

**REMOTELY PILOTED AIRCRAFT SYSTEM IN URBAN SOLID WASTE
LANDFILLS (USWL)**

**SISTEMA DE AERONAVE REMOTAMENTE PILOTADA EM ATERROS DE
RESÍDUOS SÓLIDOS URBANOS (ARSU)**

**SISTEMA DE AERONAVES PILOTADAS A DISTANCIA EN VERTEDEROS
URBANOS DE RESIDUOS SÓLIDOS (USWL)**

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ABSTRACT

Technological progress has expanded the capacity for observing geographic space. Drone technology, or Remotely Piloted Aircraft Systems (RPAS), has been widely disseminated. With the increasing use of RPAS, there is a growing application of this technology for monitoring, inspection, and planning purposes, as well as for obtaining aerial imagery for terrain studies, with special attention to environmental impacts. The use of this aircraft can significantly contribute to reducing environmental damage. The objective of this study is to take advantage of RPAS technology and its generated products to plan safety measures for combating fires in massive urban solid waste deposits. The study addressed the challenge of managing fire control in solid waste landfills, presenting RPAS as a valuable tool for surveying and monitoring these areas, especially during large-scale fire events. It is considered that this work and the proposed methodology were both appropriate and innovative, as they provided a tool-oriented approach for data collection to support fire prevention planning. The results showed that the use of RPAS for area mapping can be useful for fire-fighting planning, particularly in the context of the ARS-Aurá and Guamá sites.

Keywords: Technologies. Overflight. Urban Waste. Fire.

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RESUMO

O progresso tecnológico tem proporcionado uma ampliação da capacidade de observação do espaço geográfico. A tecnologia dos drones ou Sistema de Aeronaves Remotamente Pilotadas (SARP) está sendo amplamente difundida. Com o aumento do uso das SARP, há uma crescente utilização desta tecnologia para monitoramento, fiscalização e planejamento, além da obtenção de imagens aéreas para estudos do relevo, com especial atenção aos impactos ambientais. A utilização dessa aeronave pode contribuir significativamente para a redução dos danos ambientais. O objetivo deste trabalho é aproveitar o SARP aproveitando os recursos dessa aeronave e os produtos que podem ser gerados, visando planejar medidas de segurança para o combate a incêndios em massa de resíduos sólidos urbanos. O trabalho apresentou o desafio de gerenciar o combate ao fogo em aterros de resíduos sólidos, sendo uma ferramenta valiosa para o levantamento e monitoramento dessas áreas, especialmente durante a ocorrência de incêndios em massa. Considera-se que este trabalho e a metodologia proposta foram adequados e inovadores, pois forneceu uma orientação de ferramenta para coleta de dados para o planejamento contra incêndios. Os resultados mostraram que o uso de SARP, para mapeamento de área pode ser útil para o planejamento de combate a incêndios, neste contexto, dos ARS-Aurá e Guamá.

Palavras-chave: Tecnologias. Sobrevoos. Lixo Urbano. Fogo.

RESUMEN

El progreso tecnológico ha ampliado la capacidad de observación del espacio geográfico. La tecnología de drones, o Sistemas de Aeronaves Pilotadas a Distancia (RPAS), se ha difundido ampliamente. Con el creciente uso de RPAS, se observa una aplicación cada vez mayor de esta tecnología para fines de monitoreo, inspección y planificación, así como para la obtención de imágenes aéreas para estudios del terreno, con especial atención a los impactos ambientales. El uso de estas aeronaves puede contribuir significativamente a la reducción del daño ambiental. El objetivo de este estudio es aprovechar la tecnología RPAS y sus productos generados para planificar medidas de seguridad para combatir incendios en grandes depósitos de residuos sólidos urbanos. El estudio abordó el desafío de la gestión del control de incendios en vertederos de residuos sólidos, presentando a los RPAS como una valiosa herramienta para el estudio y monitoreo de estas áreas, especialmente durante incendios de gran magnitud. Se considera que este trabajo y la metodología propuesta fueron apropiados e innovadores, ya que proporcionaron un enfoque orientado a herramientas para la recopilación de datos que apoya la planificación de la prevención de incendios. Los resultados mostraron que el uso de RPAS para el mapeo de áreas puede ser útil para la planificación de la lucha contra incendios, particularmente en el contexto de los sitios de ARS-Aurá y Guamá.

Palabras clave: Tecnologías. Sobrevuelo. Residuos Urbanos. Incendio.

1 INTRODUCTION

The technological advancement of the last decades has transformed the way human beings observe and understand geographical space. Among the most relevant innovations are Remotely Piloted Aircraft Systems (SARP), known as drones. The term "drone", of North American origin, designates remotely controlled aircraft (DE QUEIROZ et al., 2022). SARP is the translation of the term Unmanned Aircraft System (UAS), adopted by the International Civil Aviation Organization (ICAO) (SANTOS, 2019).

Initially aimed at military purposes, SARPs have become widely used in civilian activities, such as environmental monitoring, infrastructure, mining, civil construction, and agriculture (CHOMSKY; VLTCHEK, 2022). This technology makes it possible to obtain accurate information on the earth's surface, at low cost and with high quality, especially revolutionizing geographic mapping (SANTOS, 2021). There are different types of SARPs depending on the purpose: rotary-wing, more popular, and fixed-wing SARPs, with greater autonomy and range.

According to Santos et al. (2020), SARPs provide quick and detailed data, being useful in mapping landfills and dumps, areas frequently affected by fires and fires that cause explosions and environmental and public health damage. Quintas (2005) highlights that the intensity of fires and inadequate landfill infrastructure can cause serious environmental impacts and risks to human health, requiring effective preventive measures.

The National Solid Waste Policy (PNRS), instituted by Law No. 12,305/2010 and regulated by Decree No. 7,404/2010, defines solid waste as materials discarded from human activities that must be managed in a technical, economically feasible and environmentally sustainable manner (BRASIL, 2010). This concern has its roots in the Industrial Revolution, a period in which production and disposal patterns intensified (SEARA et al., 2013), but the issue dates back to the Middle Ages, with the first urban sanitary problems (CÂNDIDO et al., 2009).

Currently, there is a crisis in the management of Urban Solid Waste (MSW), aggravated by accelerated urbanization and the lack of infrastructure. Marques (2011) points out that the inadequate disposal of USW is one of the greatest municipal challenges, due to the lack of resources and technical knowledge. This mismanagement generates impacts such as soil degradation, water contamination, air pollution, and vector proliferation (JACOBI et al., 2021).

In the Metropolitan Region of Belém (RMB), the situation is critical. Belém, Ananindeua and Marituba collect about 40 thousand tons of garbage per day, resulting in bad smells, contamination and inconvenience to the population. Household waste alone corresponds to about 1,620 tons per day (VALE et al., 2015). The inadequate disposal and the risk of reactivation of the old Aurá dump aggravate the local "garbage crisis", intensifying fires in waste masses (PORTELLA, 2014).

Urban Solid Waste Landfills (ARSU) are areas of permanent risk due to the possibility of fires caused by the accumulation of flammable materials, operational failures and climatic factors. Therefore, it is essential to use effective monitoring, control, and prevention methods. In Belém, ARSU have a high risk of combustion, even without receiving hazardous waste, which can cause atmospheric pollution and soil and water contamination.

The use of drones equipped with optical, thermal, and multispectral sensors allows for agile and safe aerial monitoring, identifying hot spots and accurately assessing fire behavior. Thus, the use of SARP in landfills represents a significant technological innovation, contributing to fire planning, inspection, and prevention, in addition to supporting environmental monitoring (SANTOS, 2021).

