3D MODELS FROM STRUCTURE-FROM-MOTION PHOTOGRAMMETRY USING MARS SCIENCE LABORATORY IMAGES: METHODS AND IMPLICATIONS. A. M. Ostwald[1], J. M. Hurtado, Jr.[2], [1,2]Deptartment of Geological Sciences, The University of Texas at El Paso (500 W. University Ave, El Paso Texas, 79902, amostwald@miners.utep.edu).

Introduction: Structure-from-Motion (SfM) photogrammetry is a low-cost method for constructing 3-dimensional (3D), geolocated terrain and object models from multiple photographs taken from cameras with arbitrary (or unknown) poses and with or without ground control points [1]. This study explores planetary applications for the SfM method using the Agisoft Photoscan Professional software package applied to imagery obtained by the Mars Science Laboratory rover (Curiosity). We reconstruct object models at the millimeter scale using Mars Hand Lens Imager (MAHLI) data and build decimeter-scale terrain models using the navigational cameras. In addition, we note that camera position and pose information is a by-product of the SfM model creation. We use this feature to demonstrate reconstruction of the traverse path of Curiosity from photographs alone, and make recommendations for applications of SfM for this purpose in current and future planetary exploration missions.

Structure-from-Motion Photogrammetry: Structure-from-Motion (SfM) photogrammetry creates 3D geometric models from photographs while simultaneously reconstructing the original camera pose without the need for control points or other *a priori* information. To do so, a set of photographs (a photoset) is texturally analyzed to find matching keypoints among multiple images [1]. Those points are linked across the photoset, resulting in a sparse point cloud (each point with an [x,y,z] position in 3D space), from which which the original camera positions can be calculated [1]. A dense point cloud is then be constructed using the photogrammetric model obtained during construction of the sparse point cloud. This point cloud can then be used to create a triangular irregular network (TIN), or mesh. Color or grayscale from the original photographs can then be texture mapped onto the TIN, resulting in a photorealistic object or terrain model of the target.

For best results, the input photographs must be high-enough resolution for the software to recognize textural similarities among multiple photographs. Sufficient overlap is also necessary for effective model reconstruction, so as to maximize the number of keypoints connected across the photoset. Lastly, camera positions relative to the target affect the quality of the model. For example, photographs taken exclusively while pivoting around a stationary point often result in a poor-quality model. Instead, a more successful imaging strategy for SfM is to acquire photographs perpendicular to a flat surface, or in a circular pattern around a target with the camera pointing inward toward the target.

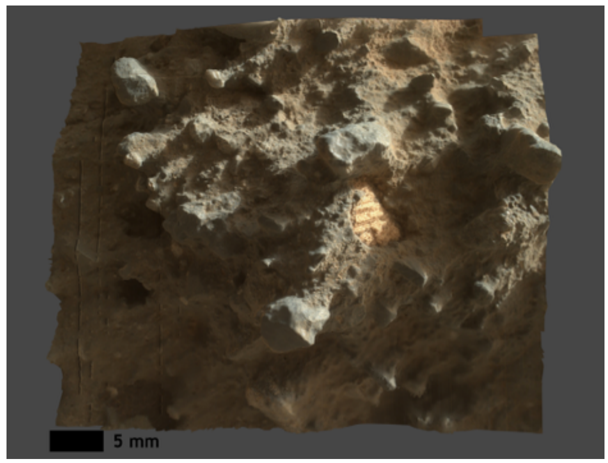

Fig. 1 Bimbe conglomerate reconstructed using Agisoft Photoscan Professional from Curiosity MAHLI images taken on sol 1409.

Small-Scale SfM Object Models: MAHLI is a 1600 x 1200 pixel color camera attached to the robotic arm of Curiosity intended for micro-imaging of rocks and outcrops. At its highest resolution, MAHLI is capable of 13.9 µm/pixel scale photographs from a 2.04 cm range [3]. MAHLI is an ideal tool for SfM imaging as it is capable of obtaining photographs from multiple view points directed toward a single target. Fig. 1 shows a 3D model of the Bimbe conglomerate we reconstructed from a set of 9 photographs captured on sol 1409 by MAHLI. The scale across the model is 45 mm.

MAHLI is capable of acquiring stereo pair photographs; the vertical error of the relief is under investigation [3]. SfM modeling should be considered as an alternative to stereoscopy.

Large-Scale SfM Terrain Models: Generally, the Mast Camera onboard Curiosity has too little overlap in its photos for point cloud construction with SfM. However, Curiosity also has a set of navigational cameras (Navcams) capable of simultaneously photographing the surrounding environment with sufficient overlap and parallax to create models with detail at a close range to the rover (the best focus of the Navcams is at 1.0 m [4]). Fig. 2 shows a 3D terrain model of the Murray Buttes we constructed from a set of 25 Navcam images taken on sol 1455. As distance from the rover increases, insufficient overlap between photographs, loss of photograph resolution, and depth-of-field results in poorer model quality and gaps in the model.

