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MAPPING MARS: HOW THE CURIOSITY ROVER USES PHOTOGRAMMETRY TO EXPLORE THE RED PLANET

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Abstract

The largest and most capable rover ever sent to Mars, Curiosity is a component of NASA's Mars Science Laboratory program who was launched on November 26, 2011 and landed in Gale Crater on Mars on August 5, 2012. Since landing on Mars, the Curiosity rover has explored the 5 km high Mount Sharp (Aeolis Mons) in Gale Crater, climbed over 612 meters, reaching younger and younger rocks. The Mars Science Laboratory (MSL) team can analyse the sedimentary deposits by using a collection of imagers placed on the rover, that provides generous pixel sizes and multiple fields of view from close to long-range observations. For this examination the ChemCam instrument, which is mounted on the rover mast, uses a Remote Micro-Imager (RMI), that functions as a 700 mm-focal length telescope, and a Laser-Induced Breakdown Spectrometer (LIBS). Up to a few kilometres out from the rover, remote outcrops can be observed with the RMI. According to this study an experiment aimed at computing for the first time with RMI Digital Outcrop Models of these remote outcrops as collecting 3D information is essential to characterizing the architecture of the sedimentary deposits. Therefore it is demonstrated how adequate collections of individual RMI frames may be used to successfully apply Structure-from-Motion photogrammetry to rebuild the 3D shape and relief of these remote outcrops. This article aims to showcase the application of photogrammetry in the exploration of Mars, highlighting the ways in which this technology has been utilized to gather and analyze valuable data about the planet's geological features and atmospheric conditions.

***Key words**: Curiosity rover, Digital Outcrop Models, MARS Photogrammetry, Structure-from-Motion, 3D.*

INTRODUCTION

Photogrammetry is a technique used to measure and analyze physical objects and environments using photographs. It has been widely used in a variety of fields, including surveying, engineering, and archaeology. In recent years, photogrammetry has also become an important tool for studying celestial bodies, such as planets and moons in our solar system.

In this article, we will focus on the use of photogrammetry technology in studying the Martian landscape, specifically with regards to the data collected by the rover Curiosity.

The rover Curiosity has been instrumental in collecting high-quality data about the geology, topography, and atmosphere of Mars. One of the key technologies used by the rover is photogrammetry, which has enabled scientists to create detailed 3D models of the Martian landscape. These models have provided valuable insights into the history and evolution of the planet, as well as the potential for supporting life.

It is believed that early on, Mars had rivers and large lakes and perhaps even a northern ocean. Since then Mars has experienced dryness, a slow loss of a sizable component of its atmosphere, and the freezing of near-surface water.

The Mars Exploration Program currently has five operating missions at Mars to help understand the climate from past to present, and even future possibilities.

In comparison to past Mars rovers, the Curiosity rover has a payload that is more than 10 times larger and has the most sophisticated scientific equipment ever used on Mars' surface. The 5-km-thick sequence of Mount Sharp (Aeolis Mons), which dominates the Gale crater on Mars, possess a significant portion of sedimentary rocks. It is the location of the Mars Science Laboratory (MSL) rover Curiosity, whose objective is to characterize the geological record using a variety of instruments and look for signs of previous habitability at a time when liquid water was available on the surface of the red planet. Therefore, a key component of its goal is the team's ability to interpret the multiscale geomorphological and sedimentological traits that are present there to describe the previous ecosystems.

In order to achieve this, the analyses rely on all the imaging tools available on the rover, such as the navigation cameras (Navcam), the color science imagers Mastcam, and the Remote Micro Imager (RMI) subsystem of the ChemCam instrument. The ability to collect multi-scale close-range to faraway observations is made possible by this collection of devices with multi-layered fields of view.

The ability to image on several scales is crucial for characterizing the Martian rock exposures that occur naturally. Despite their scientific importance, several zones are inaccessible to the rover because to travers ability concerns and resource/time optimization restrictions. Therefore, the rover's exploration is totally dependent on orbital data and remote imaging from about a hundred meters to several kilometres away utilizing onboard cameras (Mastcam, RMI).

In this study, it is suggested the use of long-range imagery from RMI's telescope to produce Digital Outcrop Models (DOM) of remote outcrops. For this it is necessary to apply Structure-from-Motion photogrammetry, a technique usually performed on close-range geologic features obtained with other imagers onboard the rover (MAHLI, Mastcam, Navcam). Moreover, it also is essentially to implement photogrammetric treatment to specific sets of recurrent long-distance RMI observations that were specifically targeted on the sulphate-bearing units.

