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# AUTOMATIC POINTING AND IMAGE CAPTURE: A FIELD STUDY

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## ABSTRACT

APIC (Automatic Pointing and Image Capture) is an automatic algorithm capable of identifying potential imaging targets in a single WAC (Wide Angled Camera) image and then reimaging these targets using a HRC (High Resolution Camera). Its aim is to maximise science data return from a rover exploration platform whilst minimising ground-based human intervention. This paper discusses APIC in a fieldwork context. Fieldwork has been undertaken in an effort to improve APIC's mission readiness. This paper discusses the issues that arose during the preparations to take APIC into the field and the lessons learned from early results that were gathered.

## 1. INTRODUCTION

APIC's goal of maximising science data return whilst minimising ground-based human intervention is very desirable for future robotic exploration such as the ESA/NASA ExoMars mission (launch 2018), and the subsequent Mars Sample Return mission. These are rather more ambitious than their predecessors and will require the rovers to travel further and faster than has previously been achieved. With this in mind it is vital that any avenues capable of increasing the rate of use-full science return be investigated. APIC is one such strategy. It was developed by the Space and Planetary Robotics Group at Aberystwyth University (AU) as part of the work associated with the ExoMars PanCam instrument and the EU FP7 PRoViScout project. APIC has been shown to be capable of increasing the rate at which useful images can be gathered by reducing the pauses in activity introduced by substantial communication distance. The feasibility and use of APIC is discussed in [1], [3]. Up until the time of [1] and [3] APIC had only been developed and tested in a laboratory environment, although this provided an ideal location for initial experimentation. APIC had reached a stage where real field trails were necessary to increase its technology readiness. A number of issues were identified during these field trails. Some of these issues were automatic parameter generation, pointing calibration, pointing error minimisation and WAC filter selection. It was also necessary to design an appropriate user interface for use in the field and carry out some algorithm optimisation to ensure APIC's suitability on a representative platform. These issues had to be overcome before APIC could be properly exercised in a realistic field environment. This paper discusses two initial field campaigns. The experimental hardware and the key problems encountered are also discussed.

Figure 1. Idris. AU's robotic platform at Site 1.

## 2. FIELD LOCATIONS

Preliminary APIC experimentation took place at two field locations, with additional unstructured testing also being carried out with available Mars Exploration Rover (MER) image samples. The two sites were chosen because of their natural diversity, suitability for robotic exploration and their similarity to known sites on Mars. The sites chosen are diverse in nature, one contains a surplus of targets while the other contains only a limited number of targets. This choice was made in an effort to exercise the rock detection aspects of APIC in a technically challenging environment.

### 2.1. Site 1 (Rocky Site)

Clarach Bay, Aberystwyth, Wales, was selected as the first field site. This site was selected as the complex field site. Clarach is a very challenging site for sample selection because of its rocky nature and the abundance of possible targets. Potential targets range in size from mm to meters and provide abundant diversity in shape and colour. The geology of these targets is not representative of a Martian site, but for the purposes of this study, the accessibility, diversity and sample richness of the site make it very suitable. Clarach Bay has also recently been identified as a suitable Mars analogue for robotic experimentation. This assessment has been carried out as part of the on-going European Framework 7 project called PRoViScout [2]. Fig. 1 shows the Aberystwyth University (AU) ExoMars

PanCam emulator installed at a representative height on Aberystwyth's Robotic platform (Idris).

### 2.2. Site 2 (Sandy Site)

Ynyslas, Borth, Wales has been selected as the second site for field experimentation. It is being considered as an analogue of a sandy site on Mars. Again, the geology of this site is not representative of a sandy site on Mars, but it presents a good visual analogue of a sparse site, with strewn bolder fields. This is an ideal site as it is similar to the type of target site that APIC was designed for. In this environment sand would occupy 70-80% of captured images.

