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Automatic Pointing and Image Capture (APIC) for ExoMars type mission

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Abstract

A major mission driver for space exploration is to maximise science data return whilst minimising ground-based human intervention and hence associated operations costs. Future robotic exploration such as the ESA/NASA ExoMars mission (launch 2018) [1], and the subsequent Mars Sample Return (MSR) [2] mission will require rovers to travel further and faster than has been achieved to date. In order to make this possible it is desirable that currently Earth bound decisions be transferred to the exploration platform wherever possible. This paper presents a novel on-board approach to Automatic Pointing and Image Capture (APIC) capable of increasing science return without removing Earth-based decision points. This on-board element utilises autonomy and basic image processing techniques to image a predefined number of potential targets with a HRC (High Resolution Camera). APIC could however be applied to any number of other non-contact instruments.

1 Introduction

The current NASA Mars Exploration Rover (MER) mission has shown the impact of ground based decision points, as it initially took a minimum of three full sols (Martian day) to place an instrument on a sample after it had been identified by ground based scientists [3]. Greater rover autonomy to reduce the amount of ground based intervention is quickly becoming an essential requirement as planed missions become more ambitious and the pressure for high value novel results increases. Going a stage further, we envisage the deployment of scout rovers capable of both autonomous science target identification and science sample acquisition. Such autonomous rovers could be utilised to identify and cache science samples as a precursor to a subsequent MSR mission.

APIC is a precursor to an autonomous exploration system. It utilises basic operations on-board the rover to identify and locate areas of interest in the scene. These areas are then imaged with the HRC providing Earth-bound scientists with a high resolution image of a selection of targets along with the standard WAC (Wide Angled Camera) image. In this way APIC images will enhance Earth-bound science assessment by providing these HRC images of potential rock targets before the initial assessment. Not only could APIC save valuable operations time by providing HRC images along with the first data download, but it would also allow for opportunistic science, as additional HRC images may identify scientifically valuable features where the initial WAC image would not. Figure 12 and 13 well illustrates this point as the white rock in the top right hand corner of figure 12 occupies only 20,000 pixels of the original WAC image, compared to 190,000 of the HRC image.

The current implementation of APIC utilises a single WAC and an HRC mounted in an ExoMars like configuration, but the method could be applied to any number of other non contact instruments. The inclusion of contact instruments would be possible if an improved three dimensional model of the environment could be achieved on-board the exploration platform. Currently effort has been undertaken to limit the computational complexity by estimating the distance to the target through use of a kinematics model of the PTU along with some heuristic approximations. During this paper the design and implementation of APIC is described and results from experimentation carried out in the laboratory and the field are presented.

2 APIC Background

Current research into autonomous systems for planetary exploration includes studies into rock detection [4], feature detection [5], novelty detection [6], and target prioritisation [7].

A notable body of work is OASIS, the On-board Autonomous Rover Science Investigation System [8]. This has been designed to enable a rover to identify and react to serendipitous science opportunities such as dust devils, clouds and novel rocks. OASIS analyses data that the rover captures, and then prioritises this data based upon established target attributes. It may also schedule new observations of interesting targets. The criteria for prioritisation are set to be appropriate to the current environment and science goals. OASIS currently uses greyscale (single filter) images for its rock identification and analysis, concentrating mainly on rock shape, size and albedo. The eventual goal of OASIS is to develop a fully autonomous rover investigation platform.

Another project of note is the Autonomous Robot Scientist Project (ARSP) [5]. ARSP has been demonstrated as an end to end implementation of an autonomous opportunistic platform. It has proved the concept of the Science Assessment framework produced by Pullan [9].