MATERIALS AND METHODS

About 3.5 to 3.8 billion years ago, during Mars' early history, a meteor struck the planet, creating Gale Crater (Figure 1.a) that is about 155km long. The landscape was pierced by the meteor's impact. Because Gale Crater offers several indications that water has been present throughout its history, scientists selected it as the landing site for Curiosity. The rover landed in the northern part of this crater, in the Aeolis Palus region. Since then, the rover has traversed a distance of around 25 km while studying the geology of Aeolis Palus and the lower flanks of Mount Sharp (Aeolis Mons) (Figure 1.b,c).

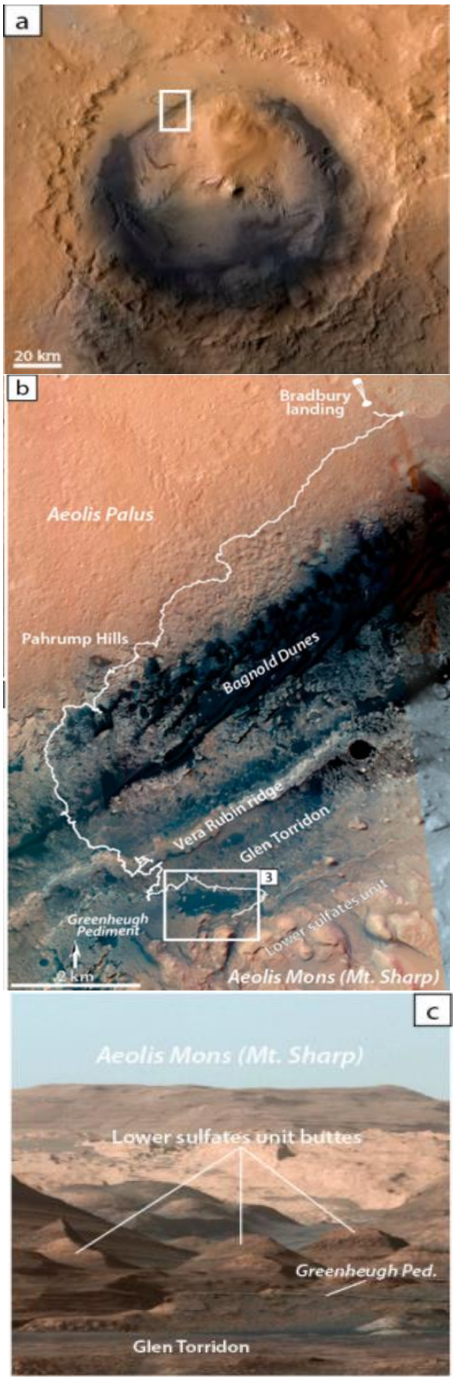

Figure 1. Localization of the studied area on Mars. (a) Orbital image of the Gale crater. The white box represents the area of operations of the Curiosity rover. (b) View of path followed by the rover (white line) since Bradbury landing in August 2012 and up to the lower sulfate unit transition (as of July 2021). (c) Panoramic view from Aeolis Palus showing the vertical succession of the major units in Mount Sharp stratigraphy, notably highlighting the location of Glen Torridon region and the lower sulfates unit.©NASA Photojournal

The layers in the central mound (Mount Sharp) imply that it is the last surviving fragment of an extended chain of deposits.
According to scientists the crater is filled in with sediments while the continuous Martian winds carved Mount Sharp which now towers 5.5 kilometres above Gale Crater's level and is three times as tall as the Grand Canyon.
This part of the sedimentary pile that has only been characterized by orbital data or by remote long-distance imaging using the onboard cameras on the rover.
The present article is focused on RMI's long-distance observations of the lower sulphate unit outcroppings above the Glen Torridon area, where the rover was located at the time the photos were collected (Figure 1.b,c).

