Cultural Heritage on HPC - Creating High Resolution 3D Models Using Photogrammetry

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***Abstract* — This study investigates the usability and applicability of High-Performance Computing (HPC) in photogrammetry for the creation of high-resolution 3D models for the preservation of cultural heritage. The study addresses the challenges posed by the large datasets generated for high-resolution photogrammetry and argues in favour of the potential of HPC to speed up processing time. By comparing different computer systems, from standard laptops to HPC, this study evaluates their potential on the basis of processing power and management. Case studies illustrate the practical applications at different heritage sites and underpin the study's approach to technology selection. The paper concludes with insights into the benefits and future directions of integrating photogrammetry and HPC in cultural heritage conservation.**

Keywords – Photogrammetry; 3D models; HPC; Cultural heritage; Agisoft Metashape; AliceVision Meshroom

I. Introduction

Cultural heritage is a valuable asset that reflects our history and identity. It is therefore of the utmost importance to preserve cultural heritage for future generations [1]. One of the challenges in preserving cultural heritage is the need to accurately document and archive these sites [2]. Since the advances in computer technology, optics and engineering, traditional and proven documentation methods such as drawings and photographs are complemented by new methods such as photogrammetry [3], laser scanning or structured light scanning.

Photogrammetry is a technique in which multiple photographs are used to create a 3D model of an object or scene. It is a powerful tool for the documentation of cultural heritage sites as it can capture fine details while providing a complete representation of the site or object in a 3D representation [4]. The benefits of creating 3D digital twins of cultural heritage sites and objects are that it gives researchers access to high quality data [5] and creates engaging resources that can be used for educational purposes or to promote tourism. The importance of creating high-resolution 3D models using photogrammetry in the cultural heritage sector lies in its ability to digitally preserve and document historic buildings, artefacts and other cultural assets with a high degree of accuracy. This technology enables the visualisation, analysis and virtual reconstruction of cultural assets and provides valuable insights for research, conservation and presentation [5]. An additional advantage is that the 3D model can be imported into integrated development environments for further processing and visualisation, e.g. for interactive 3D displays, virtual reality and augmented reality [6] [7].

Other 3D methods used in cultural heritage conservation are laser scanning and structured light scanning [8]. Laser scanning uses lasers to measure the distance to an object and create a 3D representation. This method is known for its high accuracy and ability to capture fine details. However, the equipment can be expensive and the scanning process can be time-consuming [9]. Structured light scanning, on the other hand, projects light patterns onto the object and captures the distortions to create a 3D model. It is faster than laser scanning, but can have limitations when capturing certain materials and textures [3]. Compared to photogrammetry, both laser scanning and structured light scanning offer high precision, but can be costly and potentially limited in their scope of application [5].

In this study, we focus on photogrammetry because it is less expensive [10] than the other two methods and can be performed with standard digital cameras, with modern cameras capable of capturing very high resolution images. In addition, the equipment needed for photogrammetry is easier to transport (photo cameras) and the software processing can be carried out on remote servers, making it an excellent method for cultural heritage preservation.

To create high-quality models of cultural heritage sites, a large amount of high-resolution images is required. However, processing a large number of photos using photogrammetry software can be very time-consuming, as numerous high-resolution images need to be analysed and stitched together to create a 3D model. High-Performance Computing (HPC) provides superior processing power and parallel computing capabilities that allow the software to process large amounts of input data in a fraction of the time it would take with traditional computer systems. By distributing the workload across multiple computing units, HPC can significantly speed up data processing and modelling in photogrammetry, enabling researchers and heritage professionals to create high-resolution 3D models. In addition, HPC enables the processing of larger and more detailed datasets as it can efficiently process and store large amounts of image data [11].

There are several studies on how HPC computing can be used to improve the photogrammetry process. In [12], the authors use MicMac photogrammetry software to create a 3D model of the flow of a river in northern Italy using photos taken by a quadcopter. The data was processed on the local computer cluster for which the batch processing script was build and customised. The input photos were divided into subsets, each of which was processed on a working node of the cluster. The authors were able to demonstrate a very good speedup when additional working nodes were added.

In [13], the authors performed a benchmarking test with four data sets of different types and sizes in two model quality levels on the computer clusters. The software they used was Agisoft Metashape, for which they created a customised Python script to submit parallel jobs. They concluded that the use of computer clusters was more beneficial for datasets with many photographs and those requiring high quality models. In a later work [14], the same group of authors undertook a more detailed analysis of the relative effects of the size of the dataset, the quality settings of the software and the size of the processing cluster.