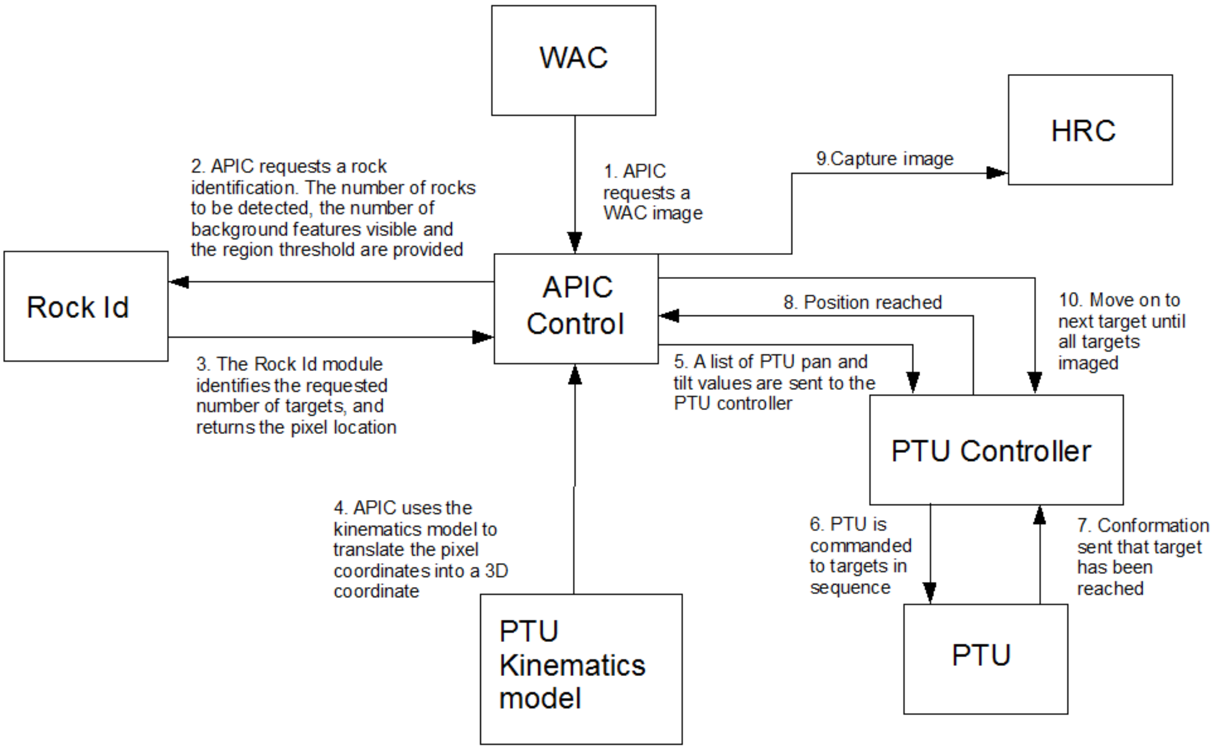

Figure 1. APIC Architecture

It has also proved the concept of geology based image assessment of potential science targets. ARSP currently does not implement any sophisticated method of assessing the science values obtained from the Science Assessment Framework (SAF) ujm [5].

Both these systems represent significant bodies of work and have demonstrated great promise during experimentation. Currently however mission hardware and resources are limited and coupled with the conservative attitude of mission scientists, autonomous systems have not been fully realised on board exploration platforms. APIC aims to improve this situation by providing some of the benefits achieved through in-situ autonomous assessment without removing the Earth-bound decision points or substantially increasing operations risk. Here no specific attention is being paid to the scientific value of the targets being imaged. In an effort to limit the computational complexity targets are simply differentiated from the background using an intensity based region growing algorithm. Once targets are located they can then be reimaged at a higher resolution with minimal computational cost. It is also envisaged that APIC could be activated during operational pauses so that the rover could be better utilised by imaging local rock targets with the HRC.

3 APIC Overview

APIC can be broken down into three parts: a rock or feature detection algorithm, a feature localisation algorithm and a sample acquisition algorithm (an overview of APICs architecture can be seen in figure 1). The APIC rock identification algorithm looks for areas of high contrast in an image, producing a region map like the one seen in figure 4.

APIC's feature localisation algorithm utilises the PTU's kinematics model along with the intrinsic parameters of the WAC to approximate the location of the feature in three dimensional space relative to the rover.

APIC’s sample acquisition algorithm currently utilises the HRC. Again, the PTU kinematics model is used to calculate the pan and tilt angle necessary to intersect the HRC’s image plane with the centroid of the identified feature. A high resolution image of each target identified by the rock detection algorithm will be taken and returned along with the initial WAC image. Figure 3 shows the result achieved by the APIC system when it was asked to identify the 20 largest features in the WAC image shown in figure 2.