The Curiosity Rover

The rover, which is approximately the size of a MINI Cooper and about as tall as a basketball player, uses a 7 foot-long arm to place tools close to rocks selected for study. These tools include 17 cameras, a laser to vaporize and examine far microscopic pinpoint areas of rocks, and a drill to take samples of the rock's powder. It hunts for special rocks that formed in water and/or have signs of organics components.
A radioisotope power generator from the U.S. Department of Energy provides the rover with electricity. The heat of the radioactive decay of plutonium-238 is converted into energy by the multimission radioisotope thermoelectric generator. The mission can operate on Mars' surface for at least a complete Mars year (687 Earth days) because to its durable power source.
The largest and most sophisticated scientific research tools ever dispatched to the surface of Mars are aboard Curiosity. The chemistry and structure of the rocks and soil record the evolution of Martian climatology and geology. By examining powdered samples taken from rock drill holes, Curiosity deciphers this record. In order to ascertain a rock or soil's composition and history, particularly its interactions with water in the past, it also analyses the chemical fingerprints that are present in such materials.
The mission's primary method of communication between Curiosity and the Deep Space Network antennas on Earth is radio relays via Mars orbiters. About 48 terabytes of data from Curiosity were downlinked by the orbiters in the first two years following its arrival.
It can only communicate with each probe for 8 minutes a day, and signals between Earth and Mars take an average of 14 minutes and 6 seconds. Originally the rover was designed to operate for two years on Mars, instead it continued to operate with success and is still conducting scientific research on the red planet.
The previous Mars Pathfinder and Mars Exploration Rover mission operations software serves as the foundation for the Robot Sequencing and Visualization Program (RSVP) for the Mars Science Laboratory Mission (MSL). The RSVP consists of two main tools:

1. The Robot Sequence Editor (RoSE) effectively supports every command in the mission dictionary through the use of a graphical user interface (GUI). RoSE also communicates with the JPL spacecraft sequence generation system (SEQGEN) and rp-check for resource calculations and sequence validation, as well as Surface Flight Software Simulation (SSim) and HyperDrive to simulate the execution of arm, turret, and driving instructions. All drive, arm, and turrnet command sequences delivered to Curiosity are created using RoSE.
2. HyperDrive provides a range of 3D graphics interfaces to enable the visualization of stereo images and 3D terrain-model data collected from Mars. This software is used to plan all of the rover's movements, from traversing the Martian surface to maneuvering the robotic arm and turret to position equipment at sites of geological interest.

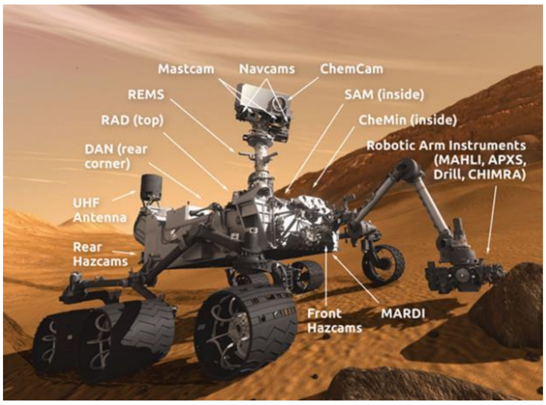

Figure 2. Instruments on board the Curiosity Rover

Instruments on board the Curiosity Rover

Curiosity is equipped with 17 instruments serving multiple purposes such as cameras: Mastcam, MAHLI, MARDI, spectrometers: APXS, ChemCam, ChemMin, SAM, radiation detectors: RAD, DAN, environmental sensors: REMS, navigation cameras: Navcam, Hazcam and atmospheric sensors: MEDLI.

The most significant instruments onboard the rover are the five cameras situated on the 2m high Remote Sensing Mast (RSM): the Navcam pair, the Mastcam pair and the ChemCam`s RMI (Figure 3.a).

The two pairs of Engineering Navigation Cameras (Navcams) (Figure 3.b; Table.1) are a visible light-based, black-and-white cameras that captures panoramic, three-dimensional (3D) images. Scientists and engineers can simulate ground navigation using the stereo pair of cameras in the navigation camera unit. Each camera has a 45-degree field of view. By offering an additional perspective of the ground, they enhance the danger avoidance cameras' job.

The Mast Camera (Figure 3.b; Table.1), which has a powerful zoom lens, captures color photographs, three-dimensional stereo photos, and color video recordings of the martian landscape. The Mars Science Laboratory rover deck supports a mast that extends upward, holding two identical camera systems positioned on it. Similar to how the human eyes work, the cameras combine two side-by-side pictures acquired from slightly different orientations to create three-dimensional stereo views. These cameras may be utilized to generate stereo mosaics or even 3D DOM but, in comparison to the Navcam pair, their unique focus length results in a smaller field of 3D data capture.

The Chemistry and Camera (ChemCam) mechanism package incorporates two remote sensing instruments: the first planetary science Laser-Induced Breakdown Spectrometer (LIBS) and a Remote Micro-Imager (RMI). The RMI sub-system of the ChemCam instrument's main assignment is to image the targets subjected to Laser-Induced Breakdown Spectrometry analysis. This enables up-close examinations of the examined rock's texture and the laser-shot marks left afterward. While the RMI was not originally designed for long-distance observation, its 700 mm focal length has proven to be advantageous for directing the telescope at distant objects.