### 2.3. Unstructured Testing

It has not been possible at this point to fully test the complete system in all representative locations. However in an attempt to raise the technology readiness of the rock detection elements of APIC, it has been exercised on a number of images returned during the NASA MER missions. These representative images are very useful as they enable the rock detection algorithm to be exercised with images of the "real" target environment. Unfortunately NASA has processed these images before their release, making the images different in nature from the ones captured by the AU PanCam Emulator. This difference is unavoidable at this stage but effort has been made to make all images as consistent as possible.

Figure 2. Idris. AU's robotic platform at Site 2.

## 3. AU PANCAM EMULATOR

AU's involvement with the ESA/NASA 2018 ExoMars mission has led to the production of a representative optical bench housing two WACs with a separation of 50cm. A HRC is mounted to the right of the optical bench. The optical bench is mounted upon a PTU (Pan Tilt Unit) with sub-degree accuracy.

Several issues however had to be resolved before the transition into the field could be properly realised. Two of these relate directly to the optical bench. These are accuracy of camera pointing and the selection of an appropriate filter for the initial WAC imaging.

### 3.1. AU ExoMars PanCam emulator specifications

The AU ExoMars PanCam emulator comprises an optical bench built from ThorLabs XT34 Optical Construction Rail. This Aluminium rail provides an ideal balance between weight, rigidity and configurability. Mounted on the optical bench are two ImagingSource DMK31BF03 Firewire cameras. These cameras have a resolution of 1024 x 768 pixels and are fitted with an 8mm lens. The 8mm lens is used to match the $34^{o}$ field of view achieved by the ExoMars WACs. With this setup the cameras will have a pixel field of view of 0.608 milliradians (see [3] appendix E for more information). This means that at a distance of 10 meters from the target each pixel will represent 6.08mm. In front of each WAC there is a multi-spectral filter wheel. This filter wheel contains optical filters to constrain the bandwidth of light allowed to pass through to the cameras. Tab. 1 shows the optical properties of the filters adopted as part of the AU emulator, they represent an early filter set proposed by the PanCam science team. The ExoMars filter selection has since been refined [4].

Table 1. Filters incorporated in AU WAC filter wheels.

| Filter Position | Centre Wavelength [nm] | Pass Band [nm] | Type |
|---|---|---|---|
| Left 1 | 460 | ~100 | Blue Colour |
| Left 2 | 550 | ~100 | Green Colour |
| Left 3 | 660 | ~100 | Red Colour |
| Left 4 | 440 | 10 | Geology 1 |
| Left 5 | 470 | 10 | Geology 2 |
| Left 6 | 510 | 10 | Geology 3 |
| Left 7 | 560 | 10 | Geology 4 |
| Left 8 | 600 | 10 | Geology 5 |
| Left 9 | 660 | 10 | Geology 6 |
| Right 1 | 460 | ~100 | Blue Colour |
| Right 2 | 550 | ~100 | Green Colour |
| Right 3 | 660 | ~100 | Red Colour |
| Right 4 | 720 | 10 | Geology 7 |
| Right 5 | 760 | 10 | Geology 8 |
| Right 6 | 830 | 10 | Geology 9 |
| Right 7 | 880 | 10 | Geology 10 |
| Right 8 | 950 | 10 | Geology 11 |
| Right 9 | 1000 | 10 | Geology 12 |

Also mounted upon the optical bench is an ImagingSource DFK31BF03-Z2 camera. This camera is a colour zoom camera and is used to emulate the HRC intended for the ExoMars mission. The camera utilises the same CCD sensor as the WAC emulators meaning that the resolution of the camera stands at 1024 x 768 pixels. The camera's motorised zoom is capable of travelling from f = 5mm to f = 45 mm making this camera more than capable of emulating the $5^o$ field of view proposed for the true HRC.

### 3.2. Camera Pointing Accuracy

The accuracy with which the camera can point at a target is significant. When APIC was first developed the PTU that was used to work along with it was made in house by AU technicians using hobbyist radio-control parts. As such it only had an accuracy of +/- 2 deg. This initially caused few problems, but as the scale of the target area increased the allowable margin for error decreased. This resulted in the need for a more accurate and reliable PTU. A commercial PTU produced by Directed Perception was selected. The PTU is capable of speeds of up to sixty degrees a second and can attain a resolution of up to 0.012857 of a degree. It has a maximum load capacity of 9 lbs. The Tilt Range is from 47° down (this can be extended to 80°) to 31° up. Pan Range is ±180° giving a full 360° rotational range.

