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ADVANCED WEATHER CONTROL SYSTEM AT THE TJO TELESCOPE

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RESUMEN

Los observatorios robóticos terrestres desempeñan un papel clave en la astronomía moderna al permitir la recogida automatizada y continua de datos de objetos celestes. Sin embargo, su funcionamiento depende en gran medida de las condiciones ambientales. Una respuesta automatizada y rápida del Sistema de Control Meteorológico (WCS) cuando las condiciones ambientales se vuelven adversas es fundamental para preservar la integridad del hardware del observatorio y garantizar datos astronómicos de alta calidad. Para hacer frente a estos retos, el nuevo WCS del Telescopio Joan Oró (TJO) del Observatorio del Montsec incorpora redundancia multisensor con varios algoritmos de redundancia, y mecanismos robustos de filtrado y validación de datos, mejorando la fiabilidad y precisión de los procesos de toma de decisiones relacionados con la meteorología y la calidad observacional.

La integración de estas características en el WCS permite al Sistema de Control del Observatorio (OCS) tomar decisiones informadas y oportunas sobre la programación de las observaciones, la protección del hardware y la adquisición de datos. Este sistema mejora significativamente la eficiencia y fiabilidad de los programas de observación astronómica llevados a cabo en el TJO. Tras un año de operaciones con el nuevo sistema, los resultados han sido excelentes, con una notable mejora de las observaciones. El uso de múltiples sensores redundantes y el filtrado de datos han demostrado ser particularmente efectivos, demostrando la eficacia del sistema en la mejora de las capacidades operativas del observatorio bajo diversas condiciones meteorológicas y fallos de hardware.

ABSTRACT

Ground-based robotic observatories play a key role in modern astronomy by enabling automated and continuous data collection of celestial objects. However, their operation is highly dependent on environmental conditions. An automated and rapid response of the Weather Control System (WCS) when environmental conditions become adverse is critical to preserve the integrity of the observatory hardware and ensure high quality astronomical data. To address these challenges, the new WCS of the Joan Oró Telescope (TJO) of the Montsec Observatory incorporates multi-sensor redundancy with various redundancy algorithms, and robust data filtering and validation mechanisms, improving the reliability and accuracy of weather-related decision-making processes and observational quality.

The integration of these features into the WCS enables the Observatory Control System (OCS) to make informed and timely decisions about observing scheduling, hardware protection, and data acquisition. This system significantly improves the efficiency and reliability of astronomical observing programs conducted at the TJO. After one year of operations with the new system, the results have been excellent, with a marked improvement in observations. The use of multiple redundant sensors and data filtering has proven to be particularly effective, demonstrating the system's effectiveness in improving the observatory's operational capabilities under various weather conditions and hardware malfunctions.

Key Words: telescope — weather control system — multi-sensor redundancy — data filtering

1. INTRODUCTION

Environmental monitoring is essential in ground-based astronomical observations. The observatory control system must be agile at responding to different environmental scenarios and the dynamic nature of meteorological variables. In the past, and even nowadays, observatories have depended on human staff to monitor weather conditions during observations. This approach, while functional, often leads to compromises in precision and is prone to human error.

Technology offers significant enhancements in accuracy, precision, and the reduction of errors. These improvements include continuous monitoring, sophisticated data storage, and retrieval mechanisms for comprehensive statistical analysis. The adop-

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Fig. 1. Night view of the OdM. Image credit: E. Herrero.

tion and adaptation of robotic and autonomous telescopes have led to the automation of these tasks, typically relying on weather stations. However, challenges arise when these stations experience errors, malfunctions, or when sensor data becomes biased or unreliable. Such issues can impact the quality of observations, the integrity of hardware, and even the mechanics of the observatory's infrastructure. The repercussions of errors in the weather control system (WCS) range from data loss due to inability to observe, to catastrophic situations involving hardware and mechanical failures. Therefore, the implementation of a robust system that relies on redundancy and data filtering is critical. Such a system should be capable of detecting and rectifying errors, thereby ensuring worry-free observations.

The motivation for developing a new WCS arises from the limitations and inefficiencies of the previous system. The old system depended solely on various sensors from different weather stations installed over time to measure new variables or replace faulty sensors. However, this setup relied on a single sensor for each weather variable. This approach was not only inefficient but also wasteful, as it ignored the potential of utilizing multiple other sensors from different stations.

Moreover, the system required manual intervention whenever a sensor malfunctioned. If a sensor used for measuring a specific weather variable encountered problems, operations had to be paused. This interruption was due to the need for human operators to replace the malfunctioning sensor with another one. That process not only led to operational delays but also resulted in the loss of valuable data during the transition period.

