MAWSON THE ASTROBIOLOGIST ROVER: TOWARDS AUTOMATIC RECOGNITION OF STROMATOLITES

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ABSTRACT

This work aims at developing a planetary rover capable of acting as an assistant astrobiologist: making a preliminary analysis of the collected visual images that will help to make better use of the scientists time by pointing out the most interesting pieces of data. This paper focuses on the problem of detecting and recognising particular types of stromatolites. Inspired by the processes actual astrobiologists go through in the field when identifying stromatolites, the processes we investigate focus on recognising characteristics associated with biogenicity. The extraction of these characteristics is based on the analysis of geometrical structure enhanced by passing the images of stromatolites into an edge-detection filter and its Fourier Transform, revealing typical spatial frequency patterns. The proposed analysis is performed on both simulated images of stromatolite structures and images of real stromatolites taken in the field by astrobiologists.

1. INTRODUCTION

Over the last 15 years, several rovers have been sent to Mars in search of signs of life. Traditionally, planetary rovers have had limited autonomy, achieving short daily missions, mainly reduced to executing a short path from their original location to a pre-defined goal. Scientists on Earth would then observe pictures taken by the rover to estimate the potential interest of rocks in regards to astrobiology. However, the actual performance of the Mars Exploration Rovers Spirit and Opportunity is inspiring more ambitious missions in the future, of both longer duration and a higher degree of autonomy.

With an increased length and complexity of missions comes an increased volume of data (e.g. number of pictures taken) collected by the rover, which can make the task of analysing every single snapshot impractical for scientists. Therefore, future projects involving longer-term missions call for a rover capable of acting as an assistant astrobiologist: making a preliminary analysis of the collected images that will help to make better use of the scientists time by pointing out the most interesting pieces of data.

Figure 1. Planetary rover "Mawson" shown in the Mars Yard at the Powerhouse Museum in Sydney, Australia.

This research concerns the development of the Mawson rovers capabilities as an assistant astrobiologist. Mawson is a prototype planetary rover developed at the Australian Centre for Field Robotics. It is exhibited at the Powerhouse Museum in Sydney, Australia, where it operates in a special area designed to simulate typical Martian terrain (see Fig. 1). It is currently working towards the automatic recognition of stromatolites from visual images acquired in the field.

This paper focuses on the problem of detecting and recognising particular types of stromatolites. Inspired by the processes actual astrobiologists go through in the field when identifying stromatolites, the processes we investigate focus on recognising characteristics associated with biogenicity, including a columnar or domal morphology, the presence of lamina walls and inter-stromatolite detrital infill, discontinuous laminae of variable thickness, and the geometries of conical stromatolites. The extraction of these characteristics is based on the analysis of geometrical structure enhanced by passing the images of stromatolites into an edge-detection filter and its Fourier Transform, revealing typical spatial frequency patterns.

The proposed analysis will be performed on both simulated images of stromatolite structures and images of real stromatolites taken in the field by astrobiologists, primarily in Western Australia. As part of this evaluation, the relevance and performance of the features considered for the recognition process will also be discussed.

The remaining of the paper is the following. Section 2 discusses characteristics of stromatolites that astrobiologists look for in the field, in particular those associated with biogenicity. Section 3 proposes machine vision techniques to automatic recognise some of these characteristics in visual images. Finally, Section 4 provides concluding remarks and elements of future work.

2. RECOGNISING STROMATOLITES

Stromatolites as referred to herein are layered sedimentary structures produced by sediment binding, trapping and/or precipitation as a result of the growth and metabolism of microorganisms (cf. [1]).

Stromatolites are the most widespread macroscopic biosignatures for life during the Precambrian, the period of geologic time covering nine tenths of Earth history, during which life was limited to microscopic organisms. Considering the evolutionary history of life on Earth, it seems likely that extraterrestrial life, if discovered, will also be microscopic. Accordingly, as astrobiologists begin to explore potential past and present microbial habitats beyond Earth, the recognition and interpretation of microbial biosignatures, including stromatolites, is set to become increasingly important.