### 3.3. Heuristic to Improve Pointing Accuracy

APIC's trigonometric calculations rely on three assumptions; that the ground plane is flat, parallel to the rover floor plane and that all targets lie on the ground plane. Of course in reality this will rarely be the case so some error will always be introduced by this inaccuracy. In practise this error is in the majority of cases well within tolerances. However, during early field trials it was discovered that if a target is tall and thin the HRC was often pointed high and off centre. This error was found to be a result of the simplistic assumptions made by the APIC system, primarily the assumption that all targets lie in the ground plane. In the target environment the majority of targets stand proud of the ground plane. In an attempt to minimise the error caused by this assumption, a heuristic correction was implemented. Instead of only calculating the centroid of the target region, APIC also notes the highest and lowest points. These points are then used to calculate the location of the lower quartile of the target. APIC then points the HRC at the lower quartile of the target rather than the centre (see Fig. 3). This heuristic provided notable improvement for targets that stood significantly proud of the ground plane.

### 3.4. Filter Selection

Fig. 4 shows images captured through the three broadband filters fitted on the right WAC. As is the case with current proposed rover missions, the cameras on board the rover are not capable of capturing full-colour images with a single exposure. Rather optical filters are utilised to maximise the science potential of the camera

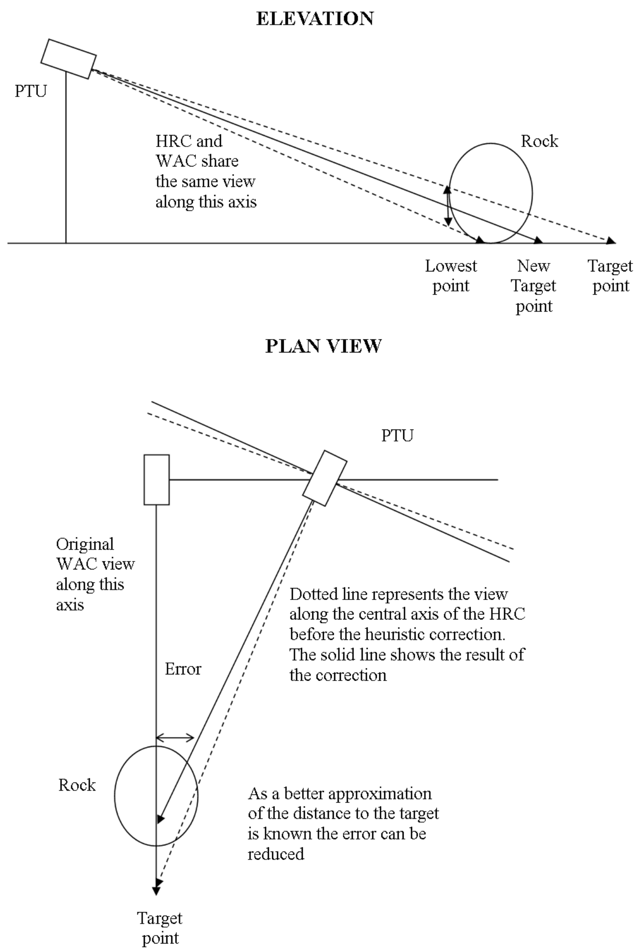


Figure 3. Illustration of heuristic correction applied to APIC.

system, enabling the capture of multi-spectral information. This means that it is necessary for APIC to use one of these optical filters rather than a true grey-scale image. As can be noted from Fig. 4, variations in the contrast between the three images can be substantial. Initially the green filter has been used as it generally allows the greatest amount of light through. However if the predominate colour of the scene changes the red filter can on occasion provide better results. Despite this the default filter used by APIC is the green filter with a centre wavelength of 550nm and a pass band of 100nm.