The use of HPC for high-quality cultural heritage documentation remains difficult, especially for practitioners and researchers with limited budgets, lack of access to HPC resources and little knowledge of HPC technologies to make informed decisions and select the most appropriate tools and techniques. The aim of this research is to address this gap by analysing the two most commonly used photogrammetry programmes – Agisoft Metashape and AliceVision Meshroom. This research analyses their support in performing computations in the HPC environment, the possible workflow models and finally compares their performances in terms of time-to-solution.

The paper is organised as follows. Section 2 describes the photogrammetry process and its basic steps. A detailed description of the software and hardware used in our analysis can be found in Section 3. In addition, the same section presents the datasets and describes how the analysis was performed in our test computer environment. The timing data is presented and discussed in Section 4. The paper is finalised in Section 5 with the conclusion and future work.

II. PHOTOGRAMMETRY

Photogrammetry is the science and technology of obtaining reliable information about physical objects, precise and accurate measurements and their textures using two dimensional photographs. By analysing the geometric relationships between multiple images of the same object, photogrammetry can be used to create detailed 3D models. In the field of cultural heritage conservation, photogrammetric technology is used to record and protect historical objects, buildings and sites [15]. This method uses high-quality photographs (Figure 1.) together with photogrammetric software to capture detailed aspects of cultural assets and create accurate 3D models (Figure 2.).

The main advantage of photogrammetry lies in its non-intrusive approach [16], which enables a thorough examination of sensitive cultural assets without physical contact. These digital models not only enable precise analysis by researchers and conservators, but also support restoration efforts by providing a comprehensive reference. In addition, the digital archives created by photogrammetry serve as a resource for educational purposes, virtual tours and digital exhibitions.

Figure 1. Photo of sculpture

Figure 2. Image of created 3D model with cammera positions

The overall method for creating high-resolution 3D models using photogrammetry involves a series of steps, which are shown in Table I. For the sake of brevity, we will not go into the details of each step, as this is beyond the scope of this research.

TABLE I: THE MAIN STEPS OF THE PHOTOGRAMMETRY PROCESS

Feature extraction	Identify unique points in each image. These points have properties that remain unchanged regardless of scale, 2D and 3D rotation and other factors such as lighting.
Image matching	Identify matching points in the images, the features of each image pair are compared and matched.
Feature matching	Compare the features between the image pairs, enabling the subsequent identification of a three-dimensional structure based on the corresponding two-dimensional positions. The matching of marker-based features is simple as only their unique identifiers need to be matched.
Structure from Motion (SfM)	Combine matches into tracks, where each track is a potential representation of a point in space visible from multiple cameras. These tracks are used to determine the camera calibration and construct the 3D structure of the scene, ultimately resulting in a sparse 3D representation.
Depth map estimation	Calculate the depth measurement for each pixel. The region must be visible from at least 2 cameras that have been verified by SfM.
Meshing	Combine multiple depth maps into a uniform dense point cloud and identify a surface within it. Each original image is used to identify the most compelling depth data (evenly distributed in the image with high similarity values), which is then converted into 3D points by back-projection.

When comparing photogrammetry with other 3D scanning methods such as laser scanning, lidar and neural radiance fields, it can be seen that photogrammetry offers several advantages [17]. One of the main advantages of photogrammetry is its cost efficiency. Unlike laser scanning and lidar, which require expensive equipment, photogrammetry can be performed with commercially available high-resolution cameras, making it more accessible to researchers and heritage professionals with limited budgets. In addition, photogrammetry enables the capture of fine details and textures, making it suitable for the documentation of heritage sites with intricate features [4].

Photogrammetry is also characterised by its ability to create high-quality 3D models with rich visual information. Unlike NeRF [18], which can be limited in capturing certain textures, photogrammetry produces detailed and accurate 3D representations that can be used to visualise, analyse and virtually reconstruct cultural heritage sites and objects [19].

