PLANETARY SCIENTIFIC TARGET DETECTION VIA DEEP LEARNING: A CASE STUDY FOR FINDING SHATTER CONES IN MARS ROVER IMAGES.
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Introduction: Robotic Mars missions contain optical instruments for various mission-related and science tasks, such as 2D and 3D mapping, geologic characterization, the characterization of scientific context, and the identification of scientific targets of interest. The considerable variability of appearance of potential scientific targets calls for well-adapted yet flexible techniques, one of them being *Deep Learning* (DL). Our "*Mars-DL*" (Planetary Scientific Target Detection via Deep Learning) approach focuses on training for visual DL by virtual placement of known targets in a true context environment. The 3D context environment is taken from reconstructions using Mars rover imagery. Objects of scientific interest, such as impact-characteristic shatter cones (SCs) from terrestrial impact craters, and/or meteorites, are captured and 3D reconstructed using photogrammetric techniques, providing a 3D data base of high resolution mesh and albedo map models. By placing the models randomly into realistic scenes using image rendering methods (Fig. 1), we create an artificial training data set, which is used to train the Deep Learning solution.

Background: Deep learning requires large amounts of training data to work reliably. In an ultimate planetary solution, many different geologic features are to be detected and to be trained for in a DL-system. Past and ongoing missions such as the Mars Science Laboratory (MSL) do neither provide the necessary volume of training data, nor existing "ground truth". Therefore, realistic simulations are required. The Mars-DL project follows this idea and intends to demonstrate the validity of using such simulations for real science assessment cases relevant for present and future planetary on-site exploration activities.

We aim at an efficient way to generate large amounts of images for the training of DL systems to support autonomous scientific target selection in future rover missions. This is based on available high resolution Martian surface reconstructions and newly created 3D models of objects of interest (shatter cones). This is established by means of PRo3D, an interactive viewer dedicated to planetary scientists for the virtual exploration and geologic interpretation of planetary surface reconstructions [1]. Within Mars-DL, PRo3D was extended for the efficient mass simulation of different DL training sets.

Shatter Cones on Mars: Shatter cones are a distinct geological features unique to impact cratering. On Earth, impact craters are difficult to distinguish from other geologic features, and, therefore, identification relies largely on the presence of evidence for shock metamorphism; during the impact of an extraterrestrial body, shock waves penetrate the target and pressures that are much higher than those of normal endogenic geological processes are created. Most shock metamorphic features are visible only under the microscope; however, shatter cones are the only macroscopic evidence of shock metamorphism [2].

Shatter cones are known from, and have been used in the identification of, many terrestrial impact craters [2]. A few rare cases of shatter cones are known from meteorites [3]. No shatter cones have yet been found on other planetary surfaces, although their possible presence in Curiosity Mars rover images was suggested [4]. However, the images were not convincing, possibly due to limited resolution. Thus, shatter cones on Mars have not yet been unambiguously identified.

Fig. 1. *Scanned shatter cone (false color) placed in realistic Mars image in a first step of the DL process.*

Method: The distinctive fan-shaped "horsetail" structures that characterize shatter cones, in the form of striations, make them suitable objects to train a DL-system and assess its detection reliability. As no shatter cones have yet been identified in real planetary imagery, no ground truth data are available to train a DL detection network. The creation of artificial visual samples based on real 3D models of shatter cones is, therefore, necessary. During impact, shatter cones form in the bedrock and usually occur within outcrops of exposed bedrock. As the realistic reconstruction of a large number of shatter cone outcrops was too challenging, we placed the SCs as float rocks as they also sometimes appear as impact ejecta or as fragments from outcrops.

For our work, about 25 terrestrial objects (SCs and meteorites) were imaged, each with several hundred photos under controlled illumination conditions. Many shatter cones from terrestrial sites have a contact surface, where they were broken or cut from the outcrop, and they often also bear an artificial label. This section of the surface must not be visible in training images, and is marked as part of the meta-data of the 3D model to keep it invisible during automatic positioning. Our data augmentation algorithm then places the scanned 3D representations of textured and properly colored SC objects into the real context of a Martian digital terrain model. This process can be repeated thousands of times in order to create a realistic image sample database, which can be used to train a visual SC detector using a DL system.

Fig. 2. *Example of SC embedded in Martian context.*

DL Simulation: Realism must be enhanced in order to achieve suitable images for training, which should resemble true rover imagery as closely as possible. High resolution digital terrain models (DTM) of the Martian surface usually have an image texture derived from rover instrument imagery. Their prebaked lighting effects, such as shading, shadows, and specular highlights, are determined by the sun's direction at the time of capture.

For a SC to perfectly blend into the scene, it first has to be color-adjusted to fit to the material properties of the surrounding landscape. Then it is shaded from the same illumination direction as the background scene. It is important that shadows cast by the shatter cones from this direction are also calculated, they contribute significantly to the realism of the final rendering. Also, sizes and rotation of shatter cones are randomly varied within the specified ranges, making sure that contact surfaces are not visible (Figs. 1, 2).

DL Inference Testing: We have used, among others, images of shatter cones placed in a Mars-analog environment (in a terrestrial desert, see [5]) as test images for the DL detection ("inference"), so far with ambivalent success, but clearly pointing the way forward for future work, hopefully being able to identify (*or at least call attention to*) objects being possible shatter cones in images from, e.g., the Mars 2020 or the upcoming ESA Mars rovers. This would help to generalize the "on the ground" identification of impact structures on a planet other than Earth.

Fig. 3: *Automatic recognition of a shatter cone placed in a Mars analog site (Danakil Depression, Ethiopia) [5], using the DL aproach described here.*

Summary and Future Work: Mars-DL has demonstrated the full workflow of simulation-based training and inference for autonomous scientific target detection in Planetary exploration environment. Future work to be done includes improvements in the similarity of appearance fidelity of background and objects, level of realism in rendering, embedding of objects in the background, variety of test cases and the choice of representative validation cases.

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