## 4. AU ROVER PLATFORM

In an effort to make the field trials as representative as possible, the AU rover platform (Idris) was fitted with the AU PanCam emulator. The emulator was mounted at a representative height for the 2018 ESA/NASA ExoMars rover mission. Idris is a 4 wheel drive, 4 wheel steering, electric vehicle, weighing about 350kg. It has a maximum driving at speed of around 10km/h. Its maximum payload is 150kg and it is comparable in size to a small car. It was initially based on a robuCAR TT design but with some notable additions.

Idris is equipped with:

- A 6DOF lightweight arm with a gripper.
- A Panoramic camera mounted on a stabilised 2-axes platform.
- A selection of additional sensors such as a GPS receiver, an inclinometer and a digital compass.

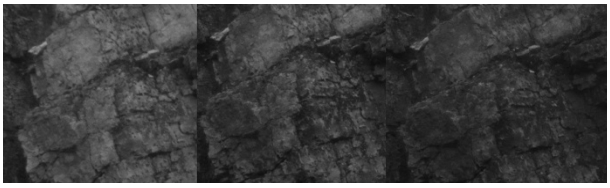

Figure 4. Images of a rock captured by Right Filters 3, 2 and 1 respectively.

## 5. ALGORITHM IMPLIMENTATION

APIC has been developed with the intention of being a lightweight piece of software that could be deployable on board a representative rover system. Early prototypes of the system were developed in Java with only a superficial concern for optimisation. As such they were relatively slow and somewhat memory-intensive. Based upon the results achieved by the APIC system in [1], a decision was made that in advance of field-testing the algorithm would be re-implemented. This would be done with the intention of optimising performance and preparing the algorithm for the target platform. The target platform in this case was to be approximated by a Pentium 1 laptop running openSUSE 10.2 with a 133MHz processor and 80 Mb of ram. It was also thought to be important that APIC be as deterministic as possible. In situations where it is not possible to calculate the specific resource requirements in advance, constraints would be put in place to limit processing time and memory use.

Table 2. Performance statistics for optimised algorithm implementation.

| Running times for: | Scaled image @ 512 x 386 pix | Full size image @ 1024 x 768 pix |
|---|---|---|
| Region detection | 2.663s | 13.304s |
| 3D coordinate calculations | 0.033s | 0.033s |
| Pan tilt calculations | 0.032s | 0.032s |
| Peak memory usage (including input image) | 700KB | 2.7MB |

### 5.1. Code Optimisation

APIC was re-implemented in the C programming language. The entire program was optimised into less than 900 lines of code. APIC's region growing algorithm uses no floating-point variables or operations. Tab. 2 shows the performance statistics achieved by APIC when deployed onto our target platform. Although this target platform is not representative of a "real mission platform", it is sufficiently resource starved to provide an indication of the feasibility of using APIC with a "real mission platform".

### 5.2. Automatic Parameter Generation

In order to deploy APIC in the field without the aid of a human operator, it was necessary to develop a basic algorithm, which could calculate the "region threshold" input. APIC uses the region threshold during the region detection process (for more information see [1]). During experimentation in the laboratory this threshold value could be kept fairly constant, but it was soon realised that in the field the values need to be changed substantially depending upon the environment. The need for a human operator to specify this value would reduce the benefit of the system.  It was also very important that the calculation of this value did not significantly add to the complexity of the system, and that it relied upon no more information than the image already supplied. Many different approaches were experimented with, with varying success, but eventually a statistical approach was investigated. The approach eventually settled upon utilised the standard deviation of the image to provide an indication of the image's variation and complexity. In order to attain the target range the standard deviation of the image pixel value is multiplied by 2.5. Checks are then carried out to ensure that the value is not below 10% or above 60% of the maximum pixel value; if they are, then they are clamped to these values. This is a very simplistic approach and adds very little complexity to the algorithm.