III. METHODOLOGY

A. *Software*

In our case study, we used two photogrammetry software programmes to create high-resolution 3D models – the commercial Agisoft Metashape and the open source AliceVision Meshroom. Agisoft Metashape is a commercial software widely used in the field of cultural heritage documentation [20], [21] and according to the available publications and published papers, it is one of the most popular and widely used software in the community to construct 3D objects from a set of two-dimensional photographs. The reason for comparing these two software solutions is that both implement the entire 3D model creation pipeline (Table I.), which includes: Feature Extraction, Matching and Structure-from-Motion (SfM), Densification, Meshing and Texturing. Although other open-source alternatives integrate the entire pipeline, such as OpenDroneMapi, we did not include them in the analysis because they do not support processing on GPUs, specialise in certain types of photos or usage (e.g. OpenDroneMap for aerial drone imagery), or do not support parallelism.

Meshroom is a free 3D reconstruction software built on the AliceVision framework, a set of tools that implement algorithms for processing each step of the photogrammetry pipeline described in Table I. Meshroom allows the reconstruction of 3D geometry and texture from both the graphical user interface (GUI) and the command line and provides several predefined photogrammetry pipelines for different use-cases. The pipeline consists of nodes, each representing a task to be executed. The tasks can be fine-tuned by setting various attributes. Figure 3. shows the overview of the photogrammetry node-based pipeline of Meshroom, where each box represents a node (a task). In addition, Meshroom can take advantage of parallelism on multiprocessor machines, multiple GPUs and computer clusters by dividing each node into chunks, that can be processed independently. The software offers both a GUI and a command line interface (CLI), making it a good candidate for running in the HPC environment, which normally lacks the classic graphical interface.

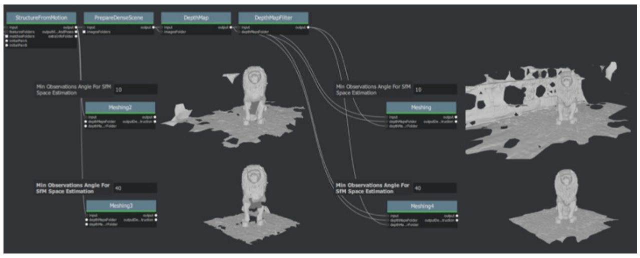

Figure 3. AliceVision Meshroom node based workflow / interface

The second software analysed in this research is Agisoft Metashape, a widely used commercial software for photogrammetry. It offers a user-friendly GUI (Figure 4.) and supports Java and Python API, which allows the automation of processing pipelines via the command line. Command line execution is achieved by preparing and executing a Python script tailored to a specific use-case. A major advantage of Agisoft Metashape over Meshroom is its support for multiple cameras, which can be very useful when documenting large cultural heritage sites with multiple cameras. Metashape supports execution on various parallel platforms, including multi-core processors and multiple GPUs, and performs processing on distributed compute nodes within the same local network. In addition, the software makes it possible to split the datasets into several chunks, each of which can process the entire pipeline, and merge them into a 3D model at the end. This feature is particularly useful when the total number of photos entered is too large to process all at once. See Table II. for the details of the photogrammetry software used in our analysis.

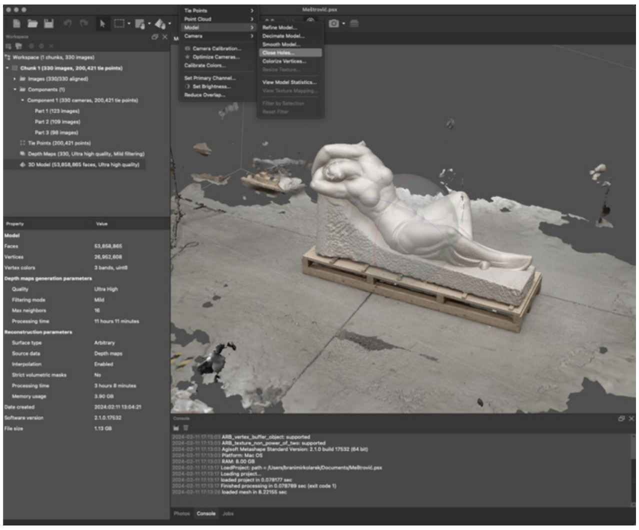

Figure 4. Agisoft Metashape interface

TABLE II. SOFTWARE

	AliceVision Meshroom	Agisoft Metashape
Version used in analysis	[v2023.2.0] Meshroom 64-bit Linux	Version 2.1.0 build 17526 (64 bit)
Price	Free	179 $ - Standard Edition 3499 $ - Professional Edition
Operating systems	Windows Linux	Windows Linux OsX
API	Yes (Python extensions)	Yes
Command line	Yes	No
Automatic workflow	Yes	Yes
Parallel execution	CPU/GPU	CPU/GPU
Cluster execution	Via extensions (Python)	Yes