In essence, the need for a new Weather Control System was driven by the desire to overcome these challenges: to make better use of the available sensors, reduce dependency on manual intervention, and minimize data loss due to sensor or device failures.

Furthermore, the new WCS benefits of increased precision in weather variable data through the use of multiple redundant sensors. In the previous system, relying on a single sensor for each weather variable not only limited the system's efficiency but also its accuracy. With the implementation of multiple sensors for the same variable, the new system can cross-verify data, leading to more accurate and reliable measurements.

This redundancy is crucial in weather monitoring for astronomical observations, where precise data is vital. By integrating multiple sensors, the system can compare and contrast the readings from these sensors to identify any anomalies or errors. This approach not only enhances the overall precision of the weather data but also provides a fail-safe mechanism. If one sensor fails or provides inaccurate data, the system can automatically rely on the other sensors without the need for manual intervention, ensuring continuous and accurate monitoring. This improvement is a key factor in the decision to develop a new, more sophisticated Weather Control System.

In this proceedings, we present a comprehensive overview of the Weather Control System employed by the Joan Oró Telescope (TJO). We discuss its design, redundancy and data filtering.

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2. THE MONTSEC OBSERVATORY

The TJO telescope is mounted at the Montsec Observatory[2] (OdM), located at an altitude of 1570 m in Sant Esteve de la Sarga, 50 km north of the city of Lleida (Catalonia, Northeastern Spain). This site was carefully selected for its exceptional conditions for astronomical observation. First of all, it is in a region certified as an UNESCO Starlight Reserve[3], and explicitly protected from light pollution by a law of the Catalan Parliament. The night sky brightness at the site reaches values as low as 22.0 mag arcsec^{-2} at the zenith, and between 21.520.6 mag arcsec^{-2} at a height of 45° above the horizon, both in the Johnson V band (Colomé et al. 2008). Secondly, the weather conditions are quite good during the year, allowing operations in around 70% of all the night time. Finally, it has a very low astronomical seeing, with a median value of 0.82" and better than 0.7" during 32% of the night time (Colomé et al. 2010), as reported by five months of measurements using a Robotic Differential Image Motion Monitor (DIMM Sarazin & Roddier 1990).

The observatory has multiple facilities that are devoted to different areas, such as:

- Research: two telescopes offered to the scientific community, the TJO (0.8 m) and the TFRM[4] (0.5 m), and an All-Sky Camera for fireball and meteor detection.
- Teleport: S-band and UHF/VHF facilities for communication with satellites.
- Services to the community: a weather monitoring station of the Catalan Meteorological Service, an atmospheric pollution and quality monitoring station, firefighter surveillance cameras, and radiolinks to provide internet access to hydroelectric generating systems and nearby towns.

3. THE TJO TELESCOPE

The main facility at the OdM is the Joan Oró telescope (TJO), which has been operated by the Institute for Space Studies of Catalonia[5] (IEEC) since its construction in 2004. It is a Ritchey-Chrétien telescope with an aperture of 80 centimeters, and is fully robotic, with no human intervention required apart from supervision and maintenance.

[2]https://www.montsec.ieec.cat/
[3]https://en.fundacionstarlight.org/contenido/46-list-starlight-reserves.html
[4]https://www.racab.cat/es/observatori-fabra/tfrm
[5]https://www.ieec.cat/

The TJO is equipped with two simultaneous instruments. The main instrument is the Large Area Imager for Astronomy (LAIA), an Andor iKon XL imaging camera with a 4096×4096 back-illuminated sensor, a pixel size of 0.4 arcsec, and a field of view of 30 arcmin. LAIA is mounted together with a rotating filter wheel that contains 5 standard Johnson-Cousins photometric filters (U, B, V, R, and I), 4 Sloan Digital Sky Survey photometric filters (g, r, i, and z), and a narrow filter centered at the Hα line.

The other instrument mounted at the TJO is the Astronomical Mid-Resolution Spectrograph (ARES), an optical spectrograph with a resolution of R=12'000 divided in two spectral windows, one centered at the magnesium triplet (495 to 529 nm) and another centered at the Hα alpha line (634 to 678 nm).

The primary functions of the TJO include satellite surveillance and tracking (SST) activities and scientific research, offering observation time to the scientific community via a Time Allocating Committee (TAC) in two yearly semestral calls for proposals. As for the research areas, the TJO is a multi-purpose telescope, with proposals aimed at stellar variability (e.g. Ribas et al. 2018), stellar activity (e.g. Baroch et al. 2020), transiting exoplanets (e.g. Herrero et al. 2011), Gaia follow-up (e.g. Wyrzykowski et al. 2020), transient sources (e.g. Morales-Garoffolo et al. 2014), or Solar System objects (e.g. Trigo-Rodríguez et al. 2008), among others.

