibited a significant 27% enhancement in power output, as described in [21].

Outside automatic cleaning arrays, research with robots have already been covered. Studies in, [6], [22] demonstrate that it is possible to use a robot without requiring specialist supervision, nonetheless, cleaning sessions are not performed on-demand, but periodically and with a deliberative approach.

Converging to our proof of concept, in [23], it is documented a robot that can operate autonomously in desert areas. Due to the nature of this zones, cleaning process only involves dry brushing and the used path finding technique relies on ultrasonic sensors.

Menéndez et al. [4] proposed a system that detects photovoltaic deterioration, checking for checking for thermal information, getting places that are overheated, classifying them. But not only detects these overheated spots but also can identify false overheated spots that produces these effects due the presence of humans or reflections from some devices. The results showed that the system increase the performance of other methods by 12%, proving that it is able of high diagnosis of hot-spots presents in photovoltaic panels [4].

Gonzalo, A. et al. [24] listed several degradation mechanisms such as Soiling, Snow and Ice, Corrosion, Degradation, Cracks, Hot Spots and Fatigue which can be detected by visual inspection, thermography, power output and electroluminescence.

The usage of a robot for cleaning up solar panels is not a very recent idea. Year after year, there are multiple attempts to develop an even more efficient, innovative, and incremental technical update while minimizing resource consumption, if possible. Each robot depends on the physical structure it will be instructed to clean, the conditions of the space and its own properties, abilities, competence and potentiality. The choice of the robot will depend on this, but so far the robots have proven to be an efficient and capable of cleaning the solar panels.

III. Proposed Solution

[25] also proposed a cleaning robot for solar panels. However, this solution used just one robot to walk along a path and clean the solar panels. Meanwhile, the solution proposed in this paper differs as in that proposes a more complete solution. This was achieved by utilizing the data from the sensors connected to the solar panel's inverters and meteorological information. In addition, a drone was used to scout the panels for any issues alongside a robot with path-finding capabilities whose function is to clean the PV panels. Due to the large quantity of data generated by each sensor attached to each inverter, and the complexity of tasks the solution had to handle, these were split into simpler tasks and assigned to specialized agents, with individual goals, that maintain a stream of communication with each other, aware of any change or action that needs to be taken to preserve the correct functioning of the panels.

A. Robotics

The robotics component of our work consisted in using version 2 of Robot Operating System (ROS2) to develop a node capable operating on a section of a solar farm with the purpose of cleaning. In this proof of concept, we used a turtle-bot in GazeboSim Simulator, specifically, the built-in model turtlebot3_burger.

A minimalist environment in Gazebo was constructed. A solar farm is constructed around a symmetry axis (x-axis), which will be the robot's path of access to the solar farm sections, and each section must be oriented in a straight line or angled. A simple example can be viewed in Figure 1.

1) Procedure: Origin in the given frame of reference is understood as a possible charge point that will allow the robot to access all sections. Only when the robot is at the origin, is ready to travel to the anomalous section by transitioning from a `WAITING` state (state that awaits the report of an anomaly) to a `GOING_TO`. This state provides a standard velocity to the robot that was set 0.1 m/s, along its orientation axis and checks whether the robot reached or not its way-point. Independently from this state, there is an `ALIGN` state that can be requested whenever an alignment with a certain (or next) way-point is needed, whose angular velocity was set to 0.1 rad/s. By setting an alignment at the end of each way-point reached in `GOING_TO` state, we are able to direct the robot to the solar panels of the selected section.

When an anomaly is reported, a set o way-points is given: the first is an intermediate way-point representing the entrance of the section and the rest correspondent to the positions of the solar panels in the section. Once the intermediate way-point is covered the next way-points will trigger a `WORKING` state that can publish to another possible ROS2 node (not implemented in this proof of concept), responsible for a cleaning robotic arm, for instance. If all way-points were covered, the robot updates its way-point to the entrance of the section and origin to initiate a return and consequently wait for new anomalies. A comprehensive scheme can be found in Figure 2.

This instances of states can be used and adapted for any further features and or tasks such as for avoiding obstacles.