Thus, this dissertation aims to analyze the use of SARPs in Urban Solid Waste Landfills (ARSU), highlighting their technical resources and products for the planning of fire prevention and fighting measures. It is intended to demonstrate how this technology can contribute to a safer, more efficient and sustainable management of urban solid waste, integrating technological innovation and environmental responsibility.

2 METHODOLOGY

The research is of a bibliographic, qualitative and descriptive nature, based on the analysis of references on the use of Remotely Piloted Aircraft Systems (SARP) in the management and monitoring of Urban Solid Waste Landfills (ARSU). Books, articles, dissertations and theses on waste management, remote sensing, photogrammetry, geoprocessing and fire prevention were consulted (BRASIL, 2010; GOUVEIA, 2011; FLORENZANO, 2016; SANTOS, 2021). The methodology comprised three stages: data collection, data analysis and fieldwork, integrating remote sensing information and on-site observations.

2.1 DATA COLLECTION

The collection was carried out in the ARSU of the Metropolitan Region of Belém (RMB) using the SARP DJI Mavic 2 Enterprise Advanced, equipped with GNSS L1, IMU, 20 MP RGB and thermal camera, autonomy of 25 minutes and range of 4 km. The experimental flyby took place at 1 pm, under favorable weather conditions measured by the UAV Forecast application (FLORENZANO, 2016). The planning and execution of the flights were done in DroneDeploy® (DD), which allows configuring routes, altitude, and image overlay (DA SILVA et al., 2021). At ARS–Aurá, the flight was carried out at 100 m altitude, with a frontal overlap of 75% and a lateral overlap of 65%, covering 0.217 km² in 13 minutes and generating 252 images. All flights followed the rules of ANAC, DCEA, ANATEL, ANTAQ and ANEEL, according to Santos (2021). The products obtained subsidized the elaboration of high-resolution digital maps for the planning of firefighting actions.

2.2 DATA ANALYSIS

The captured data was processed in DroneDeploy®, with checkpoint verification to improve the accuracy of the orthomosaic and 3D models. Products such as 2D orthomosaic, NDVI, MDE, MDT, thermal model (MIT) and 3D model (M3D) were generated, later integrated into QGIS. This integration allowed spatial manipulation and analysis, resulting in thematic maps at the scale of 1:5,000, used in the planning of firefighting actions (IBAM, 2015). The maps identified buildings, structures and risk areas, providing technical support for operational monitoring.

2.3 FIELDWORK

The fieldwork was essential to validate the data obtained by remote sensing and refine the planning of the flights. The Avenza Maps app was used to mark ground control points and risk areas. Direct observations and photographic records were also carried out to characterize the areas of waste deposition, evaluating variables such as soil type, slope, drainage and occupied area.

In addition, a fire drill and evacuation was conducted at the Urban Waste Processing and Treatment Center (CPTR-Marituba), with the support of the 25th Military Firefighter Group (GBM). The activity made it possible to recognize the operational conditions of the landfill and to prepare a safety plan for preventing and fighting fires and landslides, in accordance with current regulations (SANTOS, 2021). During the exercise, an operational

checklist was applied for flying with SARP, essential for mission planning and support for CBMPA actions.

4 RESULTS AND DISCUSSIONS

The aerial survey carried out with the DJI Mavic 2 Enterprise Advanced model generated products that provided detailed information about the Urban Solid Waste Landfills of the Metropolitan Region of Belém (ARSU-RMB). The first product generated by the remotely piloted aircraft was the digital model, or orthomosaic, which results from the union of several scenes (orthophotos) captured in the ARS-Aurá. The ARS-Aurá orthomosaic consists of a georeferenced aerial image, produced using the DroneDeploy (DD) image processing platform. This means that the spatial elements in the orthophotos — such as the embankment, the massifs, the trees and the buildings — have positions corresponding to their actual geographic location.

The orthomosaic of landfills can be used to collect information, mainly visual and updated, about these areas. It is an essential product for daily use in the activities of ARSU-RMB, and can be used by various sectors, such as engineering, topography, energy, mining, agriculture and, especially, by the Military Fire Department of Pará (CBMPA).

This product is widely used in the construction of image maps and maps, for carrying out inspections, georeferencing, area measurements, map comparison and monitoring of the evolution of projects. In addition, it has direct application in the planning of firefighting actions in the massifs. Figure 1 shows the ARS-Aurá orthomosaic, which enables the pre-mapping and identification of strategic points for firefighting planning, as well as the analysis of other relevant data for understanding the risks and threats in the ARSU-RMB.

Figure 1

Orthomosaic or georeferenced orthophoto of the ARS of Aurá



Source: Author, 2024

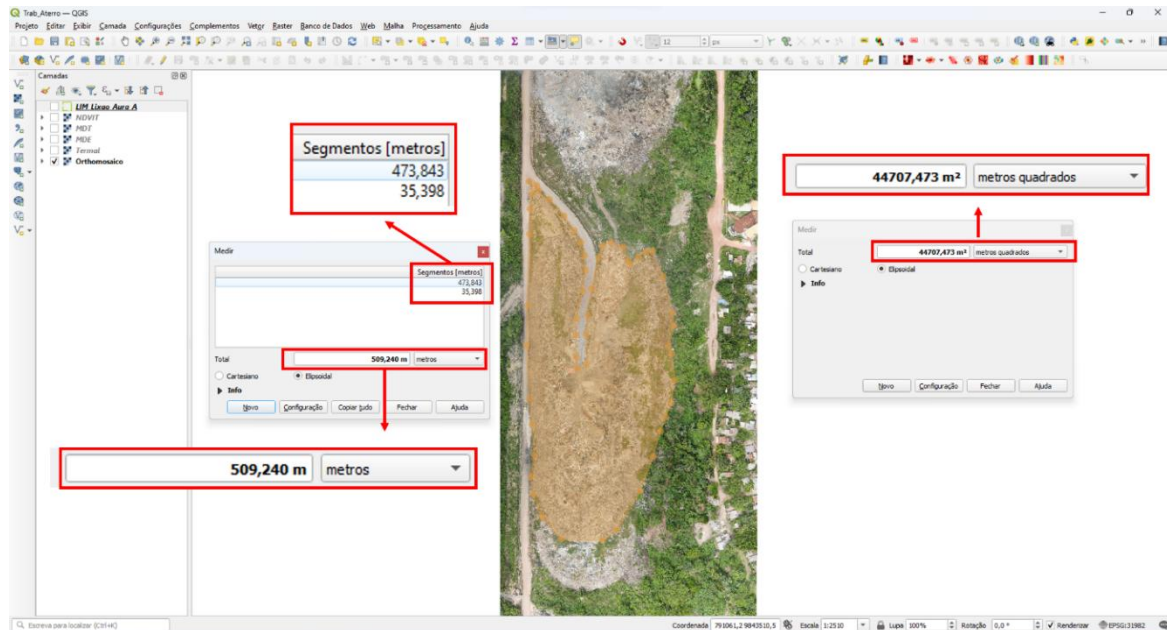
The ARS-Aurá orthomosaic provides a complete vertical view of the area, favoring the performance of forensic examinations and facilitating the collection of information with less intervention and exposure of surveyors or experts. Thus, the use of Remotely Piloted Aircraft Systems (SARP) for the collection of preliminary data in these locations is highly recommended, as it is a tool capable of obtaining, quickly and accurately, a large volume of high-quality data, in addition to allowing the collection of spatial coordinates.