B. Hardware

Four systems were used to test and analyse the photogrammetry software. The first is a standard PC laptop equipped with an Intel i7 11800H processor, 16 GB of main memory and an NVIDIA RTX 3050Ti graphics card and running the Windows operating system. The second system is an Apple Mac with an M1 SoC ARM-based processor and 8 GB of RAM. The third system is an AMD Linux laptop with an AMD Ryzen 7 4800h processor, 16 GB of RAM and an NVIDIA GTX 1650Ti graphics card. The fourth system is a small computer cluster called Orthus, which is hosted at the Ruđer Bošković Institute. The node of the cluster consists of 2 Intel Xeon Gold processors with a total of 48 cores, 512 GB of main memory and 4 NVIDIA A100 GPUs with 40 GB of local memory each.

C. Datasets

The datasets used in this study consisted of photographs of two cultural heritage objects, the statue made by Ivan Meštrović and the historical fountain "Mala Onofrijeva fontana" in the city of Dubrovnik, see Table III. Input datasets. The sites were selected for their complexity and the variety of features they exhibit. The first dataset (Mestrovic) was recorded indoors with control lighting and a single camera in a single recording session and represents a very clear dataset created following the best practises for preparing the images for the creation of high quality 3D models.

The second dataset (Onofrije) consists of outdoor images taken at a larger heritage site. This dataset was taken during 3 outdoor photo sessions. It was taken with different cameras, lenses, apertures, lens focal lengths and image orientations. This dataset comprised 1663 photos and is considered a large, complex and sub-optimal dataset. This dataset was chosen to present a greater challenge to the hardware and photogrammetry software and to test their ability to handle different conditions and variables. The creation of such a dataset should be avoided as it causes unnecessary overloading of software and hardware.

TABLE III. INPUT DATASETS

Dataset	Mestrovic	Onofrije
Cultural heritage site name	"Na odmoru"	Mala Onofrijeva fontana
Author(s)	Ivan Meštrović	Onofrie della Cava i Pietro di Martino da Milano
Year	1933	1444
Camera	Nikon Z7 II	Nikon Z7 II, iPhone 14 PRO (mobile phone)
Objective	NIKKOR Z 14-30mm f/4 S	NIKKOR Z 35 mm f/1.8 S, NIKKOR Z 28 mm f/2.8
Location	Interior, studio location	Open space, town square
Exif	30mm, f 16, 1/125, ISO 100	24 msm (iPhone), 28 mm, 35 mm, f 1.8 (iPhone), 5.6-11, 1/30 – 1/125, ISO 64-200
Photo dimensions	8256 x 5504	8256 x 5504, 8064 x 6048, 4032 x 3024
File format	RAW, converted to jpeg (compressed 9)	RAW, converted to jpeg (compressed 9)
Number of photos	320	1663

D. Configuration Runs

When working with AliceVision Meshroom, the predefined pipeline called "Photogrammetry" was used. The pipeline consists of the tasks (nodes) specified in the Table VI. Processing times and the number of chunks for each step of the predefined photogrammetry pipeline in AliceVision Meshroom on Orthus, with the leftmost column containing the names of the tasks. The default configuration parameters were used, with the number of threads set to 48 and the number of GPUs set to 1. Although our Orthus cluster system has 4 GPUs, only one was used as the tested version of the software was unstable when running on all 4 GPUs, resulting in the processing error.

The pipelines were prepared using the GUI interface on the local computers (laptops) and the graph describing the pipeline is saved in the file (with the extension .mg). When executed on the computer cluster, the graph file and a data set are copied to and processed using the \`meshroom_compute\` program in command line. Processing was performed by preparing and submitting the processing job using the Cluster Job Scheduler System – SGE. After completion, the output 3D model is copied back to the local user's computer. The tests were carried out in two qualities, high and medium. The attributes set for each quality can be found in Table IV.