B. Multi-Agent System

To develop the MAS, a framework named Python-based Ecosystem for Agent Communities (PEAK) [26] was used. This framework was build using Smart Python Agent Development Environment (SPADE) [1] [2] framework as the base of the

[1]https://github.com/javipalanca/spade

[2]https://spade-mas.readthedocs.io/en/latest/readme.html

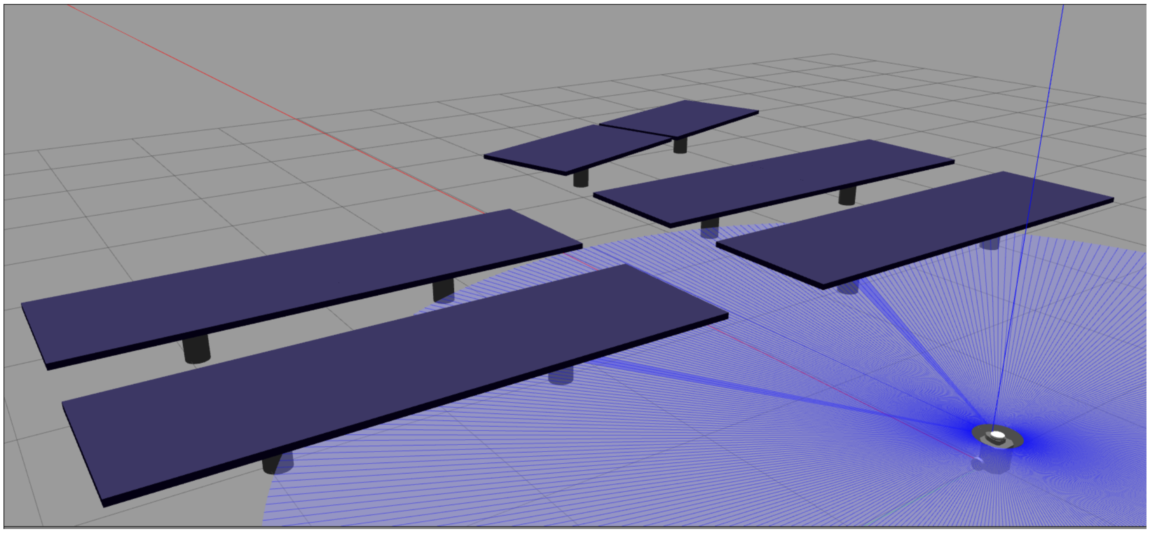

Fig. 1. Screenshot of a gazebo world suitable for the proposed proof of concept. Sections can contain any amount of solar panels (not necessarily the same) and section can be angled. Turtle-bot always starts at the origin as depicted.

project. The PEAK [3] [4] framework enables the reproduction energy communities and smart grids. The framework have tools to allow an administration of the several energy communities in a more simple, effortless and efficient way. It is key that the agents be able to communicate with each other, because its central that negotiations happen in the grid. The framework must handle all operations and agents that are set in there. In this framework, the upgrade is that it is possible to specified several MAS, simultaneous, as well as management of the environment and its agents, also includes a user interface to better management of each MAS, separately. The specification of the multiple MAS simultaneous can be performed Without causing detrimental interference to one another. PEAK differs from SPADE in that it is capable to allow a "community" of MAS, and as by the authors *'concurrent agent executions, the existence of group communication and the existence of a directory facilitator'* [26].

Figure 3 showcases how, to tackle the problem, the architecture of the MAS considered four types of agents:

[3]https://github.com/gecad-group/peak-mas
[4]https://pypi.org/project/peak-mas/

- Sensor agents (SA), to gather generation data from each PV section's inverter.
- Manager agent (MA), responsible for analyzing the generation and the weather data and detect any possible anomalies. Also gives tasks to the robots agent.
- The robots agent (RA), responsible for communicating with the robot(s) and informing them of the sectors to be checked.
- The weather agent (WA), responsible for gathering meteorological data and sending it to the Manager Agent upon request.

All sensor agents are equal, but one of them is labeled as the control. The solar panel's section of the control agent is assumed to always be operating efficiently and it is used as a means of comparison with the other sectors. The SAs receive data from the inverters through the MQTT protocol, and via a "CyclicBehaviour" send the generation data of each sector to the MA.

The MA keeps the last 60 seconds of data from each sector, and cyclically computes an average as new values are received. If there's a difference between the sensor and the control averages, the manager agent will send a request to the WA.

