Spatial Exploration of Rajgad Fort: An Integrated Approach of UAV Technology and Geographical Information System

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Abstract: Rajgad Fort, situated in the Pune district of Maharashtra, stands as a testament to India's rich cultural and historical heritage. This study employs UAV technology and Geographical Information System (GIS) to conduct a detailed spatial exploration of Rajgad Fort, aiming to document its architectural intricacies, historical significance, and environmental context. High-resolution orthomosaic imagery, digital surface models (DSM), and point cloud data were integrated to map 52 distinct features within the fort, including towers, gates, bastions, temples, and water tanks. Field surveys complemented UAV data, providing crucial insights into the fort's layout and cultural landscape. The study reveals Rajgad Fort's strategic fortifications, such as the expansive Fort Wall and intricate water management systems, highlighting its historical importance and architectural grandeur. Despite challenges posed by terrain complexity and accessibility, the study demonstrates the efficacy of UAV and GIS technologies in heritage conservation and management. The findings underscore the significance of preserving Rajgad Fort as a cultural icon and advocate for informed conservation strategies to safeguard Maharashtra's historic forts for future generations.

Keywords: GIS, UAV, Rajgad Fort, Mapping

1. Introduction

Maharashtra, a state steeped in history and culture, boasts a wealth of formidable forts that stand as silent sentinels, bearing witness to the region's rich heritage and tumultuous past. These architectural marvels, characterized by their imposing structures and strategic locations, serve as tangible links to bygone eras, offering glimpses into the lives and legacies of their erstwhile rulers. However, despite their historical significance, many of Maharashtra's forts face the looming threat of neglect and deterioration (Madaan, 2023; Phadnis, 2017), prompting a pressing need for concerted conservation efforts to safeguard these cultural treasures for future generations.

Understanding the intricate details of forts can lead to a deeper knowledge of history, making it imperative to map their structures accurately. While some forts are well-documented by the government (Gangan, 2017), others have not received comprehensive attention. Among these bastions of Maharashtra's past, Rajgad Fort occupies a place of paramount importance. Perched atop the rugged peaks of the Sahyadri mountain range, Rajgad Fort commands breathtaking vistas and harbors tales of valor and Guerrilla warfare dating back centuries (Ghanekar, 1984). It holds immense cultural and historical significance as the first capital of Chhatrapati Shivaji Maharaj's Swarajya, symbolizing the origin of Maratha sovereignty and resistance against foreign rule (Tendulkar, 2019). Yet, its preservation and documentation present formidable challenges in the face of modern-day pressures and encroachments.

Properly mapping Rajgad Fort is imperative not only for its conservation but also for gaining a deeper understanding of its architectural intricacies, historical context, and spatial dynamics (Bachagha et al. 2020; Luo et al. 2014). Traditional mapping methods fall short in capturing the nuanced details and expansive landscapes of such monumental heritage sites (Elfadaly et al. 2017; Yao et al. 2023). Hence, there arises a critical need for advanced mapping techniques that harness the power of high-resolution data and three-dimensional (3D) mapping technologies (Ioniță et al. 2021; Nishanbaev et al. 2021; Samadzadegan et al. 2023; Ulvi, 2021).

In this context, the integration of Geographical Information System (GIS) technology and high-resolution data emerges as a transformative approach to fort mapping and conservation (Lezzerini et al. 2016; Yao et al. 2023). GIS offers a versatile toolkit for spatial analysis, enabling researchers to capture, analyze, and visualize complex spatial relationships with precision and accuracy (ESRI, 2023). Coupled with high-resolution data obtained through modern aerial platforms such as drones also known as Unmanned Aerial Vehicle (UAV), this approach facilitates the creation of detailed 3D maps that not only document the physical attributes of the fort but also provide insights into its historical evolution and cultural significance (Adamopoulos and Rinaudo, 2020; Ioniță et al. 2021; Nishanbaev et al. 2021).