Any autonomous stromatolite recognition system must be able to distinguish stromatolites from images of superficially similar abiogenic sedimentary features. Human palaeontologists can recognise stromatolites in the field based on the appearance of outcrop, yet difficulties are still encountered and the biogenicity of some ancient stromatolites is debated eg. [2, 3, 4]. Moreover, human palaeontologists on Earth enjoy the considerable advantage of laboratory study of collected samples, a capability unavailable to autonomous systems deployed in the field.

Despite these difficulties, a system capable of recognising putative stromatolites within a background of other laminated sedimentary rocks seems achievable. Ideally, a three dimensional model of a stromatolite is inferred from the study of several perpendicular cross-sectional views. This would likely be unachievable in the case of a rover. We have thus focussed on features able to help such a system distinguish putative stromatolites from a laminated sedimentary background on the basis of an image of a single cross-section. Some of these features include the overall morphology; variable thickness and discontinuity of laminae; relationships with associated lamina walls and interstromatolite detrital infill and; the geometry of conical stromatolite laminae

Stromatolites occur in myriad morphologies, including stratiform, domical (Fig. 2) and conical (Fig. 3) shapes.
In the case of stratiform and low-relief stromatolites, identification based on morphological characteristics can be difficult or impossible. Stromatolites with topographic relief offer more morphological information on which to base an analysis, but these shapes may be confused with common sedimentary features such as soft sediment de-

Figure 2. Vertical section through a large domical stromatolite in a planar laminated carbonate background. The image figures a lens cap for scale. Tumbiana Formation, Fortescue Group, Western Australia.

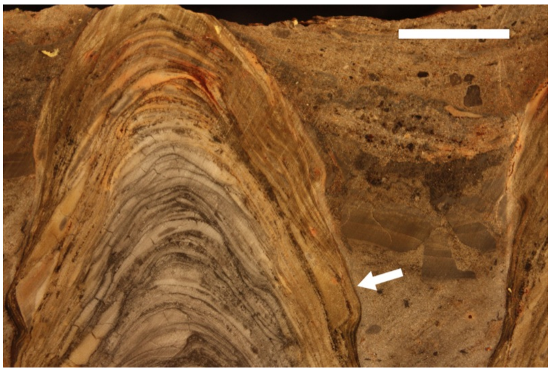


Figure 3. Cut slab showing a vertical section through two conical stromatolites. Note laminae walls (white arrows) and onlapping detrital sediments. Scale bar = 2cm. Tumbiana Formation, Fortescue Group, Western Australia.

formation, folding (Fig. 4) and ripple cross-stratification (Fig. 5).

Figure 4. Tectonic folding appearing superficially similar to conical stromatolites. Joffre Member, Brockman Iron Formation, Hamersley Group, Western Australia.

Figure 5. Laminated columnar stromatolite (below), overlain by climbing ripple cross-stratification (above). Tumbiana Formation, Fortescue Group, Western Australia.

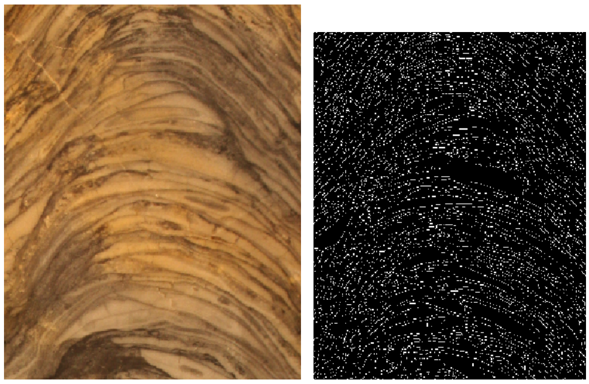
The discontinuity of stromatolitic laminae is in contrast to the continuous laminae of many common laminated but abiogenic sedimentary features. In stromatolites, where lamina growth is initiated and controlled by the presence of a biofilm or microbial mat, interstromatolite areas often comprise detrital grains of a different size, composition, porosity, colour, and/or lamination (Figs. 3, 5). Stromatolitic laminae may terminate in a sharp boundary comprising a wall of laminae (Fig. 3), with surrounding sediments onlapping the structure (Figs. 3, 5).

