INSTANT AND INTUITIVE VISUAL EXPLORATION OF PLANETARY SPATIAL DATA

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Introduction: For the purposes of space exploration, reconnaissance field geologists have trained to become astronauts. However, the initial forays to Mars and other planetary bodies (except the Moon) have been conducted exclusively by robotic craft. Therefore, training and equipping a robotic craft with the sensory and cognitive capabilities of a field geologist to form a science craft is a necessary prerequisite. Numerous steps are necessary for a science craft to be able to map, analyze, and characterize a geologic field site, as well as effectively formulate working hypotheses.

The *Automated Global Feature Analyzer*^{TM} *(AGFA*^{TM}*)* [1, 2] is a generically applicable automated anomaly detection and target prioritization framework, which operates in the appropriate feature spaces for data delivered by one or more sensors aboard space craft. Imaged operational areas are locally processed via a cascade of superpixel-based image segmentation, visual and geometric feature extraction, feature vector generation, normalization, and clustering, followed by principal component analysis (Fig. 1). Every resulting cluster is compared to every other cluster, and each cluster pair is assigned two binary anomaly flags. The first, i.e., *ratio flag*, evaluates the number of regions contained in each cluster and is set to *anomalous* if one cluster contains $\alpha > 1$ times more members than the other. The second, i.e., *distance flag*, evaluates the relative positions of the centroid vectors of each cluster in the normalized feature space and is set to *anomalous* if the distance between the two cluster centroids exceeds the sum of the lengths of the respective first principal component vectors, which are indicative of the direction of largest change in each cluster. Finally, the two clusters are considered *anomalous* relative to each other if both flags indicate anomalies, *semi-anomalous* if only one flag indicates an anomaly, and *non-anomalous* if no flag indicates anomalies.

Anomalous regions may be considered immediate targets for follow-up in-situ investigation by local robotic agents, which can be directed via autonomous tele-commanding, e.g., as part of a *Tier-Scalable Reconnaissance* mission architecture [3, 4]. These capabilities will be essential for driving fully autonomous C^4ISR missions of the future, since the speed of light prohibits real-time Earth-controlled conduct of planetary exploration beyond the Moon.

Motivation for AGFA Visualization Framework AGFA_VIS^{TM}**:** As previously described, given an imaged operational area and a set of applicable features to be considered (e.g., color, albedo, texture, angularity, or hyperspectral information), AGFA segments an image into regions by iteratively fusing highly correlated neighboring superpixels, i.e., cluster-like regions based on the considered features, and quantifies the relative anomaly between each pair of clusters using the ratio and distance flags. To remove redundancy, the two flags can be aggregated into a confusion-type (NxN) matrix by placing the distance flag values in the upper triangle and the ratio flags values in the lower triangle (Fig. 2).

Because each of the N clusters is assigned (N-1) ratio and distance flags, each relationship requires two look-ups, which results in $(N^2\text{-}N)/2$ total connections. Consequently, manual analysis for determining the relationships between clusters is tedious and error-prone, especially as N increases. Correctly deriving the inter-cluster relationships requires careful analysis and can easily be mixed with previously calculated results. Though these relations can be computed aboard autonomous agents/spacecraft when prioritizing targets, on the occasion the data are downlinked to Earth in light of an intriguing discovery, a planetary field geologist may gain interpretable insight by visualizing the relationships between the objects in the imaged operational area (e.g., planetary field site). Up to now, the vital task of visualizing and interpreting AGFA's decisions has been done purely by hand, i.e., by looking at the confusion matrix (Fig. 2) to determine the degree of anomaly among the occurring clusters.

To that effect, the *AGFA Visualization Framework AGFA_VIS*^{TM} was devised to solve the problem of displaying the pairwise relations between the many clusters in an image without checking back and forth for the associated flags in the confusion matrix. It accomplishes this by creating an interface for visualizing and interacting with the clustering results in the spatial scene itself, i.e., the imaged operational area.

There are at least two tasks a user may want to perform: (1) identifying inter-cluster relationships and (2) identifying the spatial location of these clusters, hence addressing a challenge in *planetary spatial data visualization*.

Conventional ways to visualize matrices are node-link diagrams and adjacency matrices [5] (Fig. 3). Though node-link diagrams are great for path following, they are prone to clutter and lose a sense of the spatial location of the clusters. Adjacency matrices offer a dense representation that removes the clutter, but the relationships between links are hard to follow and the spatial locations of the clusters and cluster elements are still lost. Therefore, there is a need for a novel way to visualize the confusion matrix resulting from AGFA (Fig. 2) in an unconventional but intuitive and easy-to-use way: AGFA_VIS™.

AGFA_VIS™ is a Web-based visualization with one main view of the entire mapped area with interaction support that assists in finding the relations between the clusters while preserving and highlighting their spatial locations. This is accomplished by setting the *cluster of interest* to be the cluster that contains the region that the user is hovering over at any point in time, and dynamically modifying the remainder of the segmented regions of the mapped area to accurately convey their respective relationships to the cluster of interest. Configuring the visualization as a hover effect based on pre-segmented regions is key because it allows for quick exploration of inter-cluster relations in an instant and intuitive manner.

