Design of a Prototype Remote Monitoring System for the Protection and Conservation of Territories in the Colombian Amazon Rainforest

Jorge Torres, Oscar Riveros, María Barajas, Jhonatan Chamorro, Andrés Triana, and Margarita Varón

***Abstract*—This study presents the design and implementation of a prototype Remote Monitoring System (RMS) adapted to the climatic and geographic conditions of the Colombian amazon rainforest. The system has been developed to address the challenges faced by monitoring and conservation efforts in protected areas. The prototype integrates three modules: a remote sensing module using radar technology and a pan-tilt-zoom (PTZ) camera to detect and visualize unauthorized activities; a telecommunications module employing a satellite system for real-time data transmission; and an autonomous power supply module based on a photovoltaic system. The system's functionality was assessed through a field experiment in the Amacayacu National Natural Park, where its capacity to monitor the real-time movement of vessels on the Amacayacu River, identify potential threats, and generate e-mail alerts with pertinent information was evaluated.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9884

***Index Terms*— Remote Monitoring System (RMS), Colombian amazon rainforest, radar, PTZ camera, photovoltaic system.**

I. Introduction

THE Amazonian tropical rainforest is the largest in the world, covering approximately 7.989.004 km². The Colombian Amazon spans around 531.000 km², accounting for roughly 6,6 % of the total Amazon biome and nearly 42 % of Colombia's national territory [1], [2].

The Colombian Amazon harbors about 10% of the world's biodiversity [3] and has a crucial role in regulating the global climate as a major carbon sink [4]. However, it faces increasing threats such as illegal mining and deforestation for agriculture and cattle ranching. These activities not only degrade the environment but also disrupt the delicate balance of local ecosystems and indigenous communities[3], [5], [6].

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Monitoring and conservation efforts led by Colombia's National Natural Parks (CNNP) and other organizations face significant challenges due to logistical and budget constraints. The traditional monitoring methods used by the CNNP, such as river patrols, aerial surveillance and satellite imagery, are usually expensive, limited in coverage and lack the capacity for real-time monitoring within the designated area of interest.

Therefore, the existing surveillance infrastructure is insufficient to deal effectively with the increasing threats in the region. To address these issues, technological innovations such as Remote Monitoring Systems (RMS) emerged. These systems enable real-time data collection and transmission, facilitating the remote observation, identification, and tracking of specific targets in a defined region.

RMS's previous initiatives, including those developed by Huawei's *Guardian Platform* [7], [8] and the *Preventing Illegal Deforestation using Acoustic Surveillance* project [9], use acoustic surveillance to detect illegal activity. However, these solutions rely on the availability of mobile networks. In contrast, the *Tracking Boats on Amazon Rivers - A Case Study with the LoRa/LoRaWAN* [10] utilizes LoRa technology to enhance environmental monitoring. Despite its advantages, this approach has a limited communication range and still depends on local network infrastructure. It is clear that autonomous monitoring systems, independent of local power grids and telecommunications networks, remain necessary for remote regions.

This paper presents the design and implementation of the RMS prototype adapted to the climatic and geographic conditions of the Colombian Amazon, thereby providing a continuation of the previously presented works *RMS's for Conservation of the Amazon Rainforest: A Systematic Review* [11], *Design of a prototype RMS for the protection of territories in the Rio Puré National Natural Park* [12] and *Radar based monitoring system to protect the Colombian Amazon Rainforest* [13], which presented the initial phases and preliminary tests of the RMS. This project is aligned with the United Nations Sustainable Development Goals (SDGs): 13 (Climate Action) [14], 14 (Life Below Water) [15] and 15 (Life on Land) [16]. Therefore, this initiative contributes to biodiversity conservation, climate change mitigation, and the development of effective governance mechanisms for protecting indigenous territories and natural resources.

This article is structured as follows: section 2 describes the requirements of an RMS for the Amazon rainforest. Section 3 presents the system technology and setup determination. Section 4 discusses the integration of the modules, and section 5 presents the validation of the system in the Amazon rainforest, including some results of the pilot tests.