Conical stromatolite geometries are often considered more reliable indicators of biogenicity as there are relatively few abiogenic sedimentary features for which they may be mistaken. In particular, the laminae of some conical stromatolites are thicker in the central axis of the stromatolite than on cone flanks. This thickening of the laminae is known as the axial zone and is thought to result from microbial growth and motility [5]. In addition, the minimum steepness of the laminae can be calculated from vertical cross-section, and where the value is steeper than the angle of repose for particulate sediment (see [6]), the biogenic interpretation is strengthened. Fig. 3 represents an ideal case; a conical stromatolite characterised by laminae steeper than the angle of repose for particulate sediment, with distinct lamina walls, and interstromatolite fill composed of onlapping detrital grains.

3. AUTOMATIC RECOGNITION USING MACHINE VISION

3.1. Edge Extraction

Since the main feature of stromatolites is the laminae, the first type of visual characteristic that an astrobiologist would consider is lamina structure. Therefore, a natural first step for a machine vision algorithm is to extract this structure using an edge detection filter. Using a Sobel filter, the stromatolite image (like the example in Fig. 6(a)) can be converted into an edge image. However, despite the use of a cut block, the quality of the images and the presence of additional features such as saw scratches result in rather noisy images and the laminae themselves are often broken into pieces rather than forming a continuous edge. The human eye is able to discern the laminae in the edge images obtained but tuning the thresholds applied on the Sobel image resulted in either too much noise or too few edges detected. In order to improve these results,



(a) Original image (b) Canny image

Figure 6. Example of colour image of columnar stromatolite and the corresponding image after application of the Canny filter for edge detection.

the Canny filter was used with a relatively high Gaussian sigma value of 2 and threshold values of 0.07 and 0.15 in MATLAB [11] in order to remove the smaller microedges in favour of the macroedge laminae as shown in Fig. 6(b). This still left laminae split into pieces instead of being continuous and was still not completely successful in eliminating all of the noise. The problem is that although laminae are relatively large edges, within the laminae are smaller features that are preferentially passed by the filter. This problem is further compounded by the fact that different stromatolites, even those within the same image, can vary significantly in their reaction to the canny filtering.

3.2. Detecting Possible Stromatolite Columns

Columnar stromatolites are characterised by convex laminae and vertical accretion from a flat surface. Laminae shape is typically highly inherited relative to the underlying laminae, and laminae are often closely spaced towards the edge of the column, comprising a “wall”. This means that stromatolitic columns will often appear in cross section as an inherited column of stacked horizontal edges bounded by vertical walls. We found that the

Figure 7. Broad Stromatolite Image.

horizontal edges can be isolated by passing a thin ideal fan filter of width 10 degrees as seen in Fig. 8. This

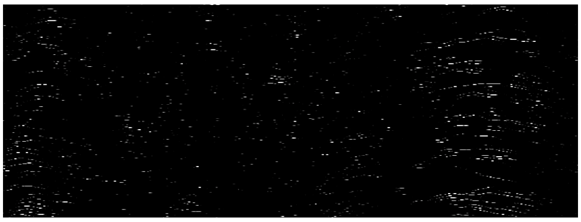


Figure 8. Horizontal Line Filtered Edge Diagram - Broad.

isolated the horizontal and near horizontal lines as seen in Fig. 9. This image can then be filtered with an averaging filter (of large size, 20 pixels square was used here) which reveals locations of high horizontal edge density. Using these horizontal edges as a starting point, the

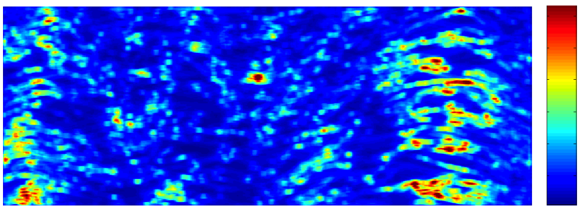


Figure 9. Horizontal Line Density Map.