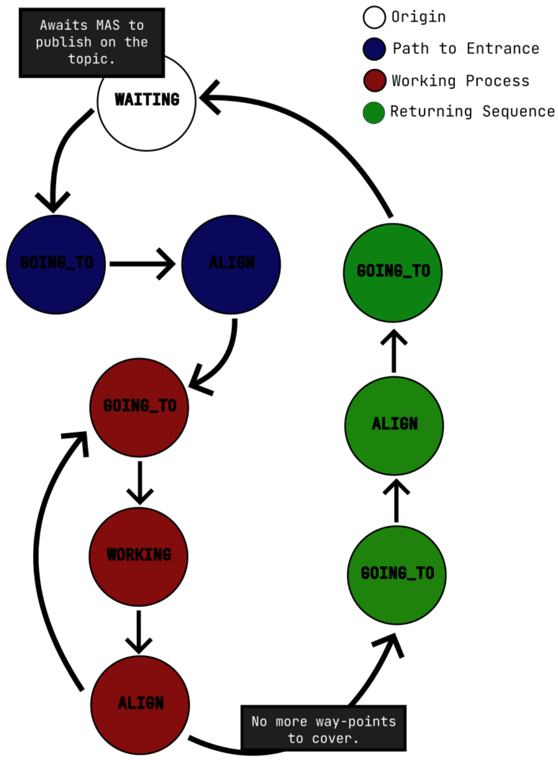

Fig. 2. Screenshot of a minimalist gazebo world suitable for the proposed proof of concept. Sections can contain any amount of solar panels (not necessarily the same) and section can be angled. Turtle-bot always starts at the origin as depicted.

In turn, the WA replies with the current weather data. The AM will then check:

- If the temperature is above 25ºC, this will cause the solar panels to lose efficiency in accordance to their coefficient.
- The current hour, to see if it is nighttime.
- If there's enough solar radiation for the PV panels to convert into energy.

If there is no issue with the weather, the MA will message the DA with the sensor at fault, as well as the priority of the task. The priority is directly proportional to the percentage difference between the sensor and the control averages.

Finally, the robots agent communicates with the robots that will perform checkup and cleaning operations on the affected solar panel sectors. Figure 13 is a sequence diagram representing the interactions between agents.

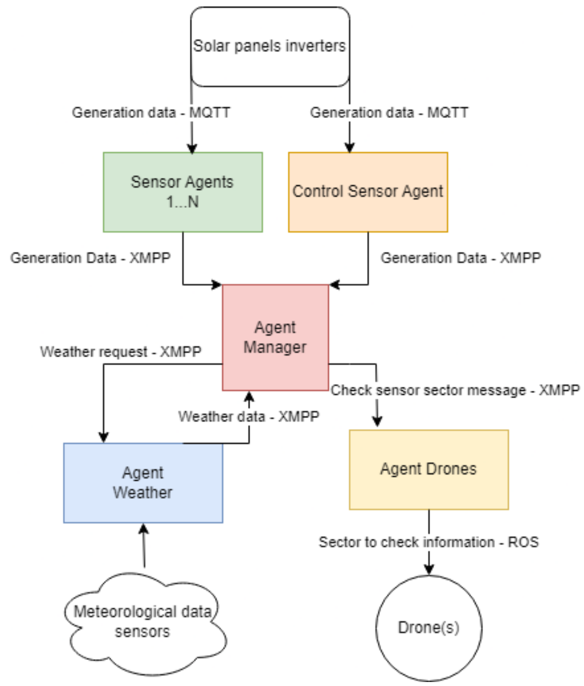

Fig. 3. MAS architecture

IV. Results

Regarding the robot routine, odometry callbacks are performed 10 times every second, with all the logic described in Robotics section contained in it. With distance and angular tolerances (to verify if way-points were reached) set to 0.05 meters and 0.05 radians, the system was able to run for 2+ hours continuously in the cycle represented in Figure 2 without losing the reference through various solar sections. The dimensions of the world used went around an area of 10×10 meters with 4 sections, each containing 2 solar panels.

As for the the agents belonging to the multi agent system are able to communicate with each other and perform the necessary tasks. Figure 4 shows the logs of one of the SA, how it connects to the MQTT broker and sends the solar panel generation data to the MA.

```
2023-06-22 18:44:43,495 - peak.bootloader - INFO - Creating agent from file
2023-06-22 18:44:43,614 - peak.bootloader - INFO - Agent starting
2023-06-22 18:44:44,731 - peak.bootloader - INFO - Agent initialized
on_connect
Connected to MQTT Broker!
report/agent1 2893
report/agent1 3028
report/agent1 3852
report/agent1 3653
report/agent1 2991
```

Fig. 4. Sensor agent communication

As Figure 5 shows, the WA is able to receive messages sent from the MA and return the meteorological data as response. In this situation, the sensor that's assumed to be at fault is the agent control sensor.

```
Weather - ReceiveMessage
Weather - agent_manager@mas.gecad.isep.ipp.pt/am sent me a message:
fault sensor:  SensorC
```