II. RMS Amazon Rainforest Requirements

In the Colombian Amazon rainforest the average annual temperature varies between 25°C and 26,5°C, with a minimum of 20,6°C to 22,3°C and a maximum of 29,1°C to 30,8°C. Annual rainfall ranges from 3.084 mm to 3.438 mm, with an average of 3,148 mm. Annual sunshine varies between 1.600 and 1,820 hours, and relative humidity is between 86 % and 87 % [5].

Given the climatic conditions of the Amazon, as well as its remote geographic location, the following requirements should be addressed when designing a monitoring system:

a) Modularity: The proposed design must integrate different modules implemented using various technologies. The design should enable future upgrades and maintenance in an environment with limited logistics.

b) Physical Design: The different components of the system should resist the harsh conditions of the Amazon rainforest. Some desired characteristics of the system are resistance to corrosion, oxidation, high temperatures, extreme humidity, fungal growth, and potential damage from wildlife. Additionally, camouflage is a crucial factor, helping the system merge into its surroundings to minimize the risk of external threats leading to detection or damage.

c) Power autonomy: Since the monitoring system will be installed in a non-interconnected zone with no access to the electrical grid, it must have an autonomous power generation system. The system's power supply must ensure continuous operation while requiring minimal maintenance.

d) Connectivity: Since telecommunication networks are absent in most of the Amazon Natural Parks, it is mandatory to ensure the capacity to transmit the data of the monitoring system using a telecommunication module. Moreover, the system must provide remote access to facilitate system control without physical intervention.

III. Remote Monitoring System Technology and Setup Determination

According to the previous requirements, a modular design is proposed as shown in Fig. 1. The proposed design is made up of three modules: A) Remote Sensing Module; B) Telecommunications Module, and C) Autonomous Power Supply Module. Additionally, the system includes a Raspberry Pi4 and Switch to enable connectivity between the modules.

A. Remote Sensing Module.

This module is responsible for detecting disturbances or threats that may occur in the protected area. For this task different solutions offered by the industry were considered as radar, acoustic, and ultrasonic technologies [17], [18], [19].

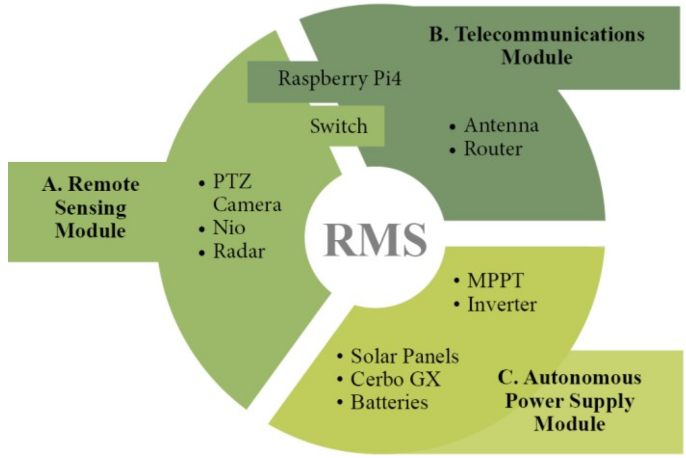

Fig. 1. Modular Remote Monitoring System Proposal.

Radar detection technology was chosen due to its effective operation in various weather conditions, including fog, rain, and clouds. Radar technology also offers the ability to collect essential information on the position, speed, and direction of potential targets, as well as enabling integration with sensors and/or cameras, thereby improving the identification and recording of disturbances in the area.

For this module a SpotterRF CK5-CE® radar was selected. The proposed detection and identification system integrates a compact radar and a PTZ camera and Networked Input/Output (NIO) device to detect and visualize unauthorized human activity (see Fig. 1-A).

The radar has an operating frequency of 24 GHz, with a resolution of 1 m and a detection range up to 175 m for boats, being able to detect simultaneously up to 10 objects. The PTZ camera has 360° rotation on the horizontal axis and 180° on the vertical axis, along with a zoom of up to 10 times. This feature allows to track moving objects, a valuable feature for effective surveillance.