In general, the orthomosaic is the main product generated by SARP, since, through software that joins orthophotos based on common points identified in two or more images — such as DroneDeploy and the Geographic Information System (GIS) QGIS® —, it is possible to carry out direct measurements of distances, areas and angles, in addition to preparing thematic maps or situation plans. with precision, agility and low cost.

With the insertion of the ARS-Aurá orthomosaic in the GIS (Figure 2), measurements, demarcations and analyses become feasible for the tactical and operational use of firefighting and for the establishment of the command post by the Military Fire Department of the State of Pará. The orthomosaic can also serve as a basis for fire and explosion forensics. In the context of planning actions against fires in solid waste landfills, the implementation of QGIS facilitates the manipulation of images captured by SARP, such as the orthomosaic, for the purposes of topographic survey, analysis of the volume of waste in the massif, evaluation of water bodies, positioning of vehicles and implementation of the Incident Command System (SCI). among others. Figure 2 illustrates the application of GIS tools used to measure segments and areas of the ARS-Aurá in the orthomosaic image, as well as in other products automatically obtained by SARP via DroneDeploy (DD).

Figure 21

QGIS interface with ARS-Aurá orthomosaic image



Source: Author, 2023

In the QGIS® SIG, it is also possible to prepare an Image Chart (IC) of the solid waste landfills of the RMB, with the objective of defining strategic points of fire fighting. In addition, this tool enables the detailed identification of structural characteristics, which are fundamental for the composition of technical reports on fire prevention in ARSU-RMB. The ARS-Aurá orthomosaic, with a spatial resolution of 2.04 cm, is a high-precision raster image, which allows the complete visualization of the landfill area and the production of Image Maps (IC) or Digital Maps (DM). These products are used both for surveying spatial information and for the updated visualization of regions of interest, especially in areas subject to fire occurrences in the solid waste massif.

Through the ASRS-Aurá maps (Figure 14), it is possible to carry out inspections, georeferencing, measurements of burned areas and monitor the evolution of firefighting actions carried out by CBMPA. Thus, Figure 3 illustrates the application of the Geographic Information System (GIS) QGIS, with the image of the solid waste landfill of Aurá, used to define strategic firefighting points, in addition to enabling the identification of structural characteristics relevant to the preparation of technical reports on fires.

Figure 32

Image Letter (CI) of ARS-Aurá for the Survey of information of interest



Source: Author, 2024.

Consequently, an Image Chart (IC) generated from the orthomosaic produced by SARP (drone) constitutes a cartographic representation that allows the full and detailed visualization of the mapped area. Among its main benefits, the time savings, the richness of details and the precision in the identification of real points and obstacles on the terrain stand out, which can interfere with the movement of vehicles to the fire outbreaks, contributing significantly to the efficient planning of firefighting.

The cartographic resource can also be viewed through mobile applications, such as Avenza Maps, which has tools for spatial location in an agile and intuitive way, in addition to allowing the exchange of information in real time between the garrisons involved in the occurrences. This resource also helps in the structuring of the Incident Command System (SCI). Figure 4 shows the ARS-Guamá Image Chart viewed in the Avenza Maps application. Thus, the CI, generated in the GIS and exported to the application, assists in decision-making as to the type and amount of resources to be sent to the occurrence, in addition to subsidizing the operational planning of the CBMPA based on updated images, which can be transmitted in real time to the SCI.

Figure 43

CPTR-Marituba (ASRS-Guamá) situation plan on the Avenza Maps App

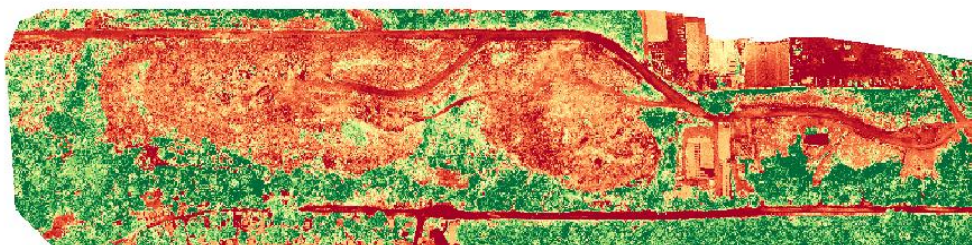


Source: Author, 2024

The Soil and Plant Interaction Image (NDVIT), also generated by SARP, results in the differentiation between occupied and vegetated areas, in a practical and effective way. Figure 16 shows the area of the ARS-Aurá, in which the red color indicates regions without vegetation cover or occupied by structures. The image presented in Figure 5 is an example of the application of Remote Sensing with SARP. In the case of the ARS-Aurá NDVIT, the product represents an essential resource for the characterization and spatialization of the physical environment, serving as a basis for the planning of firefighting actions in landfills. The NDVIT assists in the identification and characterization of soils, vegetation and access roads, which is essential for the planning of CBMPA vehicle positions, since it allows differentiating roads, streets and areas devoid of vegetation.

Figure 5

Georeferenced Soil and Plant Interaction (NDVIT) of the ARS of Aurá



Source: Author, 2024.

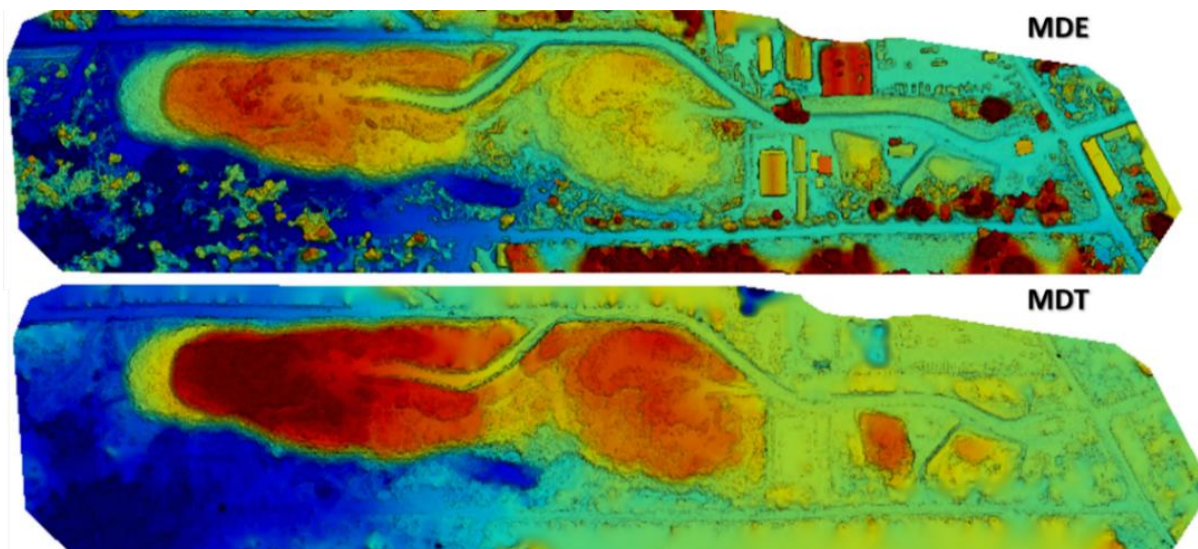
The ARS-Aurá Digital Elevation Model (MDE) and Digital Terrain Model (DTM) are SARP-generated products that represent the surface and terrain in three dimensions, including information on elevation and ground height, vegetation, and man-made structures.

The DEM, also known as the Digital Surface Model (SDM), represents all above-ground objects, such as buildings, trees, vehicles, and people. Although the MDE is not suitable for high-precision altimetry projects, it provides CBMPA with an overview of the ARS-Aurá elevation plan, constituting a valuable resource for firefighting planning. Based on this model, it is possible to build altimetric plans of specific areas, considering elements such as vegetation and buildings, which contributes to safer and more efficient tactical analysis.