The TJO has been working on a completely unattended control since 2013, requiring minimal human supervision. In order to achieve this level of autonomy, it requires having a reliable, secure, and efficient system that is able to plan, execute, and reduce images completely unattended.

The current system present at the TJO, the Robotic Observatory Control System (ROCS), is divided in two main nodes: one off-site and another on-site, as depicted in Fig. 2. Each of the nodes is equipped with its own database containing identical information, which is synchronized on a routine basis.

The offsite node, located at the IEEC offices in Barcelona, is in charge of the storage and distribution of data. The main system there is the Management for Users in ROCS (MUR), which is the interface where the users can submit proposals, define the observations, and access and download the observed data. Additionally, as part of an agreement with the Spanish Virtual Observatory (SVO), all the images older than a year stored in our database are

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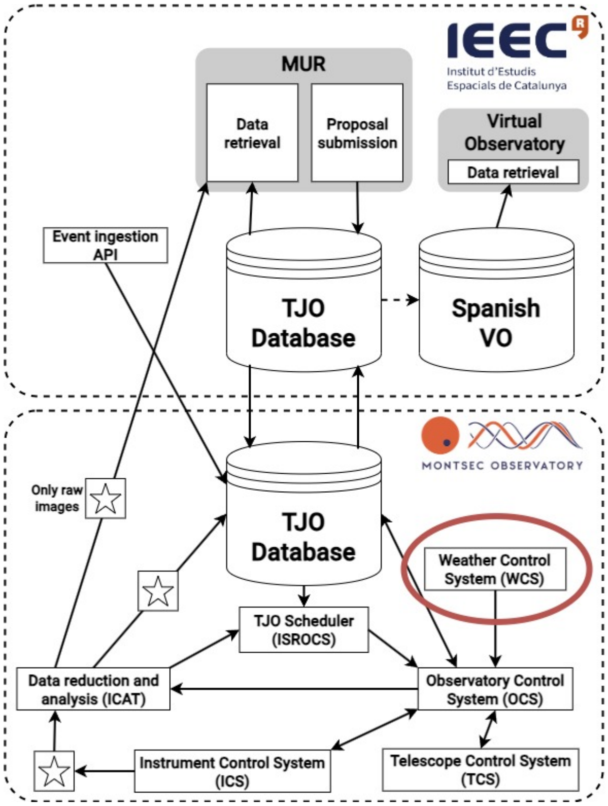

Fig. 2. Schematic diagram of the architecture of the Robotic Observatory Control System (ROCS) of the TJO.

made publicly available through the SVO webpage[6], where more than 300'000 images spanning 10 years are available to the community.

The onsite node is located at the OdM, and it is in control of unattended operations. The main system in this node is the Observatory Control System (OCS), which is responsible for issuing commands to the dome, telescope, and the instrument (via the Telescope Control System, TCS, and the Instrument Control System, ICS) based on the night plan issued by the scheduler and on the weather conditions. Additionally, the system contains a collection of pipelines (The IEEC Calibration and Analysis Tool, ICAT) used to perform data reduction and quality control. Finally, this node also contains the Weather Control System (WCS), which is the one highlighted in red in Fig. 2.

4. DESIGN AND IMPLEMENTATION

The behaviour of the overall system is fundamental to understanding the Weather Control System. The WCS is responsible for retrieving sensor data from weather devices, processing this data, and generating a validated output for each weather variable, which ultimately determines the WCS's overall status. This validated output is subsequently utilized by the Observatory Control System (OCS) to make informed decisions regarding the operation of the Telescope Control System (TCS) and, by extension, the observatory hardware.

When dealing with the challenges of this weather control system, it is important to consider a few key aspects. These include setting up a standard interface for easy communication with various drivers from different weather stations. Also, utilizing all available sensors effectively, including redundancy strategies. Additionally, ensuring that the data collected from many sensors is accurate by strong validation and filtering mechanisms to catch and fix errors and outliers before using it in the system. Lastly, the system needs to be flexible enough to add new weather devices and improvements as needed.

The WCS of the TJO considers the

4.1. *Structure and status*

The system's architecture is based on a Device-Sensor-Variable framework, coupled with state definitions. Each device is equipped with a range of weather sensors, each measuring distinct weather variables. For example, a basic device may have three sensors, measuring variables such as temperature, humidity, and pressure.