Furthermore, the module under consideration utilizes a NIO device to facilitate communication between the radar and the camera. This component allows the system to be trained to perform classification and identification of the monitored elements through the implementation of artificial intelligence.

B. Telecommunications Module.

The main function of this module is to transmit relevant information related to any disturbance or threat detected by the sensing module. Considering the lack of telecommunication local networks in the region, a satellite service for data transmission was selected, ensuring ***connectivity*** in these remote areas. A commercial Starlink® solution was selected due to its <99 ms latency and global coverage, and cost-effectiveness, with acquisition and operational costs estimated at approximately $80 USD per month and $349 USD per hardware unit, respectively, at the time of this article's writing. The system operates in the ku band, offering link speeds of 40 to 220 Mbps and power consumption of 110 to 150 W [20]. The system is composed of a router connected to an antenna (see Fig. 1-B).

C. Autonomous Power Supply Module.

This module ensures a continuous energy supply to the various components that comprise the proposed design. In accordance with the autonomy requirements and considering the Colombian Amazon as part of the so-called Non-Interconnected Zones (ZNI), the implementation of an off-grid power supply system is necessary.

The use of a photovoltaic system stands out as the best alternative, since it presents advantages for its application in remote and difficult-to-access areas such as reliability, ease of installation, capacity to take advantage of the solar radiation of the region and system maintenance.

The proposed photovoltaic system, shown in Fig. 1-C, was designed for a total power demanded by the sensing and telecommunication modules estimated at 120 W, representing an energy demand of 2880 kWh per day.

For the proposed photovoltaic system, a nominal voltage of 48 VDC was considered, consisting of two Trina Solar® 580 W [21] monocrystalline panels, connected in series. As a battery charge control and management device, a Victron Energy® SmartSolar MPPT 150/45 controller [22] was chosen, with a maximum nominal power of 2600 W for a battery voltage of 48 VDC and a nominal current of 45 A. For the inverter was chosen the Phoenix 48/375 120V VE.Direct of Victron Energy® [23] single-phase, with a nominal output power of 375 VA, an operating AC voltage of 120-230 VAC, and a frequency of 50-60 Hz.

Considering that batteries are essential in an off-grid system for storing energy generated during the day and supplying it at night or during periods of low solar availability, a storage system with at least two days of autonomy and a maximum discharge capacity of 90% for lithium batteries was proposed.

For this reason, the use of two Pylontech® US5000 [24] Ion-Lithium batteries were selected, with a nominal voltage of 48 VDC and a nominal energy storage capacity of 4800 Wh.

Furthermore, a Victron Energy® Cerbo GX [25] was installed. This energy management system (EMS) facilitates control and monitoring of the photovoltaic system and provides real-time data regarding generation, consumption, and the state of charge of the batteries, among other metrics.

D. Physical Design.

According to Section II part b, to guarantee the RMS operation under Amazon rainforest conditions, three physical design challenges were identified: i) the setup pieces design, ii) the materials, paints and finishes election, and iii) the camouflage. These challenges are addressed as follows.

i. Setup Pieces Design and Cable Protection.

To ensure the optimal positioning of all electronic components during operation, some external pieces were designed as shown in Fig. 2: A metallic structure (1) to support the solar panels (7) at a 15° inclination and to hold the antenna (8) was constructed. An electric cabinet (2) to host the electronic components was implemented, mounts to hang the PTZ camera (5) and the radar (4) to trees were created using 3D modeling and 3D printing technologies. Finally, a protection for cables (3) linking the solar panels, the PTZ camera, the radar and the antenna along with the electric cabinet were utilized. The pieces were designed with modular parts to facilitate reparation and transport and have no holes to prevent insect and water entry.

ii. Materials, Paints and Finishes Election.

To protect the pieces from environmental conditions that could lead to damage of the equipment such as corrosion, two primary materials were selected: cold rolled metal for the electric cabinet and the metallic structure, and plastic for the mounts and cable protections. Material samples with different paints and finishes were tested in laboratory in a 100-hour saline chamber to select the most suitable option. For the cold rolled metal pieces corrosion inhibitors, car paint and varnish were applied in a controlled environment, while ASA and PVC plastic pieces demanded the use of a primer, a spray paint and varnish.