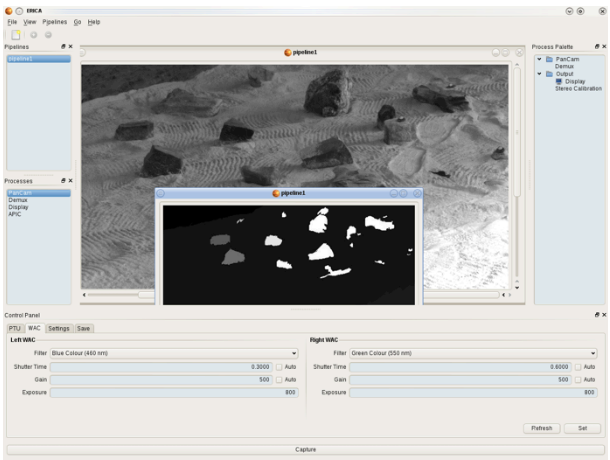

Figure 5. Screen shot of APIC running within ERICA.

### 5.3. Appropriate User interface

In the field, complex human computer interaction is challenging. So a simple yet effective user interface was needed to deploy the APIC system. It is also important that all command history and intermediate data products be logged for debugging purposes. This information can prove useful if unexpected results are returned.

In order to accomplish this ERICA was produced by Aberystwyth University's Space and Planetary Robotics group (see Fig. 5). This software has been designed to provide a simple image processing architecture, within which various image processing tools could be deployed. Erica has been developed in the Python programming language, making it very portable and versatile.

## 6. SUMMARY OF RESULTS

APIC performed well in the two target environments, at this stage no statistical analysis of the performance has been carried out (this will be presented in future publications). This paper will present a brief summary of some of the data captured during early field trials at the two sample sites. Also to be presented in this section are the results of running APIC on images returned from Mars during the NASA/JPL MER mission.

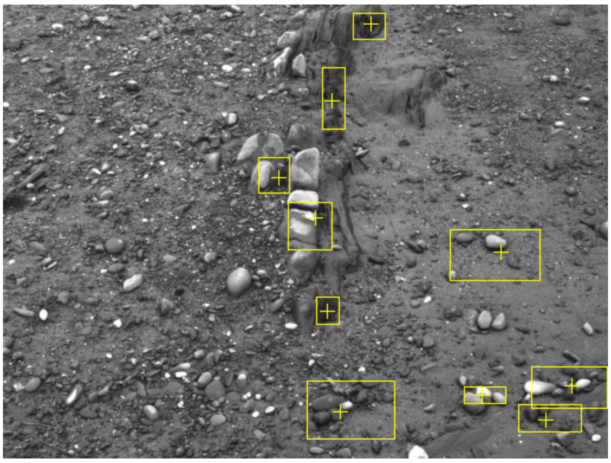

Figure 6. Site 1 Image. APIC identified centroids of the 10 largest targets.

### 6.1. Site 1 (Rocky Site)

Site 1 can be considered as a challenging scene for APIC. This site had so many potential targets that even random sampling could have produced reasonable results. However in this case APIC is able to enhance these results by ensuring that the targets imaged are distinctive and are of sufficient size to be of interest. Fig. 6 shows a WAC image captured from site 1. Marked on this image by yellow boxes are the 10 largest targets identified by the APIC system. The cross in each box represents the pixel centre of area of the detected target, whereas the box surrounds the boundaries of the detected targets. HRC images of all these targets were captured successfully and the first six of these can be seen in fig 7. These Images were all captured on-board the AU rover platform Idris. An image of this setup can be seen in fig 1 or 2.

As can be seen from Fig 6, APIC failed to identify the 10 largest targets correctly. However, it has been able to identify 10 good potential targets. In a scene this complex this is a satisfactory result. APIC uses few more resources that a random sampling system would, but removes the need for any random element. This ensures consistency and significantly reduces the risk of valueless images.

Figure 7. Site 1. APIC captured HRC images of the first 6 targets from top to bottom.