In addition, the joint use of the MOU and the MDT of the ASRS-Aurá makes it possible to identify more efficient access routes for CBMPA combat vehicles, taking into account the topography of the terrain. From this information, containment barriers can be planned to prevent the spread of fire in the massif. Figure 6 shows that the MDE and MDT products of the SARP in the ARS-Aurá can be widely used in the planning of firefighting actions. These models must be analyzed in conjunction with other tactical and strategic information defined by the Commander of the Socorro (CMD of SOS). It can be seen in the images that it is possible to identify lower and higher regions of the terrain, as well as areas with the presence of watercourses, which can be used to refuel CBMPA tanker vehicles.

Figure 6

Georeferenced Digital Elevation Model (MDE) and Terrain Model (DTM) of the ARS of Aurá



Source: Author, 2024

The SARP thermal camera is a device that uses infrared technology to capture images containing temperature information. Unlike conventional RGB cameras, which record visible light, thermal cameras detect the infrared radiation emitted by objects based on their temperatures (Figure 18). In this way, this resource generates the thermal imaging product,

which has several applications in firefighting planning in solid waste landfills, enabling the mapping and monitoring of areas.

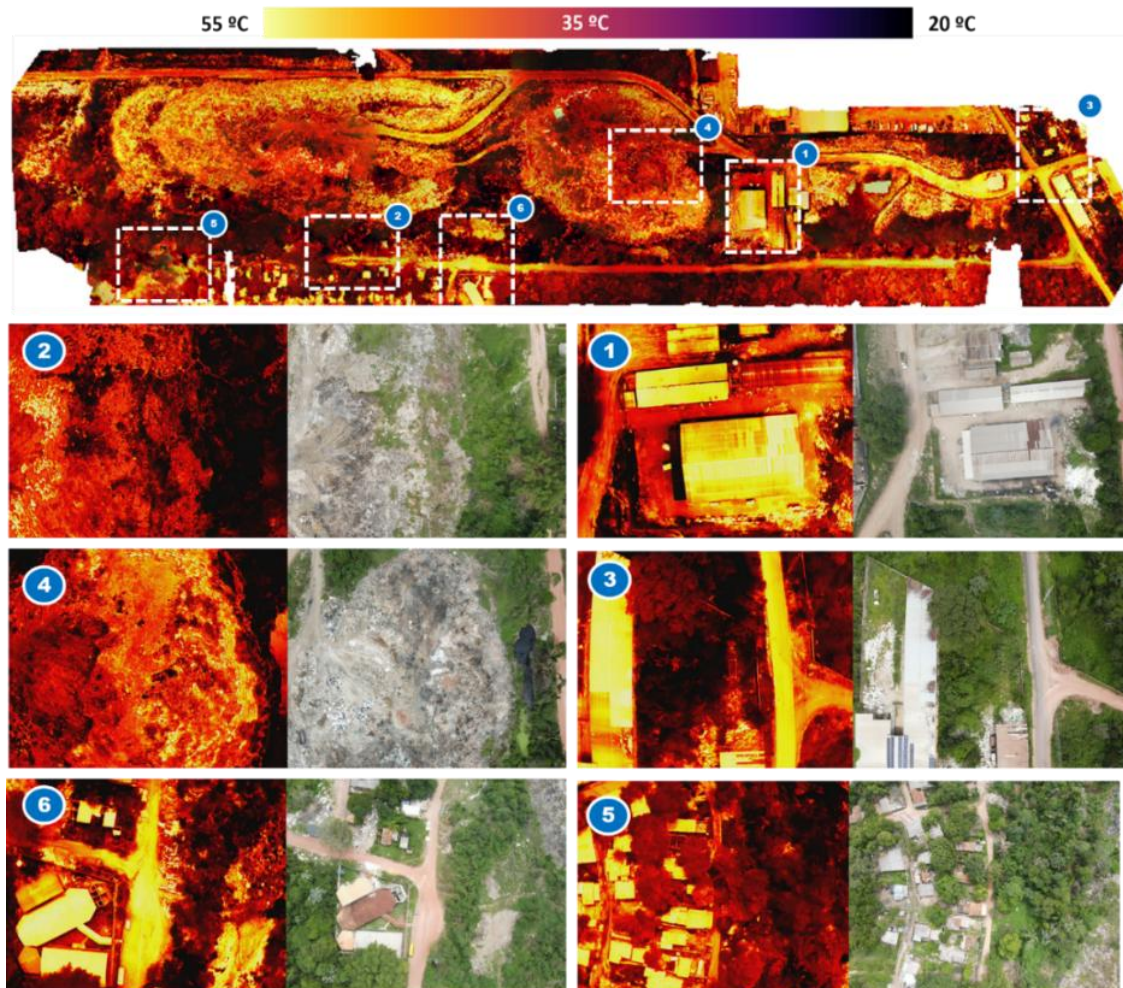
This type of image makes it possible to identify temperature variations and, consequently, thermal patterns, in addition to recognizing hot and cold spots and places that are difficult to access due to thermal intensity. In addition to supporting firefighting planning, the SARP thermal camera can be used in different contexts, such as search and rescue operations, inspections of massif infrastructures (points 2 and 4) and buildings (points 1, 5 and 6), as well as environmental and safety monitoring (point 3) of ARSU-RMB facilities.

The thermal camera applied in the ARS-Aurá captured thermal information that offers valuable perspective in low-visibility situations where conventional optical cameras may not be sufficient, such as at night or in densely vegetated environments. In the context of the ARSU of the RMB, thermal cameras play a fundamental role in the preventive monitoring of hot spots and fires, through the analysis of temperature variations in buildings, roads and homes. Regions in redder tones indicate the presence of high heat or flames, allowing quick and effective responses to prevent the spread of fire.

Figure 8 shows the three-dimensional image of the Solid Waste Landfills of Aurá (ARS-Aurá), with identification of points of interest for firefighting, such as existing buildings, streets, roads and massifs. This representation also helps in locating natural drainage points, which can be used to direct water to the burned areas. The Three-Dimensional Terrain Model (M3D) generated by SARP constitutes a detailed visual representation of the terrain, allowing fire crews to plan more effective combat strategies during and after the event.