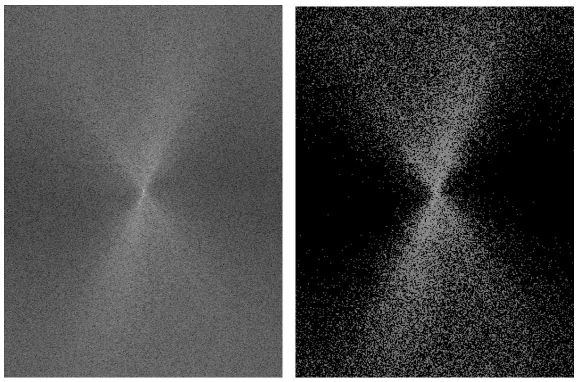
laminae were traced outwards by taking all points that were above a high threshold (80% of the maximum density was used here) and finding all connected points that were above a lower threshold (50% of the maximum was used here). The result was Fig. 10 which gives regions of possible stromatolite axes which can then be tested for variable laminae thickness and convexity. Note that de-

Figure 10. Laminae Expansion Diagram.

tected column on the far right of the figure corresponds to the extracted candidate stromatolite sample shown in Fig. 6(a).

3.3. Assessing Stromatolite Columns

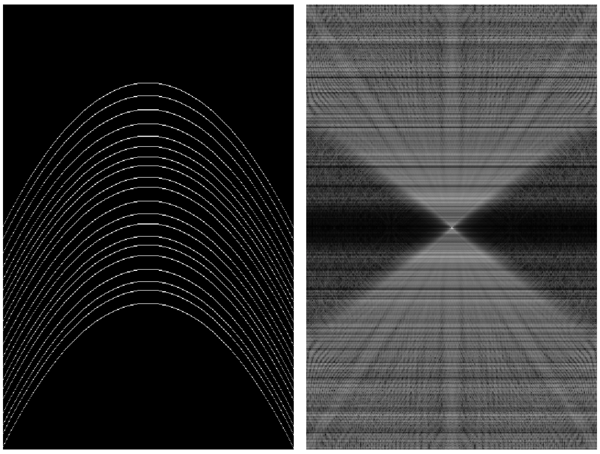
After possible columnar stromatolites have been found, the edge images were converted to frequency space using an FFT which yielded the (contrast enhanced) power spectra as seen in Fig. 11 (with application of a logarithmic contrast enhancement to help visual illustration). The convex lamination of stromatolites results in a “fan” shape, with the edges of the fan describing the limits of the angles composing the convex laminae of the stromatolite. This fan shape is clearer on the thresholded FFT spectrum shown in Fig. 11(b). It was obtained by thresholding the image with only the points with more than the median intensity retained.



(a) FFT (b) Thresholded FFT

Figure 11. FFT Spectrum of the edge image of Fig. 6.

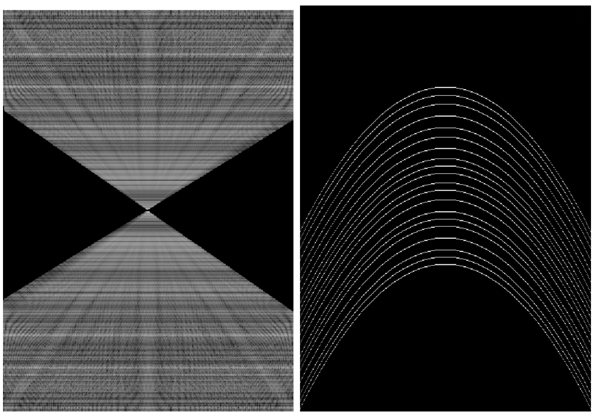
In order to verify this result we created a model of the stromatolite structure and obtained the FFT and compare the results. We used a simple model comprising of a series of parabolas separated by a constant distance (see Fig. 12(a)). This yielded an FFT (Fig. 12(b)) characterised by a similar fan shape. Varying the parameters of our model revealed that the width of the fan is dependent upon the component laminae angles, meaning the extremities of the fan correspond to the extremities of laminae convexity. Knowledge of the extremities of the fan thus allows detection of columnar laminae steeper than the angle of repose for particulate sediment, which is a useful indicator of biogenicity.