### 6.2. Site 2 (Sandy Site)

Site 2 is more representative of the target environment on Mars. It comprises a sandy terrain with a number of strewn bolder fields. Unfortunately however this site is very popular with local residents and is very difficult to restrict. Therefore there are a number of footprints in the sand, which have affected preliminary results. It is hoped that at a later stage it will be possible to cordon off an area of beach to carry out experimentation; this however is a non-trivial request. Fig. 8 shows an image captured at this site and then processed with APIC. Marked on this image by yellow boxes are the 8 largest targets identified by the APIC system. 10 targets were requested but as only 8 targets were detected all of these were returned. The cross in the box represents the pixel centre of area of the detected target, whereas the box surrounds the boundaries of the detected targets. HRC images of all these targets were captured successfully and the first six of these can be seen in fig 9. The AU PanCam emulator on board of AU rover platform captured all these images.

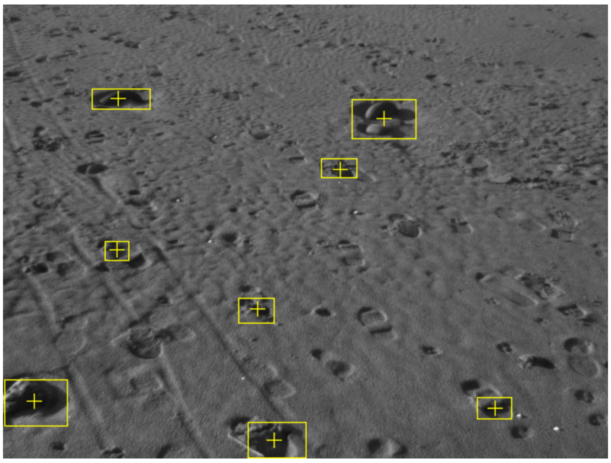

Figure 8. Site 2 Image. APIC identified centroids of 8 targets.

Unfortunately only 3 out of the detected 8 targets are actually rocks, the remaining 5 are footprints, but as there were only three potential target regions (the two rocks in the upper right hand region of the image are close enough to count as one target). The three rock regions were all captured. This was a successful result as in a realistic situation the dark footprint region would not be present.

Figure 9. Site 2. APIC captured HRC images of the first 6 targets from top to bottom.

**6.3. Additional Images**

The continued presence of the two NASA/JPL rovers Spirit and Opportunity on Mars has resulted in the availability of numerous images of the Martian terrain. Three such images have been selected from the NASA/JPL website. These images have been processed with the APIC rock detection algorithm. The results can be seen in Fig 10, 11 and 12. These results help illustrate that APIC would be viable when exposed to such scenes.

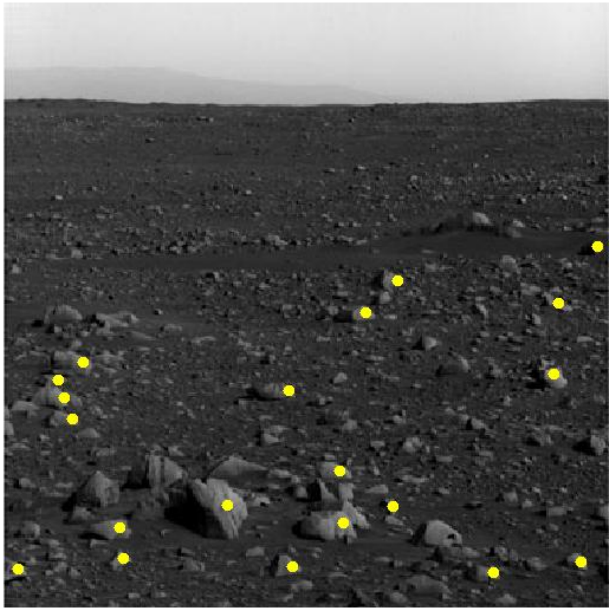

Figure 10. APIC identified centroids of the 20 largest targets. Original image courtesy of NASA/JPL

Fig 10 is a single filter MER image. This image is target rich and contains hundreds of potential rock targets. This test scene was processed with APIC, only the largest 20 rocks were requested. Fig. 11 and 12 are full colour processed images. Fig. 11 contains a significant number of targets so APIC was asked to identify 20 targets. Fig. 12 however was taken at a significantly more oblique angle resulting in fewer available targets. As a result of this only 10 targets were requested of APIC.