Fig. 5. Weather agent request

Relatively to the manager agent, Figure 6 shows the response received from weather agent after a weather request, namely the hour, the temperature and the solar radiation. It also shows the logging after the verification that the weather is in acceptable parameters, thus the robots agent will be messaged.

```
Weather - agent_weather@mas.gecad.isep.ipp.pt/aw sent me a message: '{"DateTime": 18,
Weather - Temperature: 13.0 Solar Radiation: 5.0
Weather - Weather is good, I'm sending a message to drone agent to check SensorC.
```

Fig. 6. Receiving weather data

Detailed in Figure 7 is the log of the MA receiving a message from the agent responsible for Sensor 4. After receiving the sensor value, the new average is calculated and compared against the control sensor average, resulting in the percentage difference. This percentage difference is then used to determine if the solar panel sector needs to be checked by the robots.

```
Sensor4 - agent_sensor4@mas.gecad.isep.ipp.pt/ag4 sent me a message: 'Sensor4-1003'
Value:  3070.6666666666665  Average:  3387.8888888888887  Difference:  9.363418713718803
The value is 9.36% less than the average.
```

Fig. 7. Receiving sensor data

When the RA is contacted, it receives a message that contains the sensor to be checked and the priority, as shown in Figure 8.

```
2023-06-22 18:44:43,432 - peak.bootloader - INFO - Creating agent from file
2023-06-22 18:44:43,510 - peak.bootloader - INFO - Agent starting
2023-06-22 18:44:44,469 - peak.bootloader - INFO - Agent initialized
Check-SensorC,Priority-2
Check-Sensor2,Priority-4
Check-Sensor3,Priority-0
```

Fig. 8. Robots agent message received

In the following scenario, presented in figure 9, section 2, is experiencing issues and producing less than expected.

```
Send `messages: 4383` to topic `report/agentC` using client ID: publish-342
Send `messages: 4094` to topic `report/agent1` using client ID: publish-342
Send `messages: 0` to topic `report/agent2` using client ID: publish-342
Send `messages: 4451` to topic `report/agent4` using client ID: publish-342
Send `messages: 4156` to topic `report/agent3` using client ID: publish-342
```

Fig. 9. Readings from the publisher

Therefore, the agent that read the values from section2 communicated the reading to the manager, and the manager detected this anomaly in the expected values, presented in figure 10.

```
Sensor2 - producing less than expected!
```

Fig. 10. Manager detects anomaly

Figure 11 shows meteorological data that the weather agent sent to the manager, proving that there is nothing wrong with the weather.

```
Weather - agent_weather@mas.gecad.isep.ipp.pt/aw sent me a message: '{"DateTime": 15,
Weather - Temperature: 14.0 Solar Radiation: 60.0
Weather - Weather is good, I'm sending a message to robot agent to check Sensor2.
```

Fig. 11. Agent Weather sends data. Request cleaning

No issues were diagnosed in the meteorological data, so the manager communicates with the robot agent, in figure 11, for the cleaning task.

As a result, figure 12 shows that the cleaning was successfully performed.

V. Conclusions

The use of robots in panel cleaning had already proven to be a possible approach, highly effective, promising, and very practical, as it automates

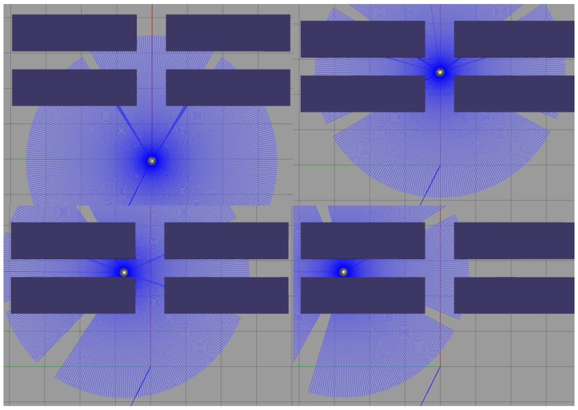

Fig. 12. Robot cleans section 2

the panel cleaning task and makes it faster. MAS (Multi-Agent Systems) are increasingly becoming essential for achieving complex tasks in the shortest possible time, while ensuring that tasks do not interfere with the execution of others, thereby avoiding serious system failures. This "division" of tasks implies not only a decrease in the time required to achieve the overall goal but also a reduction in high processing costs, task separation and responsibilities, and lower risks of compromised data.