(a) Stromatolite Edge Model (b) Stromatolite Model FFT

Figure 12. Computer generated model of the stromatolite structure and its Fourier Transform.

Isolating the fan shape in the frequency space with a filter and then converting back to image space showed that difference was imperceptible and that all the useful information was contained within this fan. There was no perceivable pattern to the phase component of the FFT.



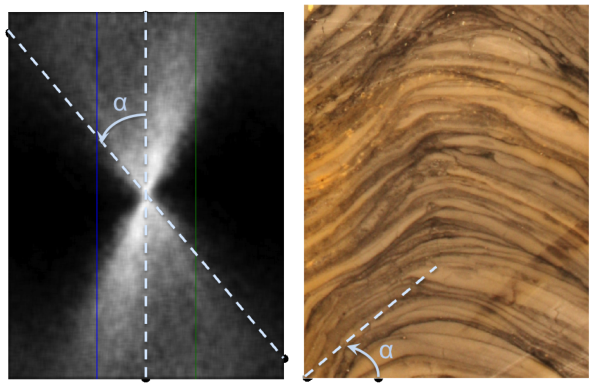
(a) Trimmed FFT of Stromatolite Model (b) Recovered Structure Model

Figure 13. "Ideal" FFT and recovered structure model.

Therefore, once regions of interest (ROI) containing columns that are considered as possible stromatolites have been found, the ROI is passed through a Canny filter to extract the structure, then converted to frequency space which will be searched for the distinctive fan shape.

3.4. Angle of Repose

To better identify the limits of the fan shape in the FFT spectrum, the thresholded FFT shown in Fig. 11(b) was smoothed by averaging (to reduce noise and produce a continuous distribution with a mask size of 20 pixels square). This creates a sharp gradient in the vertical direction for some parts of the fan shape. The result is shown in Fig. 14, where the visible limit of the fan shape gives an evaluation of the maximum angle of steepness in the laminae structure. The equivalent angle is also illustrated on the original colour image of the stromatolite. This max-



(a) FFT (b) Original

Figure 14. Approximate maximum angle of steepness of the laminae $\alpha = 40°$ as identified on the FFT (a) and shown on the original image (b).

imum steepness was evaluated at about $\alpha = 40°$. Since sand has an angle or repose of about 30°, it is extremely likely that this laminae has been formed by biotic processes. Therefore, there is strong indication that a stromatolite has been found.

3.5. Convexity of the Laminae

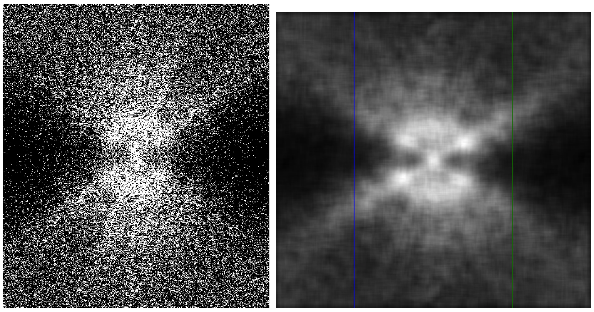
The process we propose will be illustrated with the example of stromatolite column candidate in Fig. 15(a), that was extracted from a larger rock cross-section (Fig. 15(b)). As mentioned earlier, the limits of the fan shape are necessary to constrain the features of the stromatolite and can be obtained by thresholding the edge-filtered image and smoothing the resulting image (see Fig. 16).

Fig. 17 shows the profiles of intensity along the blue and green vertical lines of Fig. 16(b). The limits of the fan are clearly visible. Taking the derivative of the intensity over these vertical allows to identify the limits of the fan shape that we need.

If corresponding slices are taken an equal distance away from the centre (i.e. frequency 0), then the distance between the graphs is an indication of the orientation of the entire fan shape.