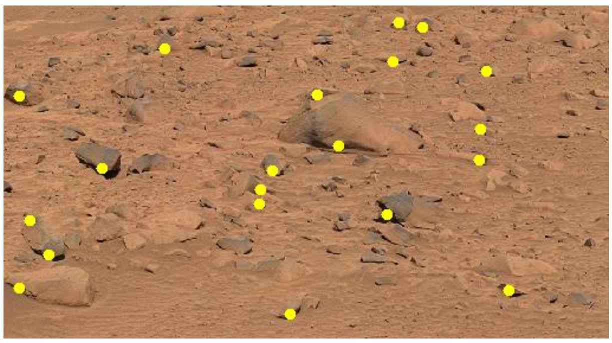

Figure 11. APIC identified centroids of the 20 largest targets. Original image courtesy of NASA/JPL

## 7. DISCUSSION OF RESULTS

Making the transition from laboratory work to fieldwork, always introduces a number of unexpected challenges. APIC's simplistic approach, however, makes this transition relatively straightforward, as the margins for error are reasonably high. This is due to the fact that a good result is achieved if the target is within the field of view of the HRC; it is not necessary for the target to be in the centre of view.

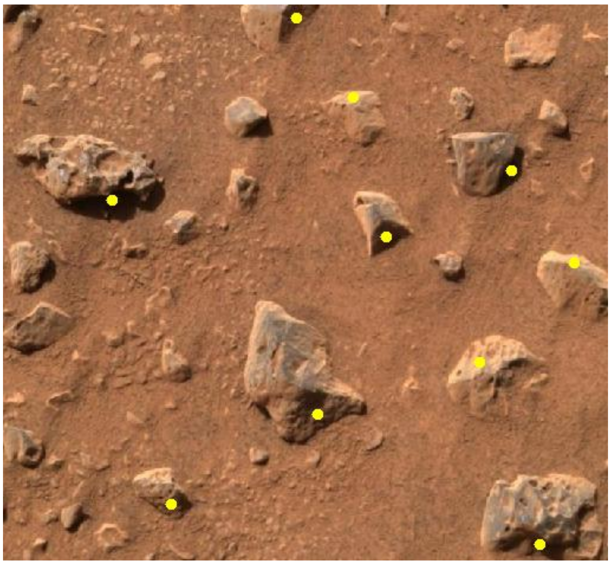

Figure 12. APIC identified centroids of the 10 largest targets. Original image courtesy of NASA/JPL

As can be seen by the results included in this paper APIC performs well in its target environment (site 2 and MER images). It is worthy of note that it is not necessary for APIC to detect and reimage every rock in any given scene. This would not only be impractical but would also produce a heavy demand for downlink bandwidth. Currently the sizes of detected regions are used to differentiate between which ones to image and which ones to ignore. This approach is relatively effective, producing results without overly increasing the level of complexity. However, it in no way assesses the science value of the targets that are ignored. Important science targets could be dismissed because they are small. This problem can also be compounded by the Sun direction. The direction of the Sun can have significant impact on the results achieved. This is primarily due to the long shadows that can be cast by rocks when the Sun is low in the sky. These long dark regions are in some cases very difficult to differentiate from the rock itself. Currently no strategy has been developed to deal with these problems within APIC.

## 8. FUTURE PLANNED DEVELOPMENTS

APIC development is on going and the eventual aim is to approach the problems associated with rover on-board autonomy from the relatively strong position of on-board automation. APIC currently contains no scientific assessment, and is only capable of pointing a HRC located on the same optical bench as the original WAC. Future development will aim to expand upon this to include a basic scientific assessment capability. It is also desirable to include more scientific instruments within the sampling capability of APIC.

### 8.1. Multi-Spectral Imaging

The WACs that are part of the AU PanCam emulator are both fitted with a filter wheel, each of which holds 9 optical filters. The first three filters on each filter wheel are broadband filters primarily for the production of full colour images. The remaining 6 filters are used to infer information about the geology of the target from its reflectance spectrum. Through the combination of both WACs it is possible to obtain 12 sample points of the target's spectral signature. This information can be used to infer the mineralogy of the target. It is planned to expand APIC to include a facility to gather multispectral information of detected targets. This would be done by reimaging the target regions with each of the filters, only storing the data contained within the target regions. This would enable a spectral signature to be produced of each of the targets along with a true colour image [5].