Figure 74

Georeferenced Thermal Image of the ARS of Aurá

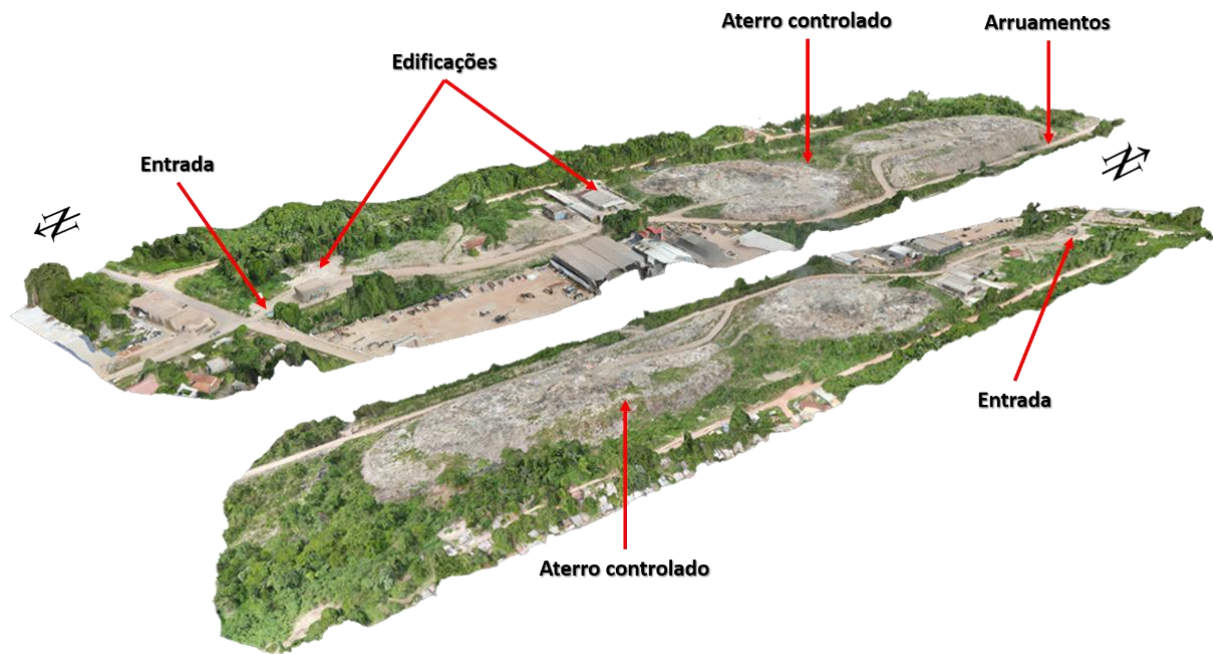


Source: Author, 2024

The 3D model is particularly useful for identifying efficient access routes for combat vehicles, taking into account the topography of the terrain of the ARS-Aurá. With the 3D image of the ARS-Aurá, together with the MDE and the MDT, firefighters can define appropriate combat techniques, such as the application of misty jets of water in rapid and controlled pulses, optimizing the cooling of the massif. M3D stands out, therefore, by allowing the visualization of access points, buildings, roads and natural barriers, which can both hinder the fight against fire and prevent its propagation, as shown in Figure 8.

Figure 8

Three-dimensional Terrain Model (M3D) of ARS-Aurá

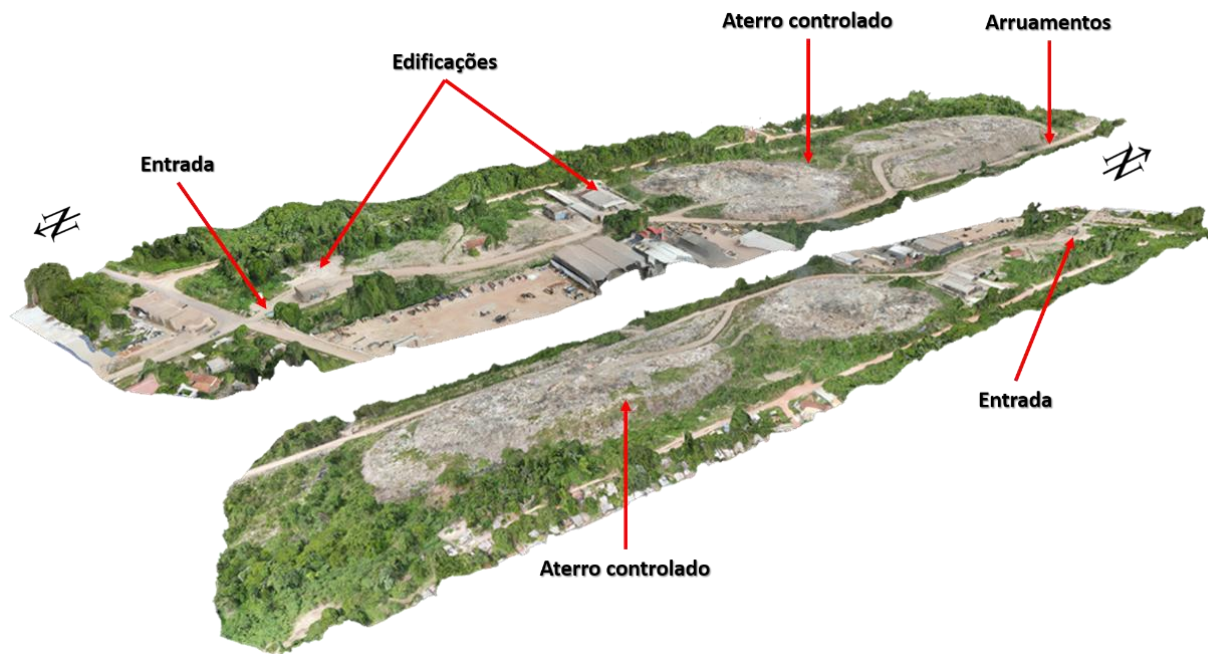


Source: Author, 2024

In Figure 9, it is possible to identify several characteristics and structural elements of the landfill, including buildings susceptible to risk during fires, with the possibility of gauging their heights. The streets and internal paths are clearly visible in the M3D, which is useful for the traffic management of CBMPA vehicles during emergency situations. Finally, with M3D, CBMPA obtains a three-dimensional view of land use, allowing the location of residential, commercial and industrial areas around ARS-Aurá.

Figure 95

Three-dimensional model of the ARS-Aurá structures



Source: Author, 2024.

In Figure 10, still with the 3D image of the ARS-Aurá, vegetated regions and the differentiation of multi-storey buildings are observed, in addition to the estimate of the volume of the landfill. This information is useful for assessing the amount of material needed to cover areas affected by fires. The ARS-Aurá 3D model is extremely valuable for the planning of actions in urban solid waste landfills, as it allows a detailed visualization of the site, facilitating the identification of risk areas and the elaboration of fire prevention and fighting strategies by CBMPA.

Figure 10

Three-dimensional model of the embankments and roads of the ARS-Aurá



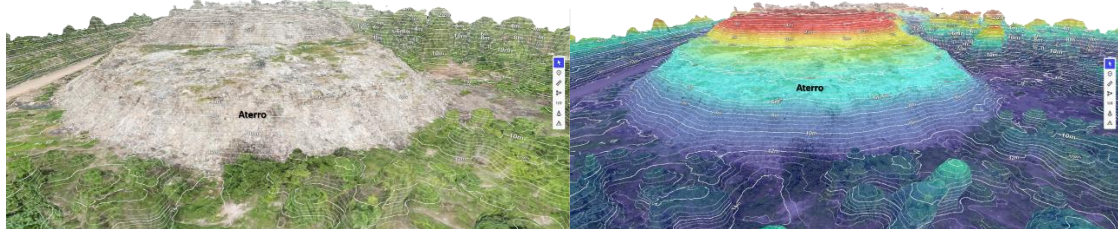
Source: Author, 2024

However, it is important to emphasize that the effectiveness of M3D depends directly on the accuracy of the data collected and the proper processing of the images. The planned flights at an altitude of 100 meters allowed the generation of detailed comparative models, enabling a refined analysis of the earth's surface and the identification of strategic zones for the positioning of combat vehicles. From the georeferenced orthomosaic, combined with other products, such as the Digital Elevation Model (MDE), it is possible to visualize slope values and contour lines, creating an altimetric profile of the ARS-Aurá.

Figure 11 shows the contour lines of the massif, which graphically represent the altitudinal variation of the embankment — essential information for planning access and combat routes, in addition to supporting the evaluation of safe areas for evacuation, when necessary. Thus, the SARP allowed to represent the variation in elevation of the terrain both in the massif and in the surroundings of the landfill. Figure 11 shows the orthomosaic and the MDE of the ARS-Aurá obtained by SARP overflight, associated with the contour lines generated in DroneDeploy, with a spacing of 2 meters between them.