More specifically, when a region is hovered over and used to set the *cluster of interest*, it is outlined with a bold stroke, and all regions of the other clusters are recolored based on their respective level of anomalousness relative to the cluster of interest. In Fig. 4, e.g., there are a total of seven clusters, identified over 79 regions. The regions that compose the cluster of interest are colored gray. The remaining six clusters are considered *secondary clusters*: In case of an *anomalous* relation between the cluster of interest and respective secondary cluster, all regions of that secondary cluster are recolored to *red*, in case of a semi-anomalous relation to *orange*, and to *gray* for a non-anomalous relation.

AGFA_VIS™ Future Work: The development of a semantic-zoom feature in the visualization would allow the user to zoom into areas that are otherwise too small to view. Furthermore, the addition of a secondary, parallel view in which the original image (Fig. 1, left) is overlaid with the segmented region boundaries would give the user a spatial reference as to which geological structures AGFA clustered together in its analysis (e.g., the water ice patch inside the crater).

Discussion: AGFA_VIS™ serves as a tool that allows immediate (i.e., real-time), intuitive, and visual exploration of otherwise abstract planetary spatial data (e.g., in form of confusion matrices) that describe relationships between locales and regions on planetary surfaces. Furthermore, the combination of AGFA™ and AGFA_VIS™ has the potential to save a significant amount of time for exploring planetary spatial data, as it completely bypasses the laborious manual data entry that is required for existing Geographic Information Systems (GIS). In case of geologic field-exploration on Earth, AGFA_VIS can serve as an instant and interactive tool for field geologists to facilitate decisions and to generate working hypotheses [6], e.g., as part of an Augmented Reality (AR) setting.

References: [1] Fink W. et al. (2018) *Proc SPIE*, doi.org/10.1117/12.2303795. [2] Fink W. et al. (2008) *Proc IEEE*, doi:10.1109/aero.2008.4526422. [3] Fink W. et al. (2005) *PSS*, 53, 1419–1426. [4] Fink W. et al. (2008) *Nova Science*, ISBN: 1-60021-826-1. [5] Shen Z. & Ma K. (2007) *EuroVis*, 83-90. [6] Chamberlin TC (1890) *Science*, 15, 92–96.

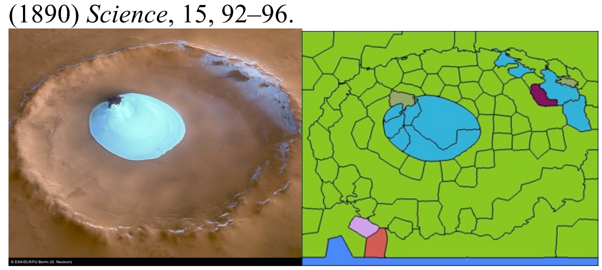

Fig 1. *Left:* Mars crater with water ice deposit imaged by Mars Express. *Right:* Corresponding AGFA™ clustering result.

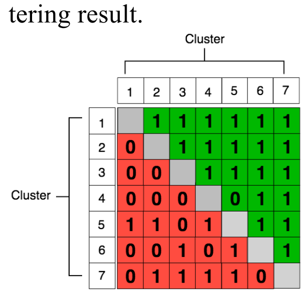

Fig 2. Confusion matrix: each cell describes the relation between the respective row/col clusters.

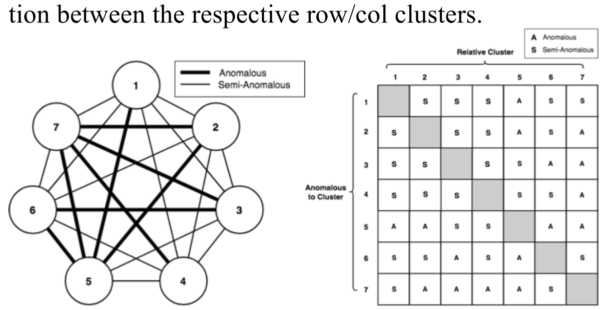

Fig 3. *Left:* Node-link diagram representation. *Right:* Adjacency matrix of the given data in Fig. 2.

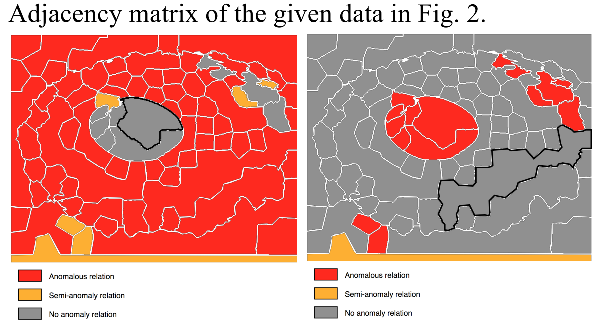

Fig. 4. *Left:* Crater ice deposit selected (black outline). *Right:* Background region selected (black outline).