Once this feature has been added it opens the way for more enhanced capabilities. For example it may be possible to provide APIC with a priority list of spectral signatures. If this were possible it would enable the detected rock regions to be prioritised according to their importance to the mission, ensuring that valuable data is not ignored and that the most valuable data is downlinked. It may also be possible to predefine some key spectral signatures for APIC to search for. APIC could then be left to survey an entire area (perhaps comprising of many WAC images), looking for candidates of a particular spectral signature.

### 8.2. Close Up Imager Pointing

The ExoMars rover is also fitted with other cameras that are not situated upon the optical bench. CLUPI is one such camera. It is a close up imager with a 5 Mpix sensor and a 50cm focal depth. CLUPI is not mounted on a PTU. In order to point the camera, the rover must be turned to face the target and be within 50cm.

APIC could be enhanced as part of the rover navigation system to relocate the rover into an appropriate position to reimage a potential target with CLUPI. APIC itself has no facility for calculating rover traverse instructions; current rover platforms however, such as the ExoMars rover are fitted with an autonomous navigation system. APIC would be able to calculate the 3D location of the target and the desired end attitude of the rover. The rest would be up to the rover's autonomous navigation system.

### 8.3. Enhanced Operational Scenario

Using the above-mentioned enhancements it would be possible to produce a new operating sequence. This enhanced operating sequence could provide the next steps towards autonomy. Currently, APIC has no autonomous component: it is purely automatic, making no decisions on-board. By adding some form of science assessment APIC could be helped to move towards autonomy. Section 8.1 discusses the possibility of using multi-spectral data with APIC. Utilising this functionality an intelligent system could be created to prioritise which targets are imaged based upon the returned reflectance spectra. The result of the returned priority could then be used to decide if further investigation is necessary. Either HRC images could be captured, or if the target is sufficiently interesting a CLUPI image could be ordered. This may require the rover to drive closer to the target; this would be accomplished by making a request to the navigation system. If this positioning is a success a CLUPI image could be captured along with a new HRC image and a new set of stereo WAC images. APIC would then be able to examine the captured data and prioritise the downlink of the most valuable data.

It is not the aim of APIC to become a fully-fledged autonomous system. Functionality such as the aforementioned however, could enable serendipitous science in situations when no high priority operations are pending. For example if the rover were traversing a large scene (perhaps 100 – 200m) it would be necessary to stop every few meters to update the navigation systems on-board DEM (Digital Elevation Model). During some of these pauses an APIC operation could be triggered, and (depending upon the derived spectral value) capture HRC images or CLUPI images. After the images are captured the original navigation operation could be resumed, or (if the target is valuable enough) stop the rover next to the target and capture a stereo image pair of the target for DEM generation. This would be done under the assumption that a sample would be taken at the new site.

## 9. CONCLUSIONS

APIC has been designed to improve science data return, by accelerating the process by which HRC images can be captured. This gives scientists access to HRC images during the initial target selection process and reduces the overall time that it takes to accomplish an instrument placement. The enhancements carried out during the transition from the laboratory to the field have significantly enhanced its mission readiness. However, the other proposed enhancements also make APIC a desirable way forward. Autonomy is a well-needed addition when it comes to extra-terrestrial exploration. Communication restrictions make deterministic strategies very slow and restrictive. In order to continue to justify the cost of these missions, it is essential that a significant amount of good quality scientific data is returned and that each mission be able to add to human knowledge. Autonomy is the only way this is going to be possible while missions remain in their current format. APIC as demonstrated in this paper can be seen as a viable way to begin pushing the boundaries on-board the platform to utilize the benefits of automation with the eventual aim of integrating autonomous elements, in the inevitable move towards full autonomy.

## 10. ACKNOWLEDGMENTS

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