Figure 116

Three-dimensional and elevation model of ARS-Aurá

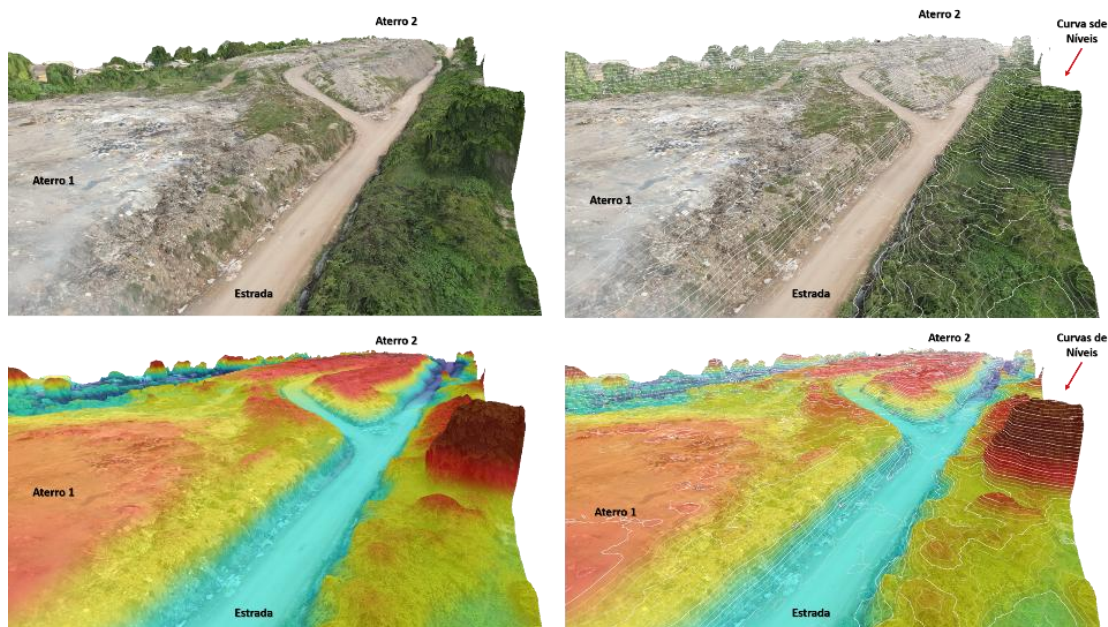


Source: Author, 2024

The products generated by the SARP overflight — such as the M3D, the MDE and the MDT — are widely applicable to firefighting planning, involving several stages of analysis. In this sense, Figure 12 presents an integrated interpretation of the terrain of the ASRS-Aurá, based on the use of orthomosaic, the MDE and the MDT, allowing the identification of areas of greater risk, as well as the planning of access routes for combat vehicles of the CBMPA and the Civil Defense.

Figure 12

Three-dimensional and elevation model of the ARS-Aurá



Source: Author, 2024

The interrelated analysis of SARP products applied to the Urban Solid Waste Landfills of the Metropolitan Region of Belém (ARSU-RMB) contributes significantly to decision-making during dynamic firefighting actions. The configuration of the massif presented in the

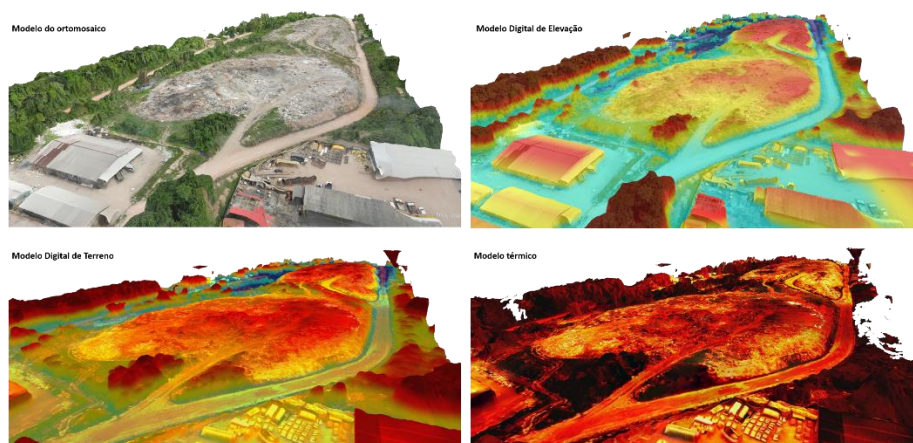
M3D, MDE, MDT models and in the contour lines provides data on height, width and slope, essential factors to assess the structural stability of the terrain and define safe conditions for combat, as illustrated in Figure 13.

In the case of ARS-Aurá, the integrated analysis of SARP products over a specific area facilitates the identification and quantification of objects, such as buildings, including altimetric information. The thermal camera can, in this context, be used to monitor the surface temperature of the landfill during and after fires, especially in regions of greater combustion or potential risk of explosion.

Figure 13 shows that the interrelation of the products generated by the SARP — particularly the high-resolution thermal and orthogonal images — allows for a detailed analysis of the condition of the ARS-Aurá terrain. The association between SARP products should be seen as a strategic tool to support CBMPA, as it enables the monitoring of fire propagation, considering topography, land use and thermal intensity, all from a safe position. This information guides the efficient targeting of combat efforts, taking into account the altimetry achievable by vehicles over the massif and avoiding the exposure of teams to risky situations. Thus, the interrelated use of SARP products in ARSU-RMB provides valuable real-time information, enhancing the safety and effectiveness of firefighting operations.

Figure 137

General SARP products of the ARS of Aurá Metropolitan Region of Belém (RMB)



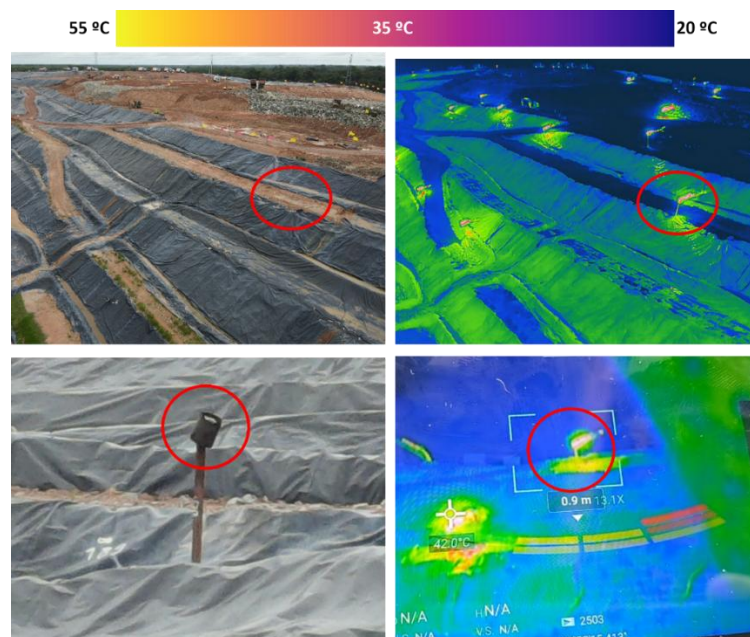
Source: Author, 2024

Specifically in relation to the SARP thermal camera applied to the data collection in the ARS-Guamá, a highly satisfactory performance was observed, especially due to the ability to detect hot spots in the massif, coming from the gas drainage systems. In the case of the ARS-Guamá massif, the flight carried out with the thermal camera made it possible to easily identify the network of vertical drains, interconnected to horizontal drains built at the base of the landfill, used for the controlled burning of the gases generated.