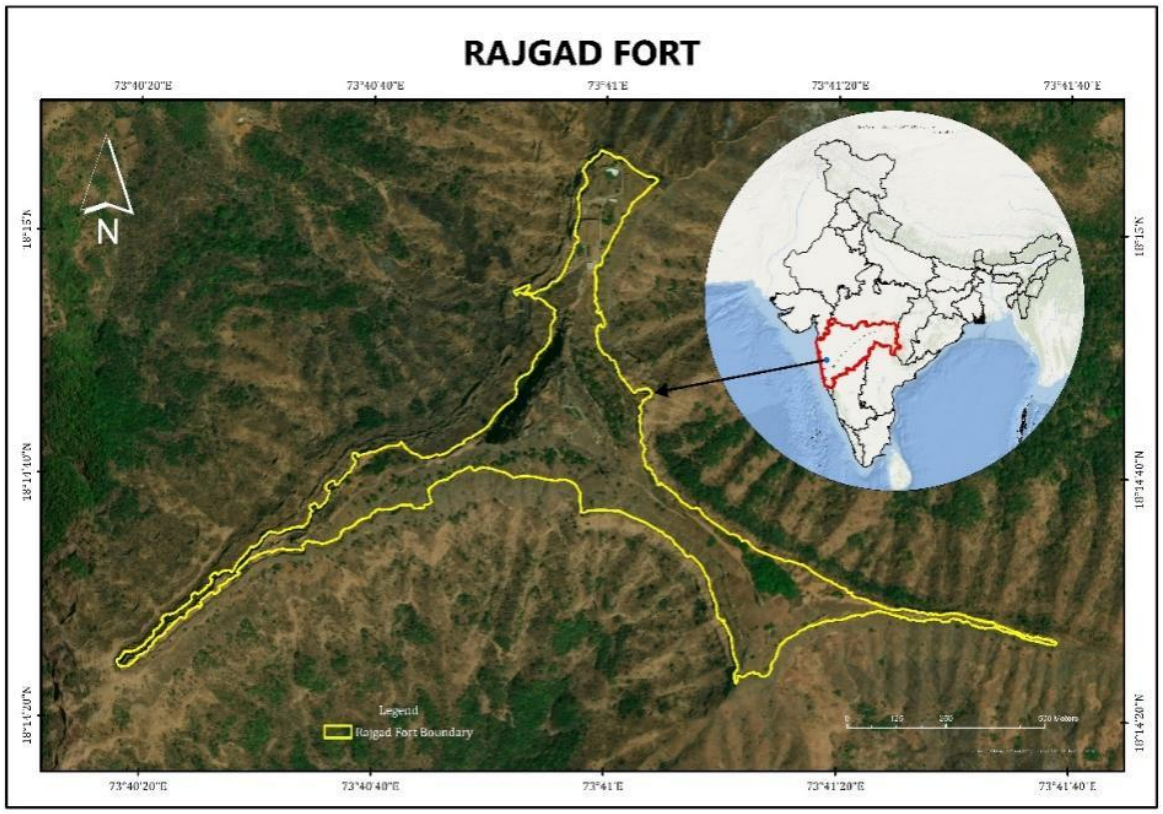

Figure 1: Geographical Location of the Study Area

This research endeavors to bridge the gap between past and present, leveraging the capabilities of GIS to illuminate the hidden dimensions of Rajgad Fort. By employing high-resolution data and 3D mapping techniques, we aim to unravel the fort's spatial mysteries, chart its historical trajectory, and contribute to its conservation and management efforts. Through this interdisciplinary endeavor, we seek to honor Maharashtra's rich cultural heritage, preserve its architectural legacy, harness the transformative potential of GIS technology, and unlock the tourism potential of Rajgad Fort for the benefit of future generations.

2. Study Area

2.1 Geographical Location

Rajgad Fort is located in the Pune district of Maharashtra, nestled in the beautiful Sahyadri mountain range within the Bhor tehsil. It stands prominently at around 18°14'45.9"N latitude and 73°40'55.6"E longitude (Figure 1). Situated approximately 60 kilometers southwest of Pune city, the fort offers a commanding view of the surrounding landscape. Access to Rajgad Fort is facilitated through two main routes. The first route is via Pune-Nesrapur-Gunjavane, providing a convenient access point for visitors traveling from Pune city. The second route, Pune-Nesrapur-Pali, also offers access to the fort, allowing visitors to choose the most suitable route based on their preferences and convenience.

Rajgad Fort sits high up at about 1278 meters (4193 feet) above sea level and covers about 88 acres of land, displaying its grand size and impressive architecture. Based on geographical terrain and fortification, the fort can be divided into four distinct parts. These include Padmavati Machi, Suvela Machi, and Sanjevani Machi, which form the three sub-plateaus of Machi, with the Ballekilla situated in the center at higher elevation. Each part of the fort offers unique insights into its strategic layout and historical significance.

With an average annual rainfall is 2000mm, Rajgad Fort experiences a moderate to heavy rainfall regime, contributing to its lush green surroundings and vibrant ecosystem. This abundant rainfall sustains the region's diverse flora and fauna, adding to its natural charm and appeal. Visitors to Rajgad Fort can experience the beauty of the monsoon season, when the landscape transforms into a verdant paradise, adorned with glistening waterfalls and vibrant vegetation.

2.2 Historical Content

The hill of Rajgad in ancient times was known as Murumdev's hill. Even today, remnants of some ancient structures can be found on this hill. The fortress of Rajgad is recognized as the first capital of the Maratha Empire, and there is a profound mutual relationship between Rajgad and Chhatrapati Shivaji Maharaj. The credit for its present magnificent and splendid appearance goes entirely to Chhatrapati Shivaji Maharaj (Sane). Although there isn't precise clarity on when exactly Chhatrapati Shivaji Maharaj took control of Rajgad, it is generally understood that after acquiring the fort, which was around 1647 AD, he initiated various types of construction works on it. Among these were the additions of structures like Sanjeevani, Padmavati, Suvela, which were bastions, and Machi, which were fortifications along the cliffs (Apate and Divekar, 1847).