The management of the state for each system component is contingent on various factors. At the highest level, the overall status of the weather control system relies on a selected set of required weather variable statuses. Each individual weather variable, in turn, depends on a group of sensor states and the redundancy mechanisms applied to those sensors. Concurrently, the status of each device hinges on the states of its respective sensors.

The system's architecture is organized into five essential modules, the configuration, input, filter, redundancy, and output modules. Each of these modules serves a specific function within the WCS:

- **Configuration Module:** This module is responsible for establishing a connection with the database to retrieve and apply user-defined configuration parameters for all system components.

- **Input Module:** The Input Module is tasked with collecting sensor values from different drivers associated with various weather devices.

[6] `https://sdc.cab.inta-csic.es/joro`

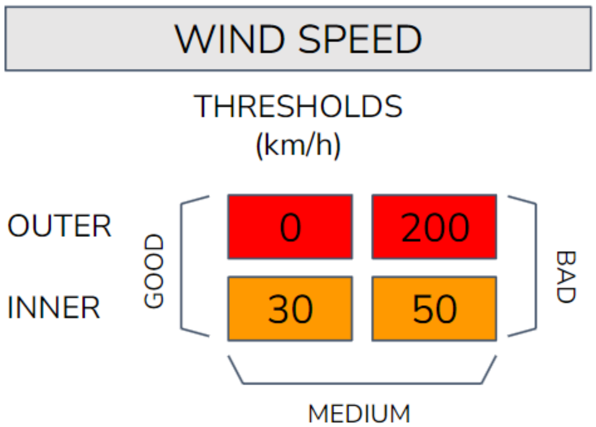

Fig. 3. Example of wind sensor thresholds for data validation and state determination.

- **Filter Module:** Responsible for processing raw data extracted from the weather stations and filtering and validating this data to ensure its accuracy and reliability.
- **Redundancy Module:** Leveraging the validated data and the redundancy configuration, the Redundancy Module generates values for each weather variable.
- **Output Module:** The Output Module is responsible for managing the delivery of data to external systems, such as databases or external software applications.

4.1.1. *Configuration module*

The Configuration Module is responsible for establishing the system's behaviour. It connects to the database and retrieves configuration parameters for devices, sensors, and variables. These parameters govern the system's operation across all modules. Specifically:

For the Input Module, configuration parameters dictate the selection of drivers and specify the location of configuration files that map devices to their respective drivers for sensor data retrieval.

In the Filter Module, configuration parameters are utilized to customize thresholds, limits, conversion factors, and validation algorithms for sensor data.

In the Redundancy Module, configuration parameters determine which redundancy algorithms are applied to weather variables.

Lastly, the Output Module's configuration governs the system's operating frequency for data publication to external software or databases.

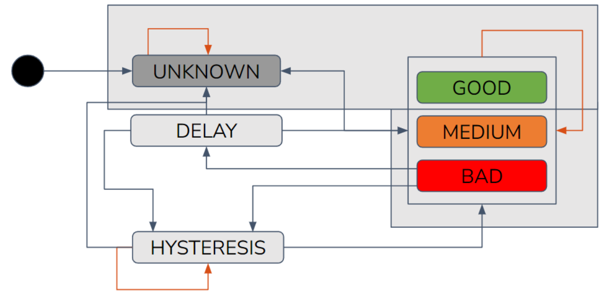

Fig. 4. High-level diagram of the WCS state machine. The gray area is only for sensors whether variables have DELAY and HYSTERESIS additional states.

4.1.2. *Input Module*

The Input Module interfaces with various drivers associated with different devices to collect sensor data. It employs a common interface, allowing multiple drivers, including APIs, SERIAL communication drivers, and web scrapers, to integrate seamlessly with the WCS.

4.1.3. *Filter Module*

The Filter Module is responsible for validating sensor and variable values, ensuring that the WCS processes accurate and precise data while determining the state of sensors and variables. Multiple validation algorithms are employed:

- **Sensor Level Validation:** This includes the Spike Validator, Unit Conversion, and Threshold and Limits.
- **Variable Level Validation:** After sensor data validation, variables undergo additional scrutiny through algorithms such as Threshold and Limits and Simple Moving Median (SMM). These algorithms not only validate data but also assign statuses to sensors and variables.

The Threshold and Limit algorithm maps sensor or variable values to states based on user-configured parameters, including two outer limits indicating erroneous data and two inner thresholds separating GOOD, MEDIUM, and BAD states as depicted in Fig. 3. Values outside this range are discarded.