The vertical drain system plays an essential role in reducing the internal pressures of the massif, resulting from the generation of biogas, in addition to conducting the effluents to the appropriate treatment site. Figure 25 shows the vertical drain system of the CPTR-Marituba (ARS-Guamá), as well as the temperature measured by the SARP thermal camera. At the end of the biogas drainage system, a temperature of 42°C was recorded.

Figure 14

ARS-Guamá biogas drainage systems in the SARP thermal chamber



Source: Author, 2024

The thermal camera technology embedded in the SARP represents, therefore, an effective solution for reading and locating heat, through the detection of infrared radiation emitted by objects, allowing to accurately determine the point of thermal origin. This information is crucial for fire attack planning, contributing to quick decision-making and, consequently, saving lives. In this way, the SARP thermal camera allows you to clearly visualize heat sources, consolidating itself as an essential tool in search, rescue, and

firefighting operations in landfills. With the SARP overflight equipped with a thermal camera, it is possible to perform an initial diagnostic image, identifying hot spots in the massif and monitoring temperature changes on the surface of the ARS-Guamá. This diagnosis is obtained by capturing the infrared radiation emitted by the biogas drainage systems, resulting in an accurate thermographic image.

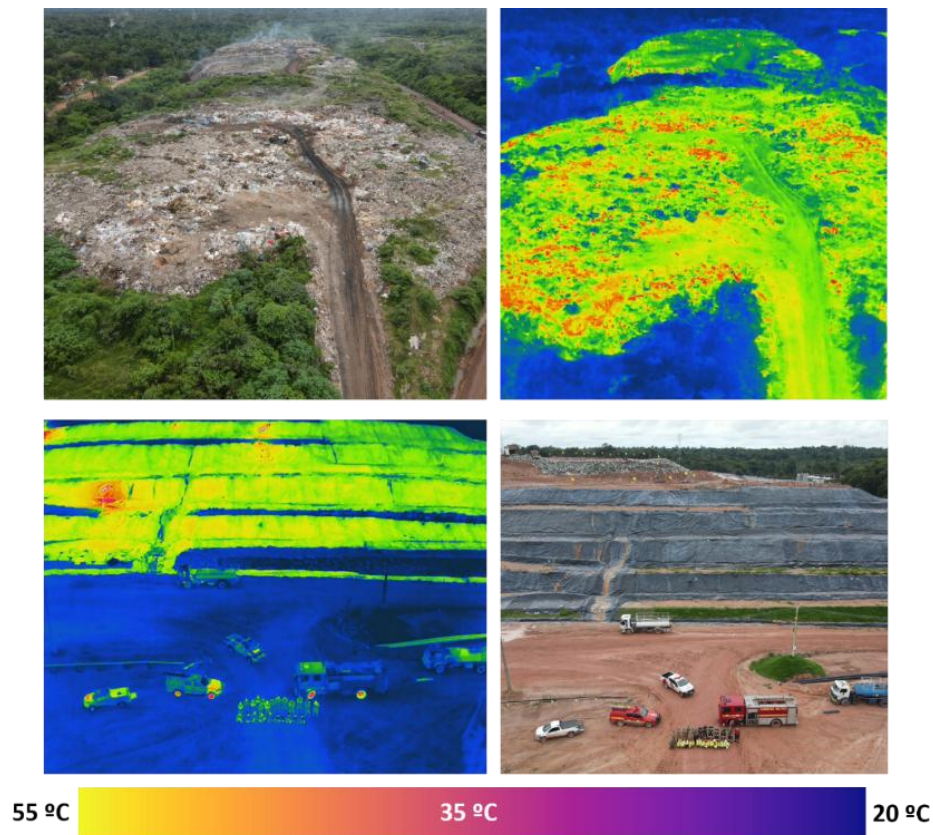
SARP infrared thermography is a fast and low-cost method for detecting hot spots or fire, allowing the targeted displacement of fire crews to carry out fire control and extinguishing actions. The thermographic examination, in the context of this work, has as its main objective to verify the different temperatures in the massif and to provide subsidies for the operational combat action.

The SARP, equipped with a thermal sensor, makes it possible to accurately identify the areas of active flames, represented by the red spots. Also in Figure 15, the massifs of the ASRS-Aurá and ASRS-Guamá landfills stand out, represented in a lateralized RGB image (Red, Green, Blue) — the conventional camera present in all SARPs, which captures images in the visible spectrum of light (the colors perceptible to the human eye). The RGB image is therefore similar to those recorded by ordinary cameras. However, although the RGB camera allows quantitative data to be obtained from the surface, it is not sensitive to temperature variations, which limits its use for thermal analysis.

In this context, SARP thermal images presented a significant advantage, by allowing the rapid detection of hot spots that indicate possible fire outbreaks, enabling more agile and targeted responses to risk situations. Figure 15 illustrates the monitoring overflight carried out in the areas of ARS-Aurá and ARS-Guamá, with RGB and thermal cameras, intended to identify fire outbreaks or abnormal thermal changes, which may indicate conditions of imminent risk during the positioning of CBMPA vehicles to fight the fire.

Figure 15

Application of SARP thermal camera in ARSU-RMB

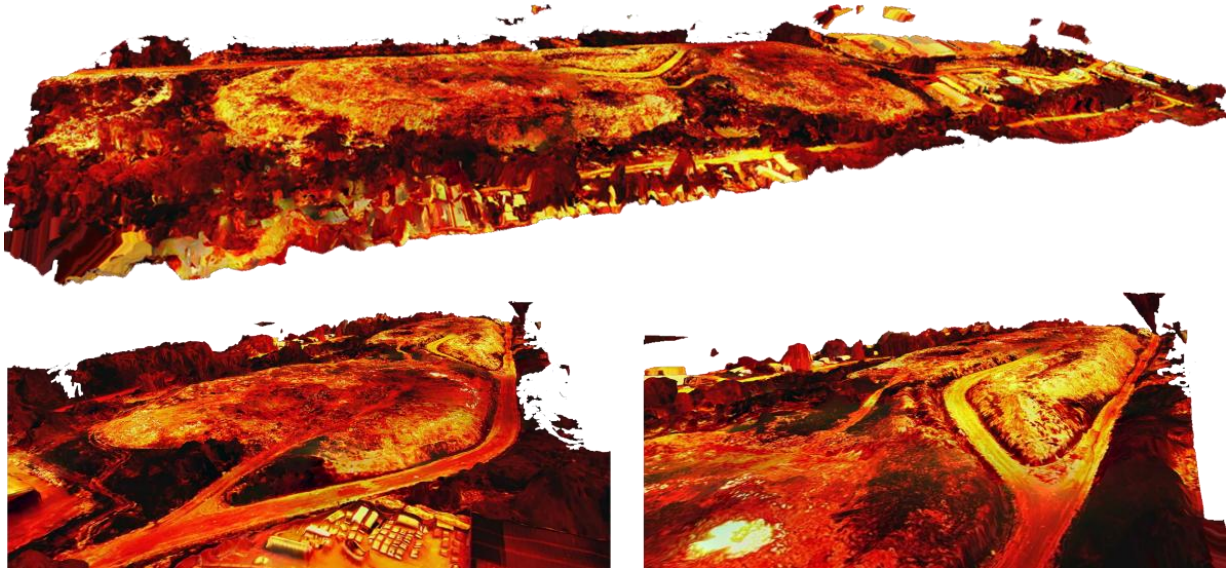


Source: Author, 2024

Also with the use of scheduled overflights with the SARP equipped with a thermal camera, it is possible to generate the Three-Dimensional Model (M3D), which provides a general and detailed view of the landfill, including in areas of difficult access. This model provides comprehensive coverage of the ARSU of the RMB, allowing the identification of strategic access points and the planning of tactical firefighting actions based on three-dimensional information. Figure 16 shows the thermal M3D of the ARS-Aurá, which provides a three-dimensional view of the extension of the land and the strategic access points to the areas of interest, including the streets of the site.