TABLE IV. TWO RUNNING CONFIGURATIONS OF ALICEVISION MESHROOM – HIGH AND MEDIUM QUALITY

Task	Attribute	High - value	Medium - value
FeatureExtraction	describerPresent	normal	medium
	describerQuality	normal	medium
DepthMap	downscale	2	4
DepthMapFilter	nNearestCams	10	3
	minNumOfConsistentCamsWithLowSimilarity	4	3
Meshing	maxInputPoints	50,000,000	10,000,000
	maxPoints	5,000,000	1,000,000

Since Agisoft does not support the standard command line interface in the bash environment, all tests were executed via the GUI started on the cluster. The pipeline was created as a batch process consisting of the following steps: Align Photos, Build Point Cloud, Build Model and Build Texture. All tasks were performed with the default settings, which means high quality. In case a lower quality model is required, the accuracy settings in Align Photos, Build Point Cloud and Build Model were set to 'medium' or 'low'.

All use cases were processed in batch mode, i.e. editing of intermediate results was not possible. This approach leads to a lot of unnecessary artefacts created around the observed objects. In practise, this approach should be avoided, as each additional point unnecessarily increases the execution time and thus wastes computing resources.

IV. RESULTS

We performed tests on four test platforms where we analysed and compared the total execution times for the two datasets "Mestrovic" and "Onofrije" in high quality with AliceVision Meshroom and Agisoft Metashape. The results are shown in Table V. Note that Meshroom was not tested on a Laptop with a Mac operating system, as this machine is not equipped with an Nvidia graphics card and the software does not support the M1 processors. The Linux laptop could not complete the pipeline with Meshroom as it produced low quality meshes with visible distortions and could not finish texturing the "Mestrovic" dataset due to memory limitations, see Figure 5. However, the "Onofrije" dataset was successfully generated on Orthus using Meshroom in medium-quality. The "Onofrije" dataset failed on both the Linux Laptop and the Orthus cluster, on the former due to memory limitations and on the latter due to a numerical error that occurred in the DepthMap task. We believe that the reason for the instabilities and failures is that the "Onofrije" dataset is an example of a poorly prepared dataset captured by multiple cameras with different configurations that Meshroom cannot process. The Mac system processed the "Mestrovic" dataset with Agisoft without error (Figure 6.), but could not create a point cloud for the "Onofrije" dataset.

TABLE V. THE COMPARISON OF THE TOTAL EXECUTION TIME FOR HIGH-QUALITY MODELS ON OUR TEST SYSTEMS. TIMES ARE GIVEN IN HOURS:MINUTES FORMAT, FAILED EXECUTIONS ARE LABELLED WITH 'X' AND NOT TESTED WITH 'N/T'

Dataset	Software	Laptop PC	Laptop MAC	Laptop Linux	Orthus
Mestrovic	Meshroom	N/T	N/T	x	04:28
	Agisoft	29:00	26:37	N/T	01:37
Onofrije	Meshroom	N/T	N/T	x	x
	Agisoft	68:00	x	N/T	08:26

We also found that while Meshroom supports processing on multiple GPUs, it does not work when more than one GPU is used. In our analysis of processing a high-quality Onofrije dataset, the program crashes with a processing error while working on the DepthMap task. Furthermore, the longer processing time of Meshroom compared to Agisoft is due to the fact that only the DepthMap node supports processing on GPUs, while all other steps are performed exclusively on CPUs. We believe that this is one of the main reasons why Meshroom is much slower in our analysis compared to Agisoft.

In Table VI. and Table VII. we analyse the processing times and the number of chunks in Meshroom and Agisoft for each step of the pipeline. The division of the input problem into chunks is done automatically by Meshroom. Interestingly, in Meshroom it was not possible to split the Meshing and Texturing nodes into chunks, although both require significant execution time, which means that it is also not possible to speed up these nodes if more compute nodes of a cluster are used. In contrast, DepthMap and DepthMapFilter utilise a large number of chunks, so their execution time can be significantly reduced if more compute nodes are used. Agisoft was able to create both medium and high quality 3D models from both data sets.

TABLE VI. PROCESSING TIMES AND THE NUMBER OF CHUNKS FOR EACH STEP OF THE PREDEFINED PHOTOGRAMMETRY PIPELINE IN ALICEVISION MESHROOM ON ORTHUS.