Rajgad Fort bears witness to many of the most significant events in the life of Chhatrapati Shivaji Maharaj and in the history of India. Over a span of about 25 years, from approximately 1645 to 1670, Chhatrapati Shivaji Maharaj and his family resided at Rajgad, making it a place of immense importance (Apate and Divekar, 1847). However, post-1700, the prominence of hill forts dwindled significantly. Maratha expansion into North India saw power shifting to the Peshwas, who delegated fort administration to the Pant Sachivs (Bhor). After India gained independence, the Bhor Institution was dissolved, and administration over the fort was consolidated, marking the end of an era.

3. Methodology

This study employs a systematic approach to map Rajgad Fort using GIS and UAV technology. Initially, high-resolution UAV photographs of Rajgad Fort are captured from various angles and elevations to provide detailed visual information necessary for mapping the fort's features. These images are then georeferenced to accurately align them with real-world coordinates, ensuring precision in spatial mapping and analysis. Subsequently, orthoimages are generated by orthorectifying the UAV photographs, removing distortions caused by terrain variations and resulting in high-quality, accurate representations of the fort and its surroundings. Utilizing photogrammetry techniques, a digital Surface model (DSM) is generated from the UAV imagery, depicting the terrain elevation and aiding in topographic analysis and visualization. GIS software is employed to identify and map various features of Rajgad Fort, including buildings, walls, pathways, and natural landmarks, through manual digitization and classification based on image interpretation and existing knowledge of the fort's layout. The generated DSM is then integrated with the orthoimages to create a three-dimensional representation of Rajgad Fort, allowing for immersive visualization and analysis of the fort's structure and topography. Additionally, 3D mesh is generated to further enhance the visualization of the fort's features and surroundings. Extensive field investigation is conducted to validate and supplement the UAV data through field surveys and handheld GPS-based feature verification, enhancing the accuracy and completeness of the mapping process. Finally, the mapped data are analyzed to extract insights into the fort's spatial characteristics, historical significance, and cultural heritage, contributing to a comprehensive understanding of Rajgad Fort and its surrounding landscape. For a visual representation of the research methodology, refer to Figure 2.

3.1 Flight Planning

Flight planning was conducted using the DroneDeploy platform (Figure 3), which facilitated the strategic planning of four UAV flights during the field survey. These flights were meticulously planned to ensure comprehensive coverage of Rajgad Fort and its surroundings, with flight paths determined based on terrain characteristics and the desired mapping resolution. High-resolution UAV photographs of Rajgad Fort were captured during each flight from various angles and elevations. The images were meticulously captured to provide detailed visual information necessary for mapping the fort's features.

3.2 Field Investigation and Drone Data Collection

The field investigation aimed to identify and document features present within the fort. Utilizing old books, handcrafted maps, and existing literature, the investigation was conducted. GPS points were collected for each feature during field surveys to facilitate post-mapping analysis. A total of four UAV flights were conducted to obtain comprehensive aerial coverage of the entire fort. In total, 545 aerial photographs were captured during these flights (Figure 4). The data collection process faced challenges due to the harsh summer conditions and rugged topography of the site. Despite these difficulties, efforts were made to ensure thorough data capture during the fieldwork (Figure 5).

3.3 Processing and UAV Data Products

The UAV photographs underwent thorough processing within ArcGIS Pro software, utilizing advanced photo processing tools and techniques. Following the processing stage, a range of output products was generated to facilitate comprehensive analysis and documentation of the fort. Firstly, a high-resolution Orthomosaic single photograph covering the entire fort area was produced, ensuring accurate spatial alignment and minimal distortions.