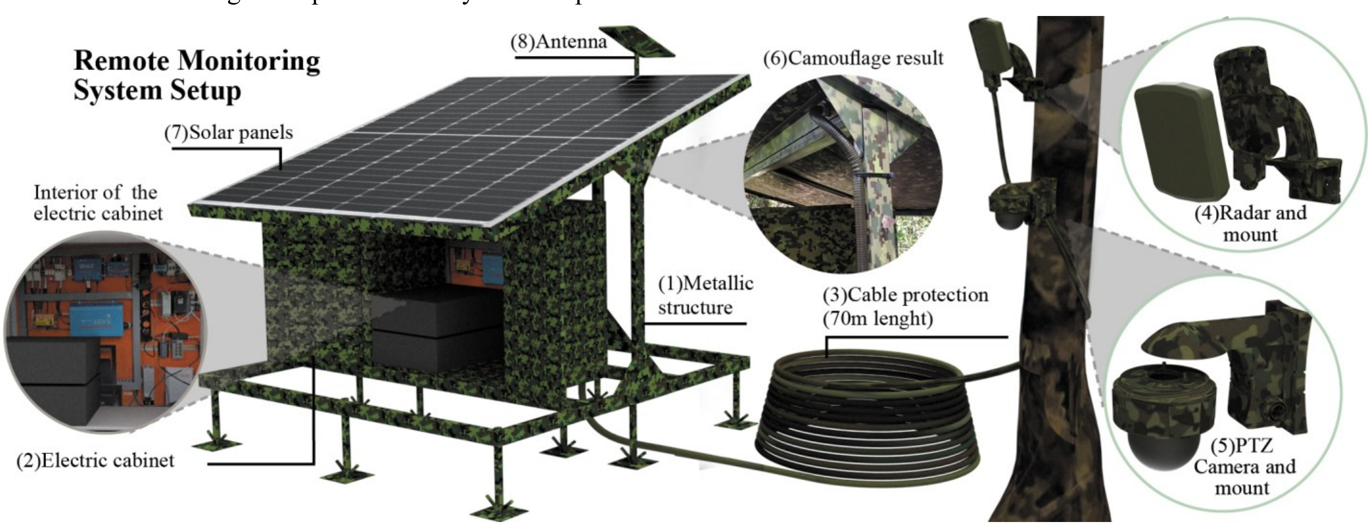

Fig. 2. Final setup for the RMS installed in the Colombian Amazon rainforest. The figure shows the main physical components, including (1) the metallic structure supporting the photovoltaic panels, (2) the electric cabinet containing the control electronics, (3) the cable protection system, (4) the radar module, (5) the PTZ camera, (6) the camouflage design based on local color palette, (7) the solar panels, and (8) the satellite antenna.

iii. Camouflage.

To hide the RMS as much as possible, the pieces were painted using a camouflaged pixeled pattern. The 5 colors were selected from a color palette based on photos from the installation site (see Fig. 2 (6)).

IV. Module Integration

Once all the technologies and materials have been selected for the three modules of the system, it is necessary to interconnect the devices and integrate software to ensure proper operation of the system. As illustrated in Fig. 3, the system is composed of three parts: the remote sensing module (A), the telecommunications module (B), and the autonomous power supply module (C). The connections between these devices are shown in two sections. The first section is network integration, where communication and data flow between devices is managed (see the dashed lines). The second section is electrical integration, where the power is distributed to make the system work (see the continuous lines).