The RMI is capable of producing highly accurate greyscale images of outcrops located several kilometers away. The RMI offers a complementary imaging feature of the distant geological features with a very high resolution, but with a limited field of view, since its pixel size is 3.7 smaller than that of the M-100. The region captured by a composite RMI mosaic created from two merged observations (15x3 and 10x3 mosaics) is highlighted by the white box in the color Mastcam mosaic of Figure 3c (top panel). RMI makes it possible to observe additional elements that were not identifiable on the Mastcam picture, such as meter-scale cross-stratifications and individual blocks indicated in the detail boxes at the bottom of Figure 3c. This ability is essential for characterizing features on distant outcrops or those that are inaccessible to the rover. However, the RMI is not inherently capable of creating stereo-images to offer a 3D picture of the observed outcrops, unlike the Navcam and Mastcam pairs.

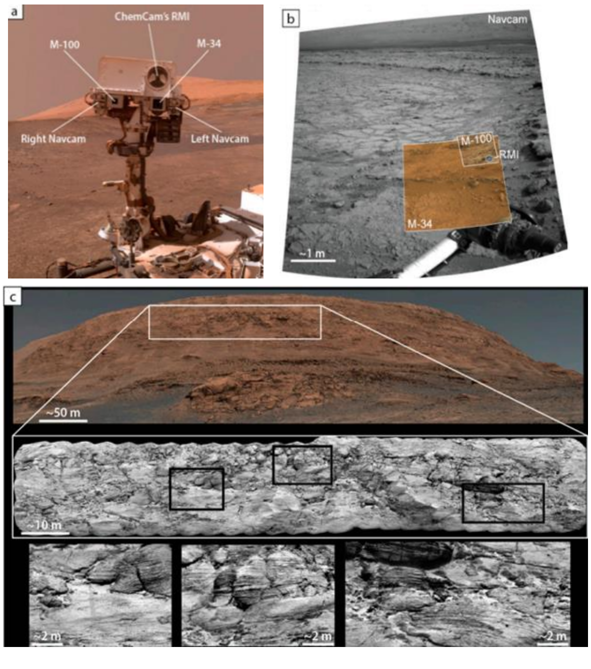

Figure 3. (a) Detail of a “selfie” picture of Curiosity taken on sol 1943 by the MAHLI camera, showing the Remote Sensing Mast of the rover and the position of its main imaging instruments: Navcam, Mastcam and RMI (base image PIA22207); (b) Composite image showing the variations in resolution, color, and field of view of the different Navcam, Mastcam and RMI imagers (images CR0_412749646PRC_F0060000CCAM02171L1, 0198MR0010070380202807E01, 0170ML0009050660104745E01,

NLA_412415874EDR_F0060000NCAM12754M1); (c) Upper part: Mastcam (M-34) color mosaic of a large butte in the lower sulfates unit (Mastcam image sol03154_ML_100270); Lower part: composite RMI mosaic (images ccam3151 and ccam4153) corresponding to the white box in the Mastcam mosaic. RMI shows a higher level of details, allowing to distinguish down to meter-scale cross-stratifications and individual blocks (bottom detail boxes) from several hundred meters.©NASA Photojournal.

By combining the colour information from Mastcam-100 photos with the high spatial resolution greyscale RMI images, an integrated output is created that can be used to understand the variety of LIBS signatures present in a particular raster. After merging the two images, color information from Mastcam can be added to the RMI image using a pansharpening algorithm in cases where targets are observed simultaneously by the RMI and M-100.

At the John Klein location in Yellowknife Bay, both cameras captured drill cuttings on Sol 183, as shown in Figure 4. Investigating the drill tailings' heterogeneity was the aim of this observation.

Figure 4.a displays a full-frame M-100 image with white circles denoting the footprints of the four RMI photos displayed on the right. The M-100 picture in the overlapped region is shown in Figure 4.b. Also Figure 4.c. is a mosaic of the four RMI photographs that represents the results of the LIBS analysis in the specific area. The positions of the individual LIBS measurements are shown by red arrows. Using the ESRI pansharpening algorithm integrated into the ArcGIS program, Figure 4.d combines RMI with the color data captured by M-100.