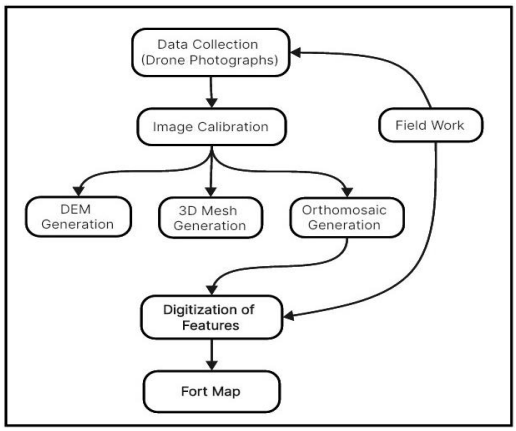

Figure 2: Flowchart of Research Methodology

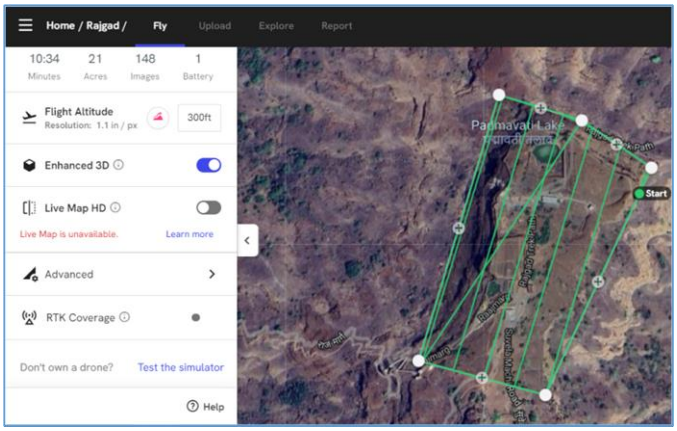

Figure 3: Flight Planning in Drone Deploy Platform

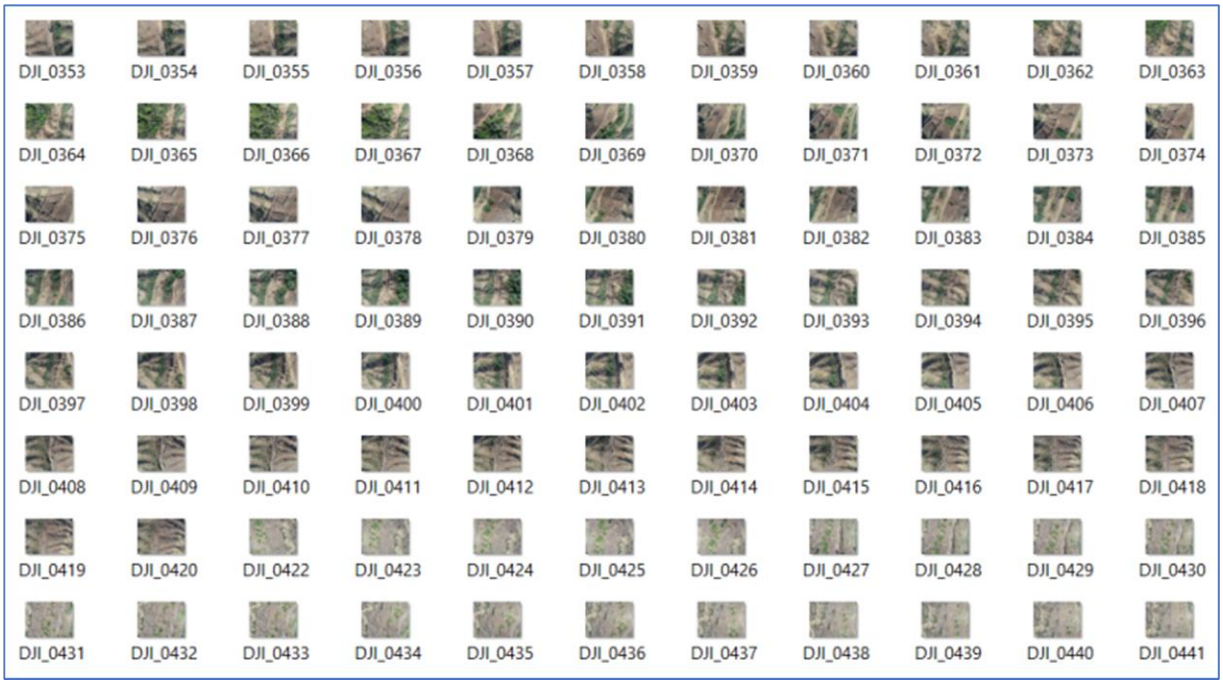

Figure 4: UAV Photos

Figure 5: Photo during Field Survey

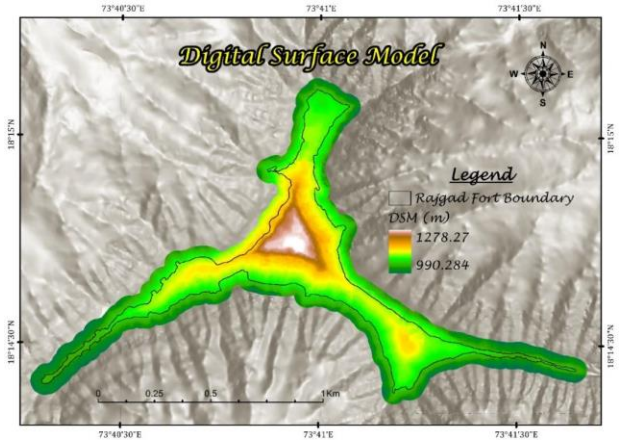

Figure 6: Digital Surface Model

Additionally, a DSM was generated to represent the terrain elevation across the fort's landscape, providing valuable insights into its topographic variations. Furthermore, a Point Cloud 3D Mesh was created, offering a detailed representation of the fort's three-dimensional structure and surroundings. Subsequently, these UAV products were integrated into the GIS environment along with field-collected feature point data, enabling the systematic documentation and analysis of the fort's features. Ultimately, meticulously crafted high-resolution maps of Rajgad Fort were generated, incorporating the integrated UAV data and field observations, thus providing a comprehensive and well-documented representation of the fort's characteristics and historical significance.

4. Results and Discussion

4.1 DSM Generation

DSM generated from UAV imagery provides a comprehensive view of Rajgad Fort's topography, revealing significant elevation variations. At its highest point, the center of the fort rises to 1278 meters above sea level (Figure 6), showcasing strategic vantage points and commanding views of the surrounding landscape. In contrast, the lowest elevation at the outer fort wall measures 1053 meters, illustrating the fort's varied terrain and natural defenses. This detailed elevation data is essential for understanding the fort's historical layout, defensive capabilities, and environmental context. It serves as a foundational dataset for spatial analyses, water management studies, and conservation planning efforts. By integrating the DSM with other GIS data layers, such as orthoimages and 3D models, comprehensive visualizations and analyses can further elucidate Rajgad Fort's architectural features and cultural significance.