The interconnection between the use of cleaning robots and MAS has proven to be a highly useful and promising approach, as different agents regulate only the sector for which they are responsible, without interfering with the responsibilities of other agents, i.e., without compromising their data. The data is sent only to the manager agent, which then communicates to the robot where to clean. This separation allows for greater coverage, performance, and system efficiency.

The manager agent was able to diagnose faults based on readings reported by the section agents, communicate with the robot, and the robot identified the section, directed itself to it, performed the cleaning, and returned to the charging point. The obtained results demonstrate the system's ability to fulfill the overall objective of panel cleaning.

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VI. ANNEX

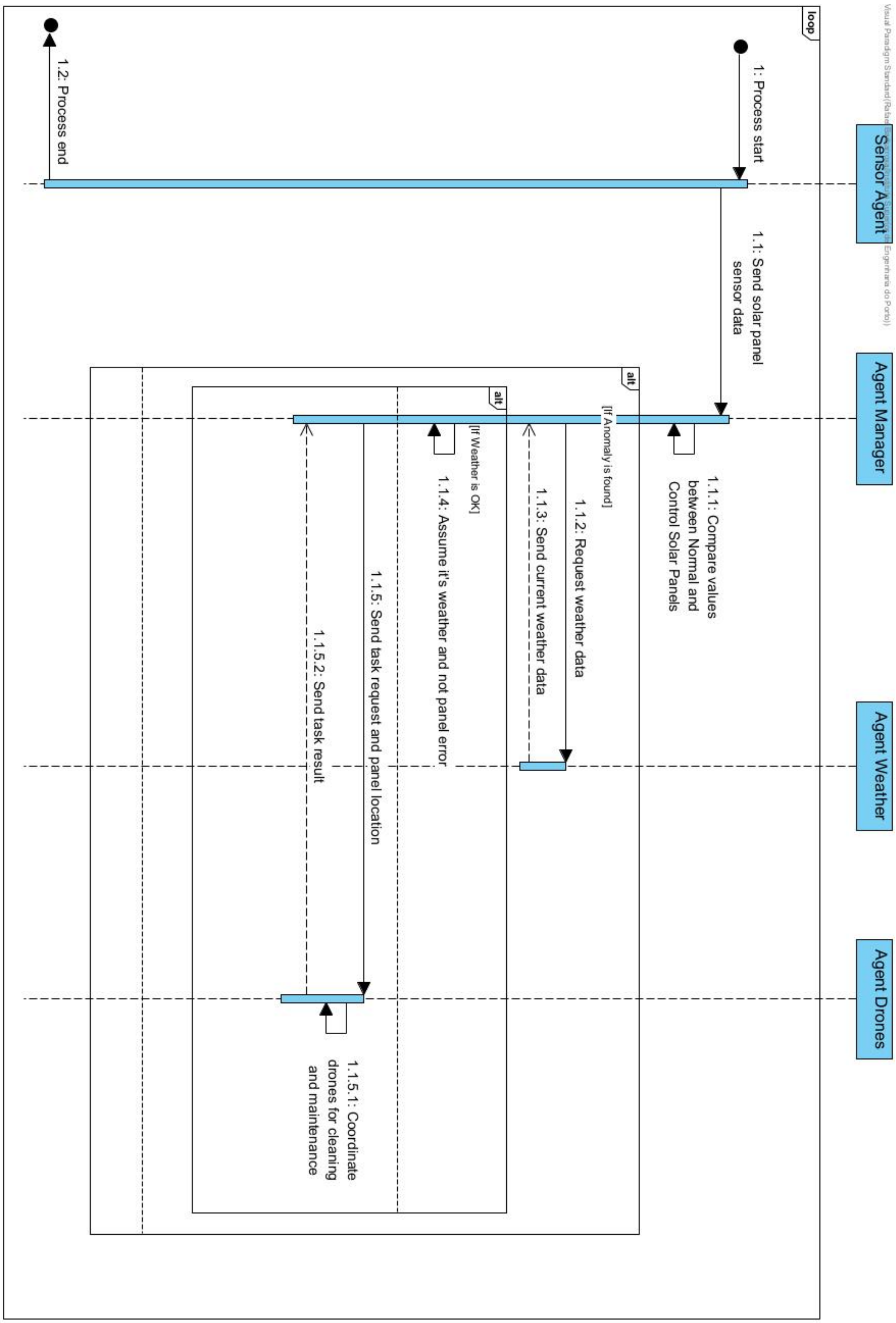

Fig. 13. Sequence Diagram