(a) (b)

Figure 15. Potential stromatolite column (a) extracted from the full picture in (b) (blue rectangle).



(a) Thresholded FFT (b) Smoothed

Figure 16. FFT of the edge image. Note the fan shape of the Fourier Spectrum. The vertical blue and green lines in (b) were added for illustration (see Fig. 15(a)).

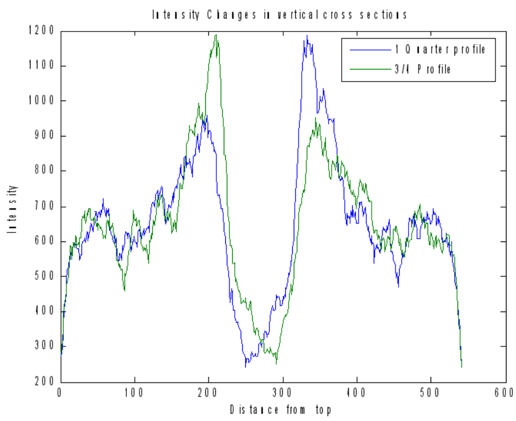
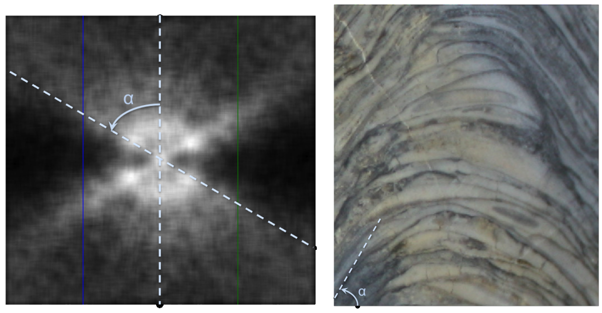


Figure 17. Intensity changes in Vertical Cross sections along the blue and green vertical lines shown on Fig. 16(b).

So far, this process may select concave and convex shapes alike, Since laminae of stromatolites are convex, concave shapes need to be distinguished and removed. In a convex shape, the centre would be horizontal and the edges on the left and right would curve downwards (i.e. they would have a specific general direction in which they face), as opposed to concave shapes which curve upwards. They can be differentiated by isolating the left part of the laminae and finding the direction they face from the FFT and repeating for the right side.

Note that the maximum steepness for this candidate stromatolite was evaluated at about $\alpha = 60°$ on the FFT (see Fig. 18). Once again, the high steepness of the laminae is



(a) FFT (b) Original

Figure 18. Approximate maximum steepness angle of the laminae $\alpha = 60°$ as identified on the FFT (a) and shown on the original image (b).

an additional strong indication of biogenic content.

4. CONCLUSION

4.1. Discussion

This is a preliminary study in the direction of our goal to endow planetary rovers such as Mawson with some of the skills of human astrobiologists. Our approach is promising for specific types of stromatolites, namely columnar and conical stromatolites with lamina walls.

However, the stromatolite images used in this study were taken in the most favourable conditions. We also used cut slabs of known horizontal sections in order to test our initial concepts. Real imagery from Mars would be considerably more challenging. A natural next step would be to adapt the techniques presented here to a larger library of "noisier", real-world imagery obtained in the field.

4.2. Future Work

In this paper, a method to determine the parameters of the "fan shape" of the FFT has been discussed, however, it requires a prior determination that the shape found in the FFT image is a fan indeed. This prior step constitutes one of the main items for future work. An improved method for clustering the side laminae also needs to be developed.

Additional avenues of investigation include the differences in colour and grain size between stromatolites and detrital fill. Remote sensing data could be used to determine associated lithological differences and rule out putative stromatolites in non-prospective settings, for example in volcanic rocks.

ACKNOWLEDGMENTS

This work was supported by the Australian Research Council, the Australian Space Research Program Stream A, Pathways to Space: Empowering the Internet Generation, the Australian Centre for Field Robotics and the Australian Centre for Astrobiology.

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