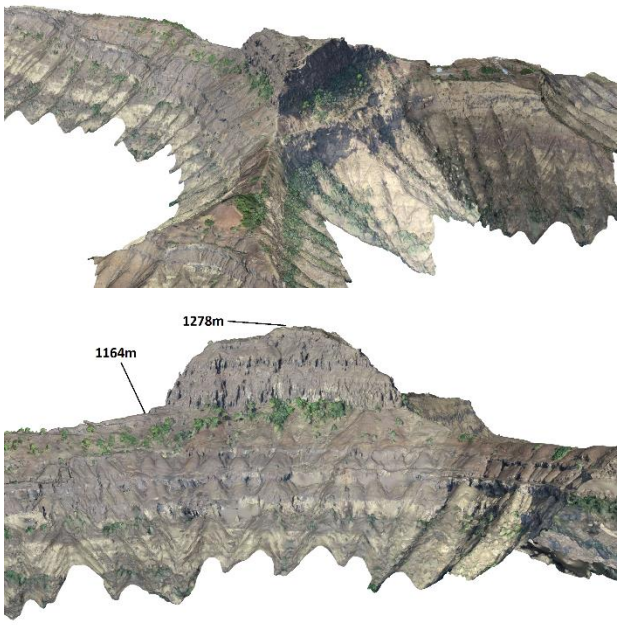

Figure 7: 3D Mesh Generation

4.2 Geographical Location

The DSM's role in monitoring landscape changes over time contributes to informed decision-making regarding fort preservation and sustainable tourism development. This study underscores the transformative potential of UAV technology and GIS in archaeological and cultural heritage studies, enriching our understanding and appreciation of Rajgad Fort's historical and spatial dimensions

4.3 Point Cloud (3D Mesh) Generation

The point cloud and resulting 3D mesh generated from UAV data offer a comprehensive three-dimensional view of Rajgad Fort's architectural features and surrounding terrain. The 3D mesh prominently features the central part of the fort (Balekilla), which exhibits a significant elevation change from 1164 meters to 1278 meters above sea level (Figure 7). This elevation variation highlights Balekilla's strategic position, commanding expansive views and reinforcing its historical defensive significance. The 3D mesh allows for immersive exploration, enabling researchers to navigate Rajgad Fort's historical features and terrain. These visualizations deepen understanding of the fort's architecture and historical significance, highlighting its adaptation to natural terrain and strategic military needs.

4.4 Orthomosaic Generation

The orthomosaic, generated from UAV imagery at a high spatial resolution of 10 cm per pixel, provides a meticulously detailed, geometrically corrected image of Rajgad Fort and its immediate surroundings. This composite image aligns features such as buildings, pathways, and vegetation with precise real-world coordinates, ensuring exceptional spatial clarity. With its fine 10 cm spatial resolution, the orthomosaic facilitates easy and precise measurements and feature identification within the GIS environment. This capability enables accurate mapping of Rajgad Fort's architectural elements, including walls, bastions, and natural landmarks, supporting comprehensive historical interpretation, conservation planning, and monitoring of changes over time with unprecedented detail. The high resolution also enhances documentation of preservation efforts and assessment of environmental impacts on the fort's structural integrity.

4.5 Fort Feature Documented Map

The creation of a meticulously detailed map of Rajgad Fort involved the seamless integration of UAV-derived data and field-collected feature points within a robust GIS environment. This process entailed overlaying the orthomosaic, DSM, and point cloud data, along with additional annotations and attributes, to produce a comprehensive representation of the fort's landscape and historical significance. Digitization played a pivotal role in delineating the fort's boundaries and accurately depicting its features on the map. Notably, during the boundary digitization process, the formidable Fort Wall emerged as a prominent and defining feature, spanning a length of 8032 meters and enclosing an expansive area of 87.5 acres (Figure 8), with the central fort occupying 5 acres. Dilapidated old building structures, identified through visual inspection of the high-resolution orthorectified image and depicted in yellow on the map, bear witness to the fort's rich architectural history. Additionally, newly constructed buildings are marked distinctly to distinguish them from the ancient structures. The map further highlights 48 water tanks scattered throughout the fort, with the Padmavati Tank standing out as the largest among them. Features such as towers, doors, machi, temples, sculptures, and more were identified with precision using the high-resolution orthomosaic imagery combined with field surveys. In total, 52 distinct features were meticulously identified and documented on the map (Figure 9).

The creation of the fort feature documented map provides invaluable insights into the architectural, historical, and environmental aspects of Rajgad Fort. The integration of UAV-derived data with field-collected feature points allowed for a comprehensive understanding of the fort's layout and significance. By digitizing the fort boundaries and key features, researchers gain a clearer picture of the fort's spatial extent and architectural complexity. The identification of dilapidated old building structures not only highlights the fort's historical evolution but also underscores the need for preservation efforts to protect these cultural assets. Furthermore, the mapping of water tanks and other features offers valuable information on the fort's infrastructure and resource management systems. This map serves as a vital tool for heritage conservationists, providing a detailed inventory of the fort's features and facilitating informed decision-making regarding its preservation and interpretation. Moreover, the map's accessibility to researchers and historians fosters ongoing studies and enhances public awareness of Rajgad Fort's cultural heritage significance.