Task	#chunks	Mestrovic high	#chunks	Onofrije high	Onofrije medium
CameraInit	1	1	1	5	5
FeatureExtraction	9	1183	42	16767	16647
ImageMatching	1	4	1	18	22
FeatureMatching	17	753	84	4870	2923
StructureFromMotion	1	380	1	43450	16783
PrepareDenseScene	9	645	42	2809	2774
DepthMap	110	7762	554	x	32940
DepthMapFilter	33	1903	167	x	1643
Meshing	1	1290	1	x	428
MeshingFiltering	1	130	1	x	7
Texturing	1	2021	1	x	8257
Total time		**16075**		**x**	**82431**

TABLE VII. PROCESSING TIMES (IN SECONDS) OF THE TASKS OF THE BATCH PIPELINE IN AGISOFT ON ORTHUS

Task	Mestrovic high	Mestrovic medium	Onofrije high
MatchPhotos	200	200	690
BuildDepthMap	644	260	2565
BuildPointCloud	3835	1119	17681
BuildModel	748	214	6124
BuildTexture	226	154	3001
BuildUV	191	115	328
Total time	**5895**	**2061**	**30389**

Figure 5. Mestrovic dataset with visible mesh imperfections and without textures, Meshroom on Laptop Linux system

Figure 6. Mestrovic, high-quality final model created by Agisoft on Laptop MAC system

V. CONCLUSION

In our research, we tested the performance and usability of the two photogrammetry software solutions AliceVision Meshroom and Agisoft Metashape on four different computer configurations. The idea was to compare the usability of HPC cluster systems with that of standard laptops found today in many laboratories and departments involved in cultural heritage preservation.

In terms of ease of use, while both software solutions support parallelism and processing in a distributed or networked computing environment, neither is ready to use out-of-the-box. The commercial Agisoft Metashape only supports distributed processing in the Professional Edition, which is significantly more expensive than the Standard Edition as it requires a licence for each computer node in the network, which significantly increases the cost of ownership. In addition, the user must set up and configure Metashape on a computer cluster with master-slave architecture via the command line. AliceVision Meshroom, on the other hand, supports parallelisation per pipeline task by splitting it into chunks that can be executed in parallel on multiple computer nodes. However, additional Python scripts (add-ons) are required to enable execution in the distributed environment with the specific job schedulers. In our opinion, the AliceVision Meshroom has a greater potential to accelerate execution on multiple compute nodes in an HPC cluster due to its finer-grained parallelism.

Furthermore, running GUI-based software in an HPC environment is neither a standard nor a recommended method of utilising HPC resources. In this regard, AliceVision allows the preparation of the pipeline on the local machines via a graphical user interface and the execution of the entire pipeline via the command line on the remote cluster. Currently, this process is not automated and must be done manually. In addition, this approach does not allow the user to interact with the pipeline and control it to fine-tuning the execution during runtime.

An interactive approach, where the user executes one task of the pipeline at a time on the remote computer cluster from the local computer, would be of great benefit to the user as it would give them more control over the entire process of creating the 3D model.

The comparison of the results obtained with the various computing systems and on two different data sets clearly shows the considerable acceleration that high-performance computing offers for the creation of 3D models. Harnessing the sheer computing power and parallelisation capabilities of HPC (Table VIII.) has proven to be a powerful tool for accelerating the processing and examination of high-resolution 3D models created via photogrammetry. Although HPC systems offer enormous computing power, the software packages cannot be used solely as a black box. Rather, careful fine-tuning and attribute optimisation of the photogrammetry pipelines should be carried out to reduce the computing time, energy consumption and operating costs of the HPC systems used.

TABLE VIII. LIST OF BENEFITS HPC BRINGS OVER STANDARD COMPUTERS

Increased Processing Power:	HPC clusters process demanding computational tasks such as bundle adjustment and dense reconstruction faster and more efficiently. Enables processing larger datasets and complex objects in less time.
Parallel Processing:	HPC distributes calculations among numerous nodes, greatly speeding up processing.
Large-Scale Projects:	HPC facilitates processing enormous datasets. Enables generating high-resolution 3D models of complex cultural heritage sites.
Complex datasets	HPC can process complex datasets comprising images captured with varying cameras, focal lengths, orientations, and dimensions.

Going forward, there is potential for further progress in two key areas. Firstly, researchers need to be educated on how to effectively utilise the capabilities of HPC for photogrammetry applications. Secondly, an accessible workflow needs to be developed that seamlessly connects photogrammetry software with HPC infrastructures to optimise the use of HPC for photogrammetry processing.

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