Additionally, variables adhere to the same threshold definitions, and they may include DELAY and HYSTERESIS states (Fig. 4) based on user configurations, allowing for delayed transitions or hysteresis-based state changes that can be combined.

The Spike Validator's purpose is to detect and discard data spikes within a specified window. This is achieved by using a window reference translated

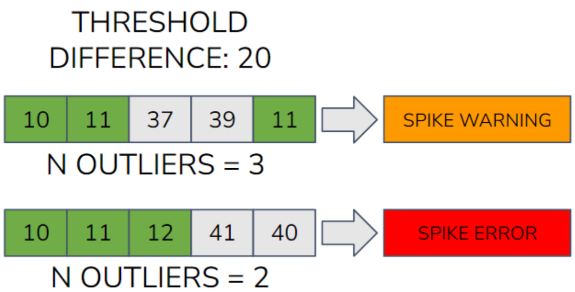

Fig. 5. Two examples of spike behaviour in a window of 4 values with a threshold difference of 20 and a configured maximum number of outliers.

into an array of values, along with a minimum threshold difference criterion for identifying outliers. When a specified number of outliers are detected within the defined window, these are considered errors and are not incorporated into the WCS as shown in Fig. 5.

The Simple Moving Median (SMM) algorithm is employed at the variable level to smooth data and prevent the WCS from making the observations stop when certain variables report a BAD state for a very short period of time (for example, gusts of wind short humidity peaks or small clouds passing by as in Fig. 6).

4.1.4. *Redundancy Module*

The Redundancy Module is responsible for delivering the final output for each weather variable, particularly when multiple devices provide the same variable. To facilitate diverse user requirements and in alignment with the WCS's design philosophy, users have to configure the redundancy settings for different variables. The Redundancy Module offers several algorithms, including:

- **Mean:** This algorithm calculates the mean of sensor values and assigns it to the corresponding variable.
- **Fallback:** Users define a preferred priority order for sensors from 1 to N, and if one sensor fails or produces an error, the subsequent sensor in the priority order is used for the weather variable.
- **Least Restrictive:** Only when all sensors report a BAD state is the weather variable assigned a BAD state.
- **Most Restrictive:** In contrast to the least restrictive algorithm, when one or more sensors report a BAD state, the variable is assigned a BAD state.

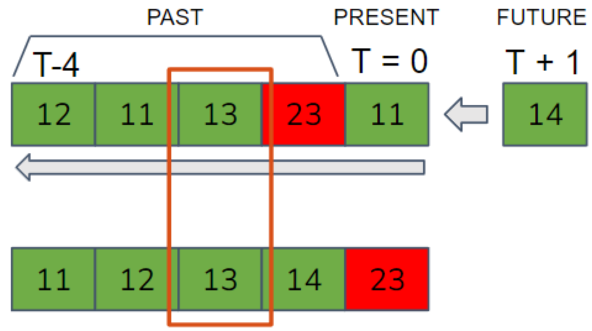

Fig. 6. Example that shows how the SMM works given a user-defined window and with a short-lived BAD state.

The Redundancy Module also offers an interface to facilitate the development and integration of new redundancy algorithms.

4.1.5. *Output Module*

Lastly, the Output Module determines the frequency of data publication and is responsible for delivering raw sensor data (prior to validation), validated variable data, and the overall WCS status. This data is transmitted to the Observatory Control System (OCS) for integration with the observatory's overall structure and is concurrently stored in a database for visualization and statistical analysis.

5. SUMMARY

The proceedings highlighted the successful implementation of the Weather Control System employed by the TJO telescope at the OdM, showcasing its capabilities and contributions to the field of weather control systems.

The WCS, which has been in production for over a year, demonstrated exceptional versatility by using various weather devices, eliminating the need for manual intervention when dealing with different sensors and drivers. This extended period of practical application proves the system's reliability and effectiveness in real-world scenarios. The WCS is notably fault-tolerant, handling device or sensor failures smoothly to ensure continuous data collection and system operations.

In terms of data accuracy, the WCS has a robust filtration and validation process, ensuring that sensor values are consistently and accurately represented. The system's ability to manage redundancy is another strong point, reliably producing accurate weather variable outputs even with overlapping data from multiple devices, which is crucial for data integrity and system dependability.

Customizability is another key attribute highlighted during the proceedings. The WCS allows users to tailor and define the system's behaviour to suit their specific requirements. This adaptability ensures that the system can be fine-tuned to meet the unique needs of various applications. Moreover, the WCS is committed to ongoing improvement, regularly incorporating new methods and algorithms to enhance its performance and expand its capabilities.

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