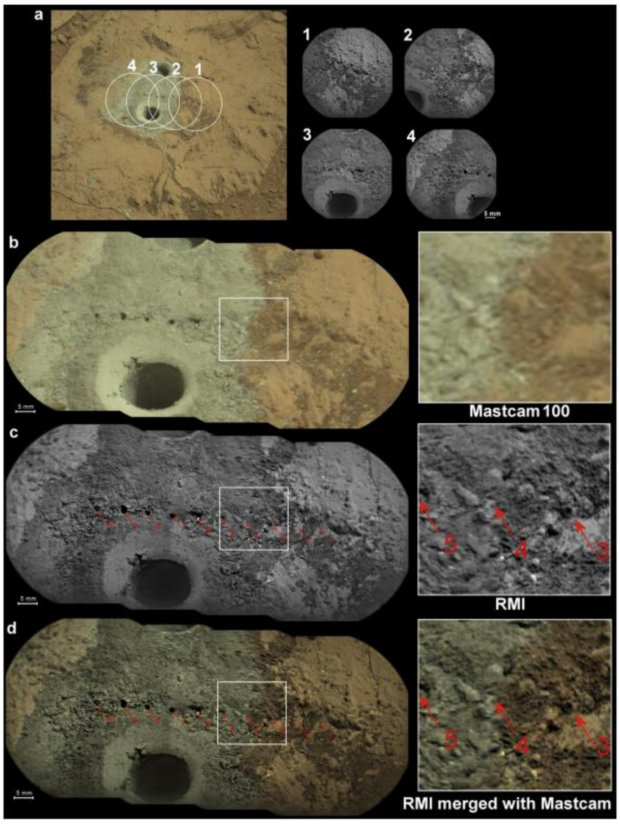

Figure 4. Example of RMI-Mastcam color fusion on the drill tailings observed from a distance of 2.46 m during Sol 183 at John Klein site in Yellowknife Bay. (a) M-100 image 0183MR0009930070202041E01 (left) and RMI images (right) CR0_413737102EDR_F0060000CCAM02183M1, CR0_413737471EDR_F0060000CCAM02183M1, CR0_413737 840EDR_F0060000CCAM02183M1 and CR0_413738369EDR_F0060000CCAM02183M1.

(b) Portion of M-100. (c) RMI post-LIBS mosaic. (d) RMI mosaic merged with M-100 using pansharpening. The white rectangle corresponds to the insets on the right, illustrating the benefits of merging the two datasets .

Table 1. Main optical parameters of the Navcam, Mastcam and RMI imagers onboard Curiosity.

Instrument	Common Designation	Colorization	Resolution	Focal Length
Navigation Cameras	Navcam	Greyscale	1024 × 1024 px	14.67 mm
Mast Camera(left)	Mastcam left(M-34)	RGB	1600 × 1200 px	34 mm
Mast Camera(right)	Mastcam right(M-100)	RGB	1600 × 1200 px	99.9 mm
Remote Micro Imager	RMI	Greyscale	1024 × 1024 px	700 mm

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RESULTS AND DISCUSSIONS

Digital Outcrop Modelling (DOM) - Structure from Motion for generating DOM

An outcrop is a part or area of rock that appears or emerges at the surface of the terrain. To define and comprehend the circumstances leading to the creation and/or change of a geological outcrop, 3D information might be significant. This is especially true in the case of the detrital depositional record found in Gale crater and the discovery of structures caused by sedimentary processes. Nevertheless, when examining Martian outcrops from orbit and/or from rover-derived data, this 3D information is not easily accessible. One way to make up for the inability to see these characteristics "in person" is to digitally reconstruct the 3D geometry of the investigated outcrops using the data the rover collected.

Structure from motion (SfM) is a photogrammetric range imaging technique that can estimate 3D structures from 2D picture sequences that might be combined with local motion data by overlapping. This method can be used to generate these DOMs.

SfM photogrammetry is frequently used on Earth and in the planetary community and is especially well suited for geological investigations. Using Navcam, MAHLI, Mastcam, or a combination of these sensors, numerous effective examples of DOM reconstruction to define the sedimentary record have been successfully achieved in the case of the Gale crater.

The current study shows how this technique is applied to images provided by the RMI telescope, in order to restructure the 3D shape of remote and unattainable outcrops that are several hundreds of meters away from the rover.

For the SfM procedure it was used the commercial Agisoft Metashape Professional software v.1.7.1 (Agisoft LLC, St. Petersburg, Russia).

Using information from the Mars Hand Lens Imager (MAHLI), it was possible to rebuild item models at the millimetre scale and create landscape models at the decimetre scale. Additionally, it was pointed out that information about the camera's position and attitude is a by-product of the SfM model construction.

There were given some suggestions for uses of SfM for this purpose in present and future planetary exploration missions using this capability to illustrate reconstruction of Curiosity's traverse path from pictures alone.