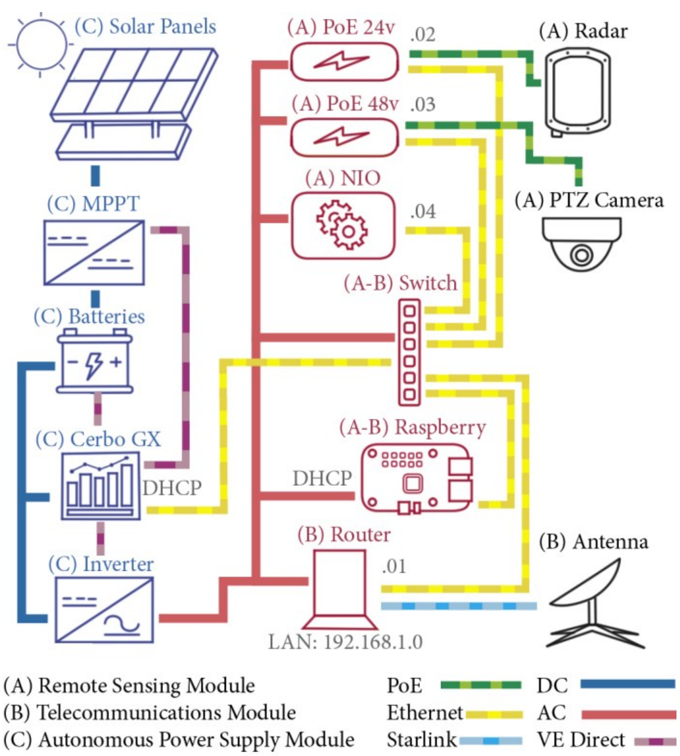

Fig. 3. Diagram of device interconnections in the RMS. The dashed lines represent data communication links, and the continuous lines indicate power connections. The system integrates three modules: (A) the Remote Sensing Module, composed of the radar, PTZ camera, and NIO device; (B) the Telecommunications Module, which includes the router and satellite antenna; and (C) the Autonomous Power Supply Module, consisting of the photovoltaic panels, MPPT controller, batteries, inverter, and Cerbo GX monitoring unit.

1. Network Integration.

The system transmits data about detected targets and provides remote access to the users. The remote sensing module captures images and extracts technical details of the targets, while the power supply module reports system status data. Therefore, device interconnection over a Local Area Network (LAN) is important to acquire data of sensors and send it through the internet.

In Fig. 3 the interconnections between the elements and the modules are shown. The dashed lines represent the data connections, and the continuous lines represent the power supply connections. A first group of connections (shown in Fig. 3 with green and yellow lines), links the radar, camera, NIO, CerboGX, Raspberry Pi4, and router. These devices operate under the Ethernet standard and are all connected to a common switch linking to the communication module's router. This router assigns IP addresses to the devices using the DHCP (Dynamic Host Configuration Protocol). However, some devices, such as the camera and the radar, do not have a local domain name. These devices are configured with a static IP to prevent changes after system reboots and avoid communication losses.

The second network connections include the monitoring device (Cerbo GX) that communicates with the autonomous power supply module devices using its proprietary VE.Direct protocol (Fig. 3, purple line). The system status information is sent to an external server for processing and visualization.

Once communication between the devices is established, it is crucial to coordinate and process the information from the remote sensing module. For this purpose, a Networked I/O (NIO) device is used. It employs artificial intelligence to analyze radar data and detect potential threats in the area. Additionally, it coordinates the PTZ camera movement to focus on targets. Furthermore, the NIO can send emails containing information about targets via the SMTP (Simple Mail Transfer Protocol).

Enabling remote access to the system requires external network connectivity to the local network. However, the implemented communication system operates under a CGNAT (Carrier-Grade Network Address Translation) topology, preventing external network access since the system lacks a public IP address. To address this limitation, a Raspberry Pi4® was utilized to encapsulate local network protocols using Tunneling. This enables remote access via an external server acting as an intermediary, which assigns domain names to local network addresses. As a result, users can access the web interfaces of all network devices and even remotely control the Raspberry Pi4® using VNC (Virtual Network Computing), if additional system configuration is required.

2. Electrical Integration:

The devices in the autonomous power supply module operate exclusively on DC power (Fig. 3, in blue). The communication and sensing module devices, including the NIO, POE, Switch, Raspberry Pi4, and router (see Fig. 3, in red), are designed to operate on a standard household electrical network. Therefore, they are directly connected to the AC output of the system's inverter.