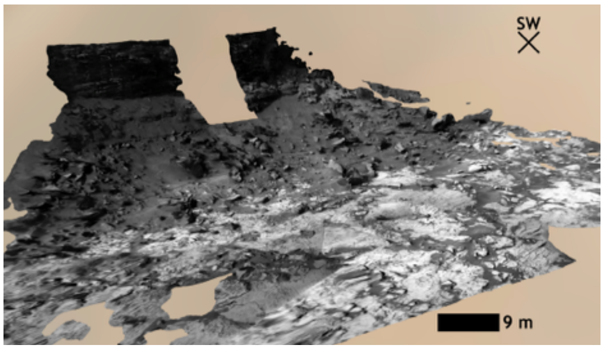

Fig. 2 Murray Buttes reconstructed using Agisoft Photoscan Professional from Curiosity Navcam images taken on sol 1455.

Traverse Reconstruction: SfM is capable of calculating original camera position from keypoint connections [1]. As such, we can recreate the Curiosity traverse path from the photos alone. We reconstructed the Curiosity traverse (Fig. 3) for sols 692-703 using 210 photos from the Navcams. The result is a model (Fig. 3a) constructed using Navcam photosets taken on five separate sols (692, 695, 696, 702, 703). Our reconstructed traverse is very similar to the actual traverse map. Future work will explore using the size of the rover wheels and their tracks to establish a scale in order to improve the derived SfM model quality. Given sufficient overlap and quality of photographs, we have shown that photographs obtained from onboard cameras can suffice to determine locations of the rover. Camera reconstruction, therefore, can serve as a low-cost positioning redundancy in addition to, or in place of, inertial measurements.

Implications for Planetary Exploration: SfM, and its capabilities for reconstructing object and terrain models as well as traverse paths, has broader implications with regards to future planetary exploration. The camera pose reconstruction capability of SfM may serve as a method to track the position of a rover throughout its traverse, in addition to inertial measurements. This ability could extend the lifespan of any robotic mission in the event of navigation instrument failure. For example, the 2020 Mars rover

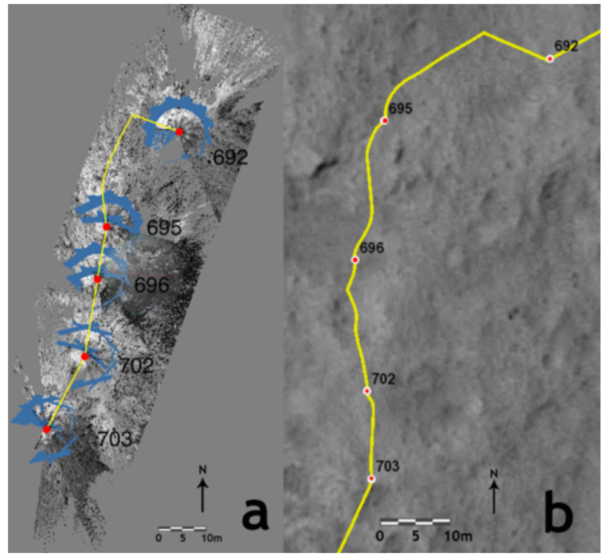

Fig. 3 (a) Reconstructed traverse path (yellow) of Curiosity as determined using Agisoft Photoscan Professional and Navcam images from sols 692, 695, 696, 702, and 703. Red points show estimated rover position on these sols and blue polygons denote estimated camera poses. (b) Actual traverse map for Curiosity for sols 692-703 [5].

will rely on inertial measurements for positioning. SfM could be used as a supplement for rover positioning or as a primary navigation tool for proposed payloads such as a drone. SfM photogrammetry is a low-cost method for constructing both small-scale object models and large-scale terrain models using existing rover capabilities. Object models are useful tools for habitability studies [3]. Terrain models also have important uses in traverse planning and geologic mapping [4].

References: [1] Westoby M.J. et al. (2012) *Geomorphology, 179,* 300-314. [2] Rychov I. et al. (2012) *Computers & Geosciences, 42,* 64-70. [3] Edgett, K. S. et al. (2015) MSL MAHLI Technical Report 0001, Version 2. [4] Alexander, D., Deen, R. (2015) *Mars Science Laboratory Project Software Interface Specification*, Version 3.5. [5] Image from MSL Curiosity Analyst's Handbook, map of Sols 692, 695, 702, 703.