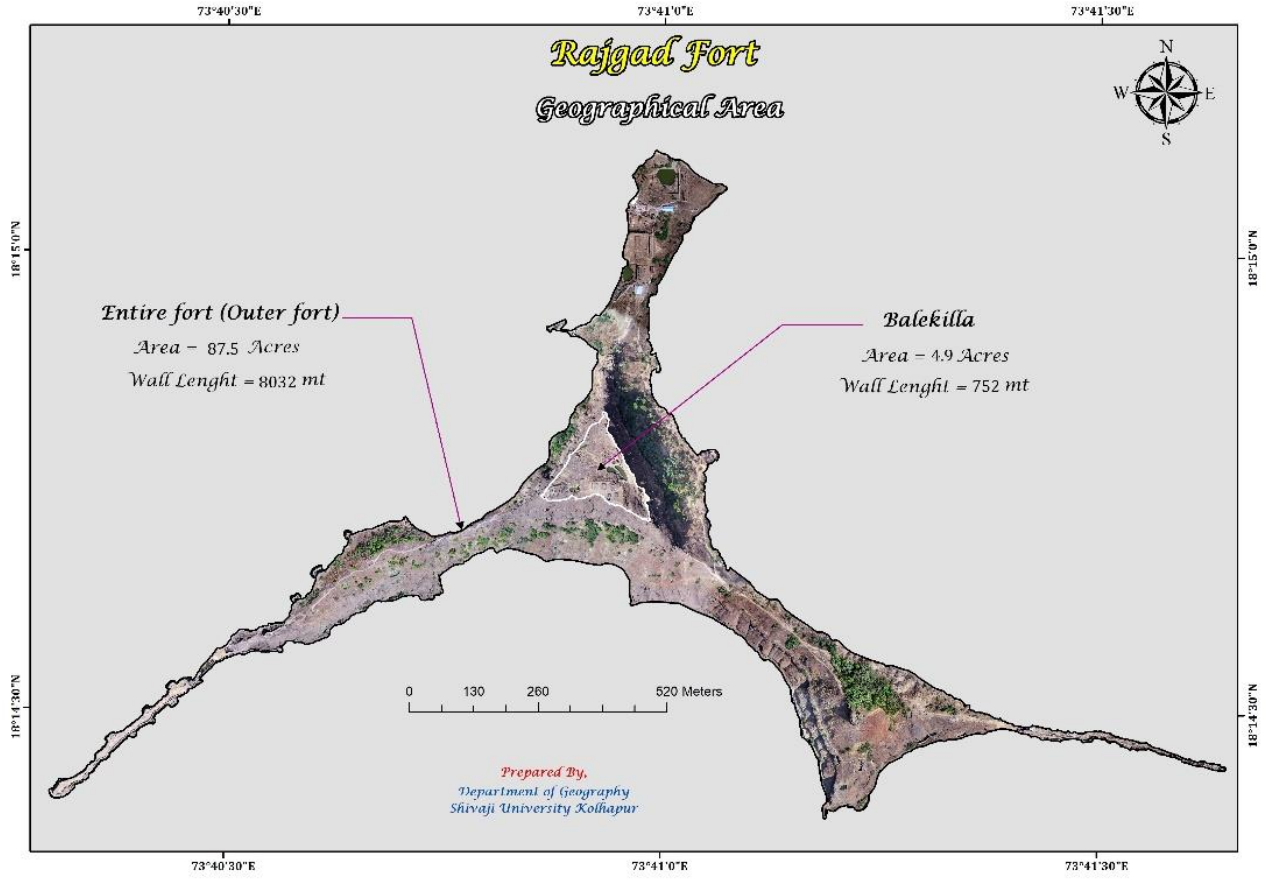

Figure 8: Area Measurement of the Fort

Regarding environmental aspects, the UAV imagery captured during the summer season reveals varying forest cover across Rajgad Fort. Dense evergreen forest pockets are observed in certain areas, while steep slopes exhibit low forest cover. During the rainy season, seasonal grass covers most of the area, altering the landscape dynamically throughout the year. Understanding these seasonal changes in vegetation cover is crucial for assessing ecological dynamics and planning conservation strategies that consider the fort's natural surroundings.

5. Limitations of the Study

Despite its successes, this study faced several limitations that impact the interpretation and application of its findings. Firstly, due to the challenging topography of Rajgad Fort, ground control points using Differential Global Positioning System (DGPS) were not feasible. This limitation may have introduced slight inaccuracies in the georeferencing and alignment of UAV imagery, potentially affecting the overall precision of spatial data.

Secondly, the study conducted multiple UAV flights at different times to cover the expansive area of the fort, leading to variations in lighting conditions and brightness values across the acquired imagery. These discrepancies can influence the consistency and uniformity of image quality and may impact the accuracy of subsequent image processing and analysis.