The input images must have a high enough quality for the program to detect material similarities between several photographs in order to get the best results.

For optimal model reconstruction and to maximize the number of key points connected across the photoset, sufficient overlap is also required.

Small-Scale SfM Object Models

To obtain small-scale SfM Object Models, MAHLI camera, which is a 1600x1200 pixel color camera attached to the robotic arm of Curiosity, cand be used because of its capacity of micro-imaging of rocks and outcrops.

At its greatest resolution, MAHLI can produce images with a resolution of 13.9 m/pixel from a range of 2.04 cm. MAHLI is the perfect instrument for SfM imaging since it can gather images from many angles pointed at a single subject.

A 3D model of the Bimbe aggregate that was created from a collection of 9 photos taken by MAHLI on sol 1409 is shown in Figure 5. The model is scaled at 45 mm across.

MAHLI is able to capture stereo pair images and the vertical inaccuracy of the relief is being researched. Stereoscopy should be compared to SfM modelling as a substitute.

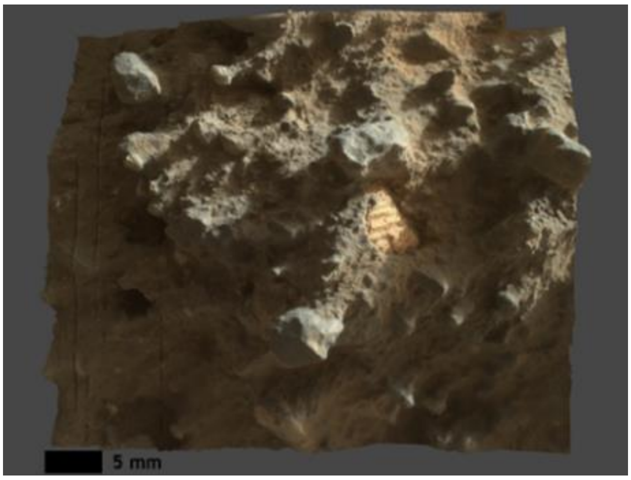

Figure 5. Bimbe conglomerate reconstructed using Agisoft Photoscan Professional from Curiosity MAHLI images taken on sol 1409.

Large-Scale SfM Terrain Models

Additionally, to create large-scale SfM Terrain Models, the Navcam onboard Curiosity is a better fitted option since it has the capability of simultaneously photographing the surrounding environment with enough overlap and parallax to create models with detail at a close range to the rover.

Also 3D terrain model of the Murray Buttes was developed from a collection of 25 Navcam pictures from sol 1455 is illustrated in Figure 6. With increasing distance from the rover, there are gaps in the model and insufficient overlap between photos, loss of photo resolution, and depth of field.

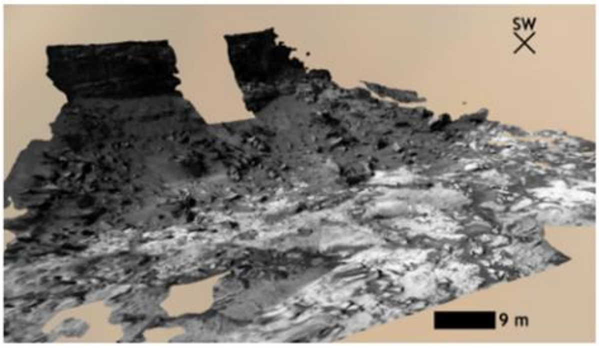

Figure 6. Murray Buttes reconstructed using Agisoft Photoscan Professional from Curiosity Navcam images taken on sol 1455.

Traverse Reconstruction

Traverse Reconstruction can be accomplished with the SfM method due to its capacity of calculating original camera position from key point connections. The Curiosity`s traverse (Figure 7) was reconstructed for sols 692-703 using 210 images acquired from the Navcams resulting in a model assembled from photosets taken on five different sols (692, 695, 696, 702, 703) (Figure 7.a), that is similar to the actual traverse map (Figure 7.b). In order to enhance the quality of the resulting SfM model, future work will investigate utilizing the size of the rover wheels and their tracks to construct a scale. From previous experiment it was demonstrated that images captured by the rover's onboard cameras may be used to estimate its location if there is enough overlap and image quality. Therefore, camera reconstruction can replace or supplement inertial measurements as a low-cost positional redundancy.