Figure 168

Application of SARP thermal camera in ARS-Aurá



Source: Author, 2024.

The results obtained from the interrelated analyses of SARP products, both in ARS-Guamá and ARS-Aurá, represent significant advances in compliance with fire safety standards, as well as for monitoring and inspection conducted by the Military Fire Department of Pará (CBMPA). Based on the products presented and analyzed in an integrated manner, it is possible to understand more accurately the reality of the ARSU of the RMB, especially from the perspective of the prevention of large fires. These methodologies can also be expanded and applied to other complexes or risk areas, consolidating a model of preventive monitoring and rapid response.

The three-dimensional mapping of the ARSU of the RMB generates high resolution and detailed products, allowing the visualization of elevations, slopes and obstacles existing in the terrain. Such SARP resources and applications directly assist the planning of firefighting operations, by allowing teams to visualize the topography of the terrain and identify critical and risk points. This approach contributes to more efficient allocation of resources by the CBMPA, since teams can be directed based on accurate and up-to-date information provided by the SARP. As a result, there is a reduction in operational response time and optimization of financial and human resources during firefighting operations in RMB landfills.

5 FINAL CONSIDERATIONS

The present work addressed the challenge of managing and fighting fire in urban solid waste landfills, proposing an innovative approach based on the application of the Remotely Piloted Aircraft System (SARP) as a technological tool to support the actions of the Military Fire Department of the State of Pará (CBMPA). This technology has proven to be highly effective in generating high-resolution geospatial products, useful for tactical and operational firefighting planning, with significant gains in efficiency, safety, and accuracy of information.

The use of SARP in the Urban Solid Waste Landfills (ARSU) of Aurá and Guamá proved to be a robust and innovative technical strategy, which allowed the survey, mapping, diagnosis and detailed monitoring of these areas. The proposed methodology proved to be adequate to local conditions and efficient in the collection, processing and analysis of georeferenced data, applicable to the planning of fire fighting and prevention in the Metropolitan Region of Belém (RMB). The results obtained proved the potential of using SARP in the mapping of risk areas and in the production of high-precision geospatial information, with low operational cost and great temporal and spatial flexibility. The products generated, such as orthomosaics, digital elevation models (MDE), terrain models (DTM), three-dimensional models (M3D) and thermal images, proved to be essential for the detection, analysis and monitoring of thermal events, and can be used before, during and after fire occurrences. This capacity increases the efficiency of monitoring and response actions, ensuring greater safety for CBMPA teams and professionals involved in operations.

The aerial surveys carried out with the SARP made it possible to build accurate and up-to-date space bases, with delimitation of the perimeter of the affected areas and generation of image maps and digital maps. These products showed high technical quality and reliability, allowing for rapid data collection and significantly reducing human exposure to risk areas. In addition, they showed potential for application in forensic investigations, enabling a detailed survey of burned areas, the measurement of waste volumes and the analysis of structural damage in the massif and in the surroundings of the landfill.

The integration of thermal and optical images provided a global and dynamic view of the fire scenario, contributing to the efficiency of the Incident Command System (SCI). The real-time monitoring of the evolution of the flames, the identification of multiple hot spots and the analysis of the spread of the fire offered fundamental subsidies for the strategic decision-making of the CBMPA. This integration optimized planning and operational response,

reducing the time of operation and increasing the security of the garrisons and the effectiveness in the use of available resources.

The study demonstrated a pioneering proposal of great practical relevance for the Military Fire Brigade of Pará, by introducing the systematic use of SARP equipped with thermal cameras in the planning and execution of firefighting actions in urban solid waste landfills. This technologically advanced approach has proven to be efficient in the early detection of fire outbreaks and in the management of complex environmental emergencies, contributing directly to the modernization of security and civil defense practices.

The incorporation of the geospatial products generated by the SARP into the operational planning of the CBMPA represents a significant advance in its institutional activities. The data obtained provides accurate and up-to-date information in real time, supporting tactical decision-making, environmental preservation, and the safety of field operations. These products strengthen the integrated management process, allowing CBMPA to act with greater predictability and precision in emergency response actions. Thus, this research reinforces the importance of using emerging technologies of remote sensing and geoprocessing as fundamental tools for the modern and sustainable management of critical areas.

In the context of the Metropolitan Region of Belém, which faces structural challenges in waste management, with the interdiction of the ARS of Guamá and the reactivation of the ARS of Aurá, still classified as an open-air dump, the use of SARP is configured as an innovative, sustainable and indispensable solution to improve operational efficiency and environmental safety in the fight against fires in urban solid waste landfills.

It is therefore concluded that the use of SARP in the management of fires in urban solid waste landfills represents not only a technological and scientific advance, but also a concrete contribution to public safety, environmental management and the protection of life. The proposed methodology serves as a model for the integrated application of geotechnologies aimed at monitoring, prevention, and response to environmental emergencies, reaffirming the commitment to innovation, efficiency, and sustainability in the operations of the Military Fire Department of the State of Pará and other civil defense institutions in the country.

6 FUTURE WORK

Considering the results achieved and the potentialities observed in this research, it is recommended to expand studies involving the use of Remotely Piloted Aircraft Systems (SARP) in the management and monitoring of Urban Solid Waste Landfills (ARSU). The possibilities for improvement include both the technological advancement of data acquisition tools and the integration of new methodologies for spatial analysis and computational intelligence.

First, it is suggested to improve SARP surveys, through the use of multispectral and hyperspectral sensors, capable of increasing the accuracy in the detection of gases and thermal hotspots associated with the combustion and decomposition of waste. This approach can contribute to the early prevention of fires and to the assessment of the environmental impacts resulting from the release of toxic and greenhouse gases.

Another relevant perspective is the integration of the data obtained by the SARP with Geographic Information Systems (GIS) platforms in real time, through Internet of Things (IoT) systems and cloud-based models, which would allow the continuous and automated monitoring of ARSU. The adoption of these technologies would enable the creation of intelligent operational control centers, capable of issuing automatic alerts and optimizing decision-making by the teams of the Military Fire Department of the State of Pará (CBMPA) and civil defense agencies.

It is also recommended to carry out controlled experimental tests to validate the efficiency of thermal detection models in different environmental conditions, such as seasonal variations, solar intensity, relative humidity and wind speed. These experiments may contribute to the development of standardized protocols for SARP operation in emergency scenarios, increasing the reliability of data and the safety of flight missions.

Additionally, it is proposed to apply artificial intelligence (AI) and machine learning techniques for the automated processing of aerial images, in order to improve the classification of critical areas, the identification of thermal patterns and the automatic recognition of fire outbreaks. This approach can reduce operational response time and offer real-time analytical support to CBMPA's field actions.

Finally, it is recommended the establishment of institutional partnerships between universities, environmental agencies, city halls and the Fire Department, aiming at the implementation of public policies for monitoring and waste management based on remote sensing and applied geotechnologies. Such partnerships could contribute to the

modernization of landfill management and the mitigation of environmental risks, especially in the Metropolitan Region of Belém, which still faces serious structural challenges in the final disposal of urban solid waste. In summary, the advancement of studies in this area tends to consolidate the use of SARP as strategic tools to support environmental management and public safety, promoting a more efficient, sustainable and technically based action in the fight against fires in urban solid waste landfills.

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