Despite these limitations, the study's integrated approach of UAV technology and GIS provided valuable insights into Rajgad Fort's spatial dynamics and historical significance. Future research could address these challenges by exploring alternative methods for ground control point acquisition and optimizing flight planning strategies to mitigate variations in lighting conditions.

6. Conclusions

The study on Rajgad Fort represents a significant endeavor in leveraging UAV technology and GIS for the comprehensive mapping and documentation of a historical landmark. By integrating high-resolution orthomosaic imagery, DSM, and point cloud data, we successfully mapped 52 distinct features, ranging from ancient structures to natural landmarks. This detailed mapping not only enhances our understanding of Rajgad Fort's architectural complexity and historical significance but also provides a vital resource for heritage conservation and management.

Through the precise delineation of fort boundaries, including the extensive Fort Wall and numerous water tanks, the study highlights Rajgad Fort's strategic importance and cultural heritage. The identification of dilapidated structures and modern developments underscores the ongoing challenges in preserving historical sites amidst contemporary pressures. The map and data generated from this study serve as essential tools for heritage conservationists, enabling informed decision-making and sustainable tourism initiatives.

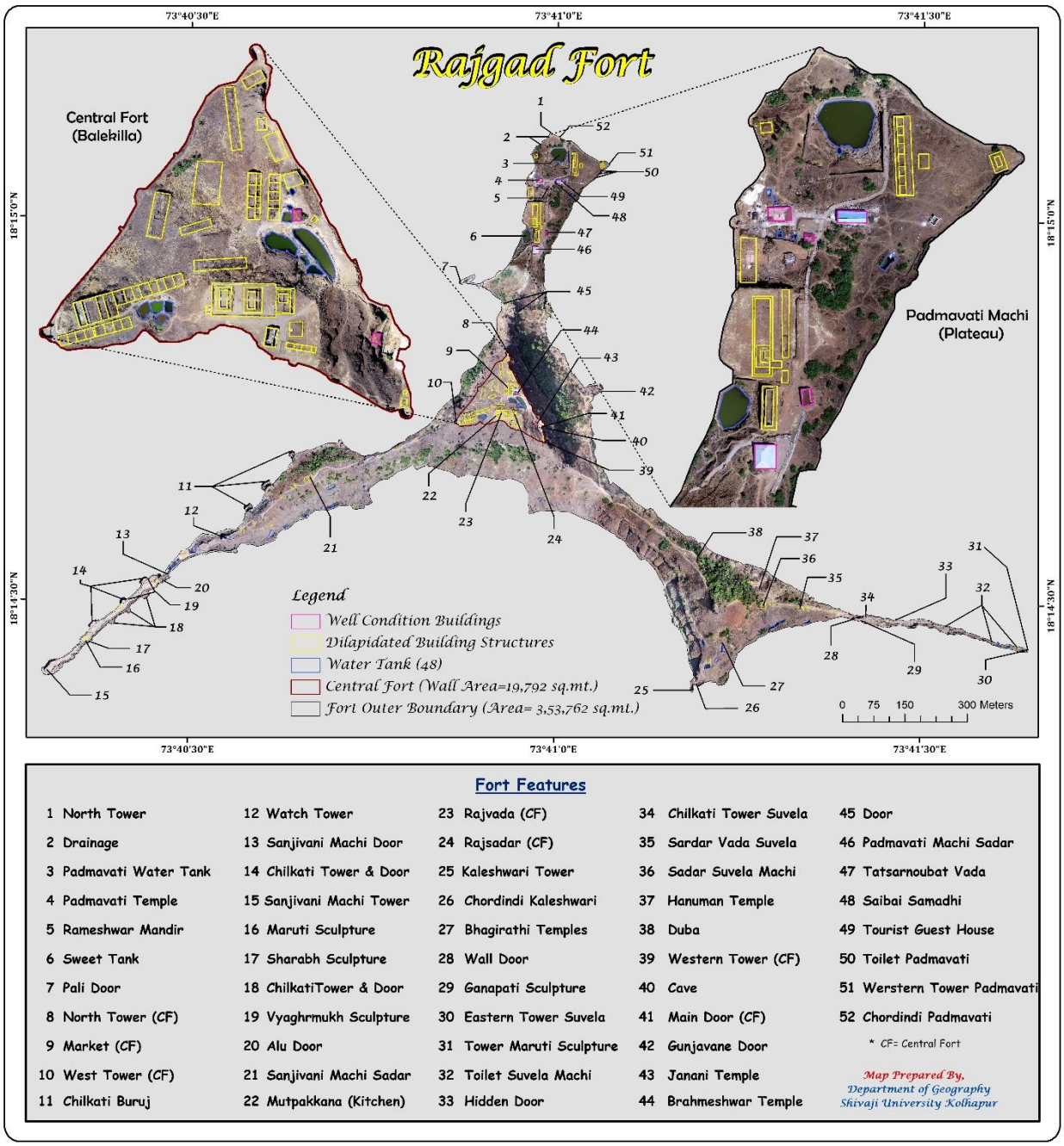

Figure 9: Fort Feature Documented Map

While the study faced limitations such as terrain complexities and seasonal vegetation changes affecting data collection, the adaptability of UAV and GIS technologies proved instrumental in overcoming these challenges. Future research could explore advancements in imaging techniques and interdisciplinary approaches to further enhance our understanding and preservation of Maharashtra's historic forts. Ultimately, by safeguarding Rajgad Fort and similar cultural treasures, we not only preserve our shared heritage but also promote cultural identity and tourism opportunities for future generations.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No funding was received for this work.