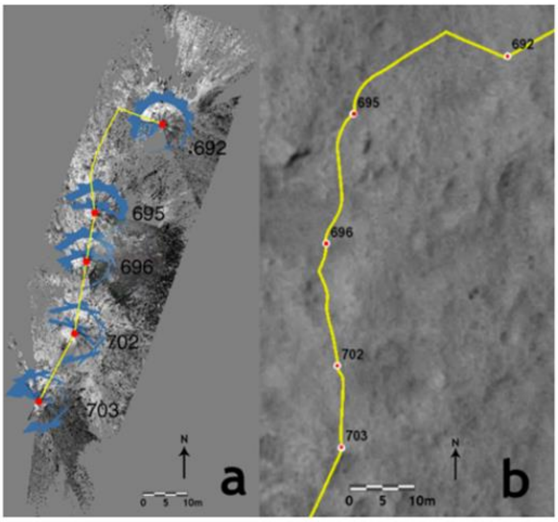

Figure 7. (a) Reconstructed traverse path (yellow) of Curiosity as determined using Agisoft Photoscan Professional and Navcam images from sols 692, 695, 696, 702, and 703. Red points show estimated rover position on these sols and blue polygons denote estimated camera poses. (b) Actual traverse map for Curiosity for sols 692-703.

The Case Study of Reconstruction of Distant Sulfates Unit DOMs

The proposed mesh is a 3D reconstruction of a region photographed by the RMI targets LD_Sulfates_2947b and LD_Sulfates_2962a (Table 2, Figure 8.a), which exhibits a blocky outcrop of cross-stratified lower sulphate unit sandstones that have likely undergone significant diagenetic events. A virtual baseline of around 200 m separated the two points of view from which 41 aligned photos (out of a total of 43, or 95%) were used to rebuild the DOM. From a dense cloud of 2,264,005 points, a mesh of 452,976 polygons is generated as an outcome (Figure 8.b). The shaded model in Figure 7.b shows how successfully the 3D mesh reconstructs the outcrop's blocky expression.

Table 2. List of targets used to compute 3D DOM of remote outcrops and associated data.

Mesh	Target	SeqID	Type	Sol Taken	Dist.From Rover	Virtual Baseline
	LD_Sulfates_2947b	ccam04947	12x1	2947	~650 m	~200 m
	LD_Sulfates_2962a	ccam04962	16x2	2964	~510 m	

Eight tiles of 4096 x 4096 pixel are used to texture the model (Figure 8.c). By visually comparing and choosing GCPs against scaled and calibrated original 2D RMI and Mastcam mosaics (whose scale is derived as a function of the pixel size and distance to the outcrop), the resultant mesh has been scaled. In order to further restrict the area coverage, we additionally used the orbital HiRISE orthoimage, which produced an error with a sub-metric size, comparable to what is detected in 2D mosaics. The generated mesh, “Long-distance 3D reconstructions using photogrammetry with Curiosity’s ChemCam Remote Micro-Imager in Gale crater (Mars is viewable the study of Caravaca G. (2021).

Sub-metric cross-stratification is extremely common on the outcrop and is unaffected by the various deflation surfaces, as can be seen from the model's 3D reconstruction. The orange arrows in Figure 8.d,e show some arcuate lineations that emerge out of some blocks as additional structures in this location.

The spatial distribution of these characteristics can be seen in this case thanks to the 3D mesh representation, and they appear to crosscut the outcrop's overall apparent stratal pattern. These formations might be understood as mineral veins that are most likely diagenetic in origin.

A more in-depth look at the outcrop's topographic expression in 3D enables the viewer to recognize it's possible that a contact that is barely visible on the mosaic extends farther to the left. In fact, the contact seen at the base of the outcrop's right portion is clearly visible at the base of the largest blocks (right Figure 8.a,d).

However, in the more damaged area on the left, it is more challenging to evaluate its continuity. Even so, the 3D mesh allows us to perceive a topographic "step" in this rubbler portion (as seen in differential shading in Figure 8.b), allowing the spectator to follow the continuity of this contact all the way to the model's boundaries (red line in Figure 8.d).

Even with high-quality 2D imaging, it may be challenging to identify the 3D form of the sedimentary structures in the Gale crater, despite their importance for understanding sedimentary processes. Recently, high-resolution DOM of numerous places explored by Curiosity have been proposed using SfM photogrammetry, but they only apply to outcrops that the rover has "physically" visited. Many remote locations have limited 3D data because they are inaccessible or have not yet been accessed by the rover.