The camera and radar are powered using the PoE (Power over Ethernet) standard, as illustrated in Fig. 3. Each device has a dedicated PoE adapter that supplies the required operating voltage. The PoE standard supports connections of up to 100 meters. In this application, the devices were installed at 70 meters to ensure reliable operation.

Fig. 4. Final RMS prototype installed in the Amacayacu National Natural Park (December 2024).

V. Implementation in the Amazon Rainforest

A prototype of the complete system was installed in the Amacayacu National Natural Park (3°48'20.0" South and 70°18'21.3" West) in December 2024 to detect the passing of boats in the Amacayacu River. Fig. 4 illustrates the installed prototype, which complies with the requirements established in sections II and III of this research. The electric cabinet, the solar panels, their support structure, the antenna, and the cables with their corresponding camouflage can be observed on the left side of Fig. 4. The components were installed approximately 30 meters away from the riverbank, where they were hidden by the surrounding dense foliage. On the right side of Fig. 4, the radar and camera are shown, mounted with their respective supports on a tree at a height of 8 meters above river level and approximately at 70 meters from the electrical panel.

Upon detection and tracking of a target by the RMS, an ID is assigned, and an e-mail is sent containing target information and photographic evidence. This e-mail includes the date and time of the event, an access link to the NIO to the consultation of the target's history and track, the duration of the detection in seconds, the geolocation of the target (coordinates and location in Google Maps), and the target's velocity. Photographs of the detection are sent as attachments of the email, as shown in Fig. 5.

VI. Conclusion and Future Work

The Remote Monitoring System (RMS) prototype implemented in the Colombian Amazon is an innovative and effective technological solution to address the challenges of monitoring and conservation in this region. The system is working effectively in challenging environmental conditions and in a remote location, and it has demonstrated its capacity to detect, classify, and send warnings regarding potential vessel intrusions in real time. The integration of technologies such as radar, PTZ cameras, and satellite connectivity, along with an autonomous power system, ensures uninterrupted surveillance. The results of the pilot tests validate the potential of the RMS to contribute to the conservation efforts in the Amazon and other regions with similar characteristics.

Given that the field tests are currently underway (as of April 2025), future work will include the following: optimization of the installation design, definition of maintenance protocols and frequencies, and evaluation of the durability of the materials, coatings, and components used in the prototype. In parallel, a mathematical and quantitative evaluation of the RMS performance will be carried out, including the optimization of the photovoltaic system's energy performance, the characterization of the radar's behavior under variable environmental conditions, the analysis of false detection rates, the classification of images using artificial intelligence, and the statistical evaluation of detection accuracy and communication latency. In addition, a protocol for technical evaluation and financial feasibility of strategically deploying several RMSs at the entrances around a specific protected area will be developed.

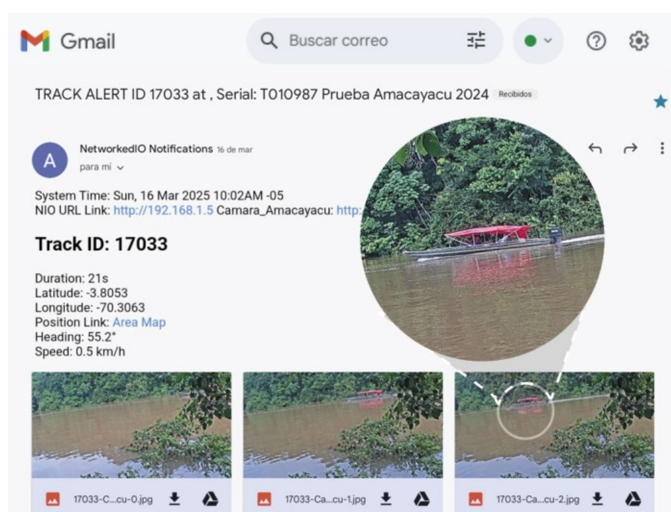

Fig. 5. E-mail track ID 17033 in the Amacayacu riverbank.

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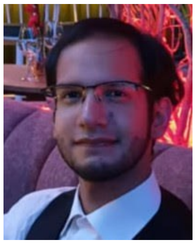

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