References

Adamopoulos, E., and F. Rinaudo. 2020. “UAS-Based Archaeological Remote Sensing: Review, Meta-Analysis and State-of-the-Art.” *Drones* 4(3):46. https://doi.org/10.3390/drones4030046

Apate, D. V., and S. M. Divekar. 1847. *Shivcharitra Pradip*. Vol. 4. Jedhe Karina.

Bachagha, N., X. Wang, L. Luo, L. Li, H. Khatteli, and R. Lasaponara. 2020. “Remote Sensing and GIS Techniques for Reconstructing the Military Fort System on the Roman

Boundary (Tunisian Section) and Identifying Archaeological Sites." *Remote Sensing of Environment* 236:111418. https://doi.org/10.1016/j.rse.2019.111418

Elfadaly, A., R. Lasaponara, B. Murgante, and M. M. Qelichi. 2017. "Cultural Heritage Management Using Analysis of Satellite Images and Advanced GIS Techniques at East Luxor, Egypt and Kangavar, Iran (A Comparison Case Study)." Pp. 152–168 in *Computational Science and Its Applications – ICCSA 2017*, edited by O. Gervasi et al. Springer International Publishing. https://doi.org/10.1007/978-3-319-62401-3_12

ESRI. 2023. "What Is GIS?" Retrieved (https://www.esri.com/en-us/what-is-gis/overview).

Gangan, S. 2017. "Shivaji's Capital, Raigad Fort, to Be Spruced up for Rs600 Crore." *Hindustan Times*, March 16.

Ghanekar, P. 1984. *Gadancha Raja Rajgad*. Snehal Prakashan.

Ioniță, S., and D. Turcanu-Carutiu. 2021. "Use of Drones for Digitization and Monitoring the Built Cultural Heritage: Indoor and Outdoor." In *Heritage—New Paradigm*. IntechOpen. https://doi.org/10.5772/intechopen.100346

Lezzerini, M., F. Antonelli, S. Columbu, R. Gadducci, A. Marradi, D. Miriello, L. Parodi, L. Secchiari, and A. Lazzeri. 2016. "Cultural Heritage Documentation and Conservation: Three-Dimensional (3D) Laser Scanning and Geographical Information System (GIS) Techniques for Thematic Mapping of Facade Stonework of St. Nicholas Church (Pisa, Italy)." *International Journal of Architectural Heritage* 10(1):9–19. https://doi.org/10.1080/15583058.2014.924605

Luo, L., X. Wang, C. Liu, H. Guo, and X. Du. 2014. "Integrated RS, GIS and GPS Approaches to Archaeological Prospecting in the Hexi Corridor, NW China: A Case Study of the Royal Road to Ancient Dunhuang." *Journal of Archaeological Science* 50:178–190. https://doi.org/10.1016/j.jas.2014.07.009

Madaan, N. 2023. "Tourists Increase Littering, Damage Maharashtra Fort." *The Times of India*, December 17. Retrieved (https://timesofindia.indiatimes.com/city/pune/tourists-increase-littering-damage-to-maharashtra-forts/articleshow/106056643.cms).

Nishanbaev, I., E. Champion, and D. A. McMeekin. 2021. "A Web GIS-Based Integration of 3D Digital Models with Linked Open Data for Cultural Heritage Exploration." *ISPRS International Journal of Geo-Information* 10(10):684. https://doi.org/10.3390/ijgi10100684

Phadnis, A. 2017. "Your Plan to Camp at Harishchandragad Fort This Weekend Just Got Cancelled, Here's Why." *Hindustan Times*, November 29.

Samadzadegan, F., F. Dadrass Javan, and M. Zeynalpoor Asl. 2023. "Architectural Heritage 3D Modelling Using Unmanned Aerial Vehicles Multi-View Imaging." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-M-2–2023:1395–1402. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1395-2023

Sane, K. n.d. *Shivachhatrapati's Life History*.

Tendulkar, M. 2019. *Swarayachi Pahili Rajdhani Rajgad*. Snehal Prakashan.

Ulvi, A. 2021. "Documentation, Three-Dimensional (3D) Modelling and Visualization of Cultural Heritage by Using Unmanned Aerial Vehicle (UAV) Photogrammetry and Terrestrial Laser Scanners." *International Journal of Remote Sensing* 42(6):1994–2021. https://doi.org/10.1080/01431161.2020.1834164

Yao, Y., X. Wang, L. Luo, H. Wan, and H. Ren. 2023. "An Overview of GIS-RS Applications for Archaeological and Cultural Heritage under the DBAR-Heritage Mission." *Remote Sensing* 15(24):5766. https://doi.org/10.3390/rs15245766