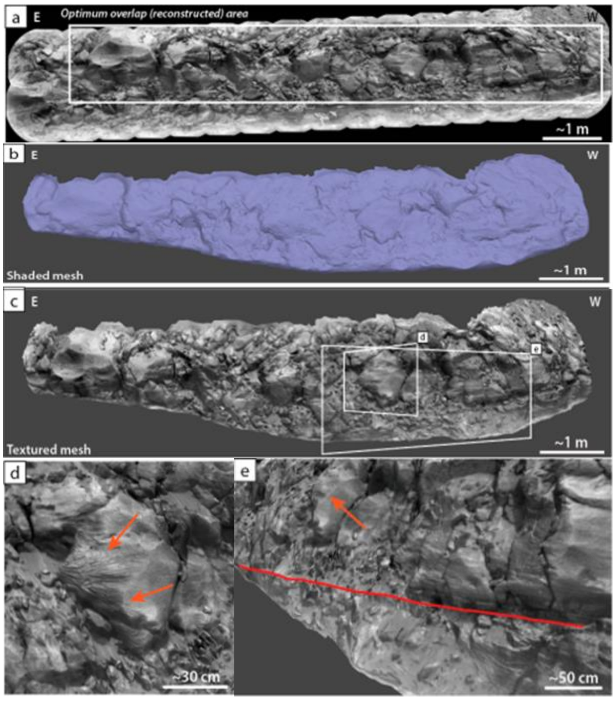

Figure 8. Mesh #1, DOM for the target LD_Sulfates_2962a. (a) Original RMI mosaic (LD_Sulfates_2962a, ccam04962). The white box indicates the optimum overlap with associated mosaic LD_Sulfates_2947. (b) Resulting 3D mesh in shaded view, highlighting the surface relief. (c) Same view with a photorealistic texture applied. (d) Detail on a specific block reconstructed in the DOM. Orange arrows highlight the presence and distribution of probable diagenetic mineral veins. (e) Detail on the lower right part of the DOM, highlighting a topographic step (red line) corresponding to a possible continuation of the sharp contact between two sedimentary beds. The orange arrow also points to features illustrated in (d).

However, this 3D data might be essential in characterizing the sedimentary record viewed from a distance with greater accuracy and detail than in typical orbital digital elevation models.

Therefore, in this study, it was investigated whether it was possible to recreate the 3D geometry of a remote outcrop using distant photos captured by Curiosity's RMI telescope.

RMI is the most potent imager in terms of pixel size, despite not being created with long distance stereo imaging in mind.

CONCLUSIONS

In this study we illustrated the benefits provided by the use of photogrammetry and its derived products such as DOMs to better understand, evaluate and organize further research on Mars.

Structure-from-Motion photogrammetry, which is carried out by the Metashape program, can be utilized to successfully compute the DOMs of these distant outcrops using individual frames from overlapping long-distance RMI mosaics.

The models that are created as an outcome of computing these RMI mosaics allow analysis of the overall precise 3D form of the geologic objects that are outside of the rover's reach. The science team will be able to characterize, for example, the distant sulfates unit of Mount Sharp, a key-objective of the MSL mission, with the assistance of this new, powerful, and original method of characterizing the 3D geological record remotely observed from several hundred meters, in combination with existing imagery such as Mastcam (stereo-)mosaics and typical RMI mosaics.

To optimize the science result and identify high-interest locations in advance, it may be helpful to organize the upcoming exploration of this sulfates period before the arrival of the rover on site by calculating a DOM remotely using RMI.

The photogrammetry data collected by the rover Curiosity has allowed researchers to study the Martian landscape in unprecedented detail. By analyzing the 3D models of the Gale Crater and other regions of Mars, scientists have been able to identify and analyze the layers of rock that make up the planet's surface. This has enabled them to reconstruct the history of Mars and understand how the planet's environment has changed over time.

In conclusion, the use of photogrammetry technology has been instrumental in advancing our understanding of the Martian landscape, and has provided valuable insights into the history and evolution of the planet. The data collected by the rover Curiosity has enabled scientists to create detailed 3D models of the Martian surface, which have been used to study the geology, topography, and atmosphere of the planet.

The photogrammetry data has also provided important information about the potential for supporting life on Mars. By analyzing the mineralogy and chemistry of the rocks and soil, scientists have been able to determine the presence of key elements and compounds that could be used for sustaining human life on the planet. This information is crucial for planning future missions to Mars, and could ultimately pave the way for human colonization of the planet.

Furthermore, the use of photogrammetry technology on Mars has demonstrated the potential for using similar techniques in the study of other celestial bodies in our solar system and beyond. As our understanding of photogrammetry technology advances, it is likely that we will continue to uncover new insights into the universe around us.

Overall, the use of photogrammetry technology in the study of Mars has been a remarkable achievement, and has provided a wealth of valuable data that will continue to be analyzed and studied for years to come.

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