4 Rock detection

The algorithm proceeds in four main phases:
1. Assign pixels to regions.
2. Merge regions.
3. Remove unwanted regions
4. Generate centroid and bounding boxes

Details of these algorithm phases are as follows:

4.1 Assign pixels to regions phase

Start with an empty region list, and no pixels assigned to any regions. Begin with the pixel at (0,0) and process pixels in column-major order ((0,0) to (0,MAX) then (1,0) to (1,MAX) and so on).

FOR EACH PIXEL not yet assigned to a region: Examine the 8 neighboring pixels for possible compatible regions to join.

A compatible region is one whose mean intensity value is within "threshold" intensity units of the pixel's intensity. "Threshold" is a parameter of APIC that may be user-supplied or may be calculated in a pre-processing step from the global image pixel variance.

IF at least one compatible region is found: Assign the pixel to the most compatible region (smallest intensity difference)

ELSE: Create a new region and assign the pixel to this region

4.2 Merge regions phase

Start with the first region on the region list.

FOR EACH REGION in the region list: Make a list of neighbouring regions of the current region by examining neighbours of the pixels within the region.

A pixel has a neighbouring region if one of its 8 neighbouring pixels is assigned to a different region than that of the pixel itself. A pixel's "best" neighbouring region is the neighbouring region with the smallest difference between the mean intensity value of the neighbouring region and that of the pixel's own region (the current region). Each pixel's best neighbouring region is added to the neighbouring regions list (note: each best neighbouring region only occurs once in the list)

IF size of current region is less than a pre-defined minimum size:

FIND the most compatible neighbouring region (the neighbouring region whose mean pixel intensity is closest to that of the current region)

MERGE the current region with the most compatible neighbouring region as follows:

Assign all of the pixels of the current region to the chosen neighbouring region.

Delete the current region from the global region list.

ELSE FOR EACH REGION in the neighbouring regions list:

IF the difference between the mean intensity of the neighbouring region and the current region is less than a small pre-defined amount,

MERGE the neighbouring region with the current region as follows:

1. Assign all of the pixels of the neighbouring region to the current region

2. Delete the neighbouring region from the global region list

4.3 Remove unwanted regions phase

To eliminate the background (usually sky or soil), the 'background_regions' largest regions (in terms of pixel count) are discarded. 'background_regions' is a user-defined APIC parameter which is typically set to 2 (to eliminate ground and sky regions). APIC also allows the user to define the maximum number of targets to return. In this case the largest regions are retained, and the rest discarded.

4.4 Generate centroid and bounding boxes

In order to generate a target's centroid the mean X and Y value of the pixels within the target region are calculated. The bounding box is defined by the (x,y) pixel coordinates of the top-left and bottom-right corners of the rectangle that just encloses the region. Both the centroid and the bounding box details are output.

Figure 2. Input WAC image taken during the AMASE 2009 campaign

5 The rock localisation algorithm

The pixel position generated by the rock detection algorithm has to be translated into a real x-y-z location for the benefit of pointing the PTU and hence the HRC at the generated target points. APIC accomplishes this through use of the camera's intrinsic parameters, trigonometric calculations, and configuration heuristics. Firstly the kinematics of the PTU must be known accurately; these are illustrated in figure 5.

Figure 3. Image is marked with the centroid of the 20 largest rock targets

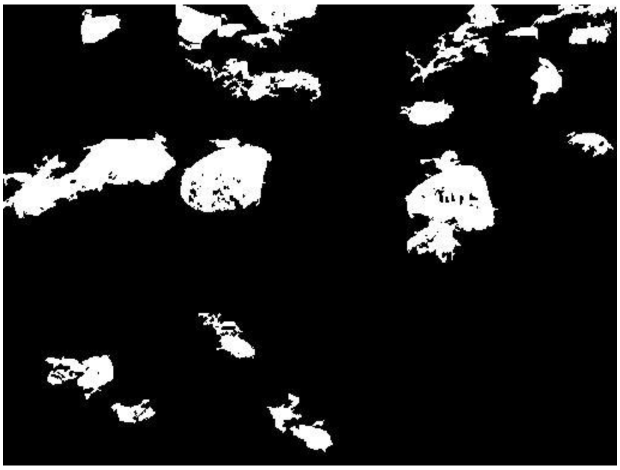

Figure 4. Output of the rock detection algorithm. The white regions represent the 20 largest rock targets

5.1 Requirements and assumptions

The kinematics model makes the following assumptions:

1. The PTU (pan/tilt unit) and camera system is mounted above the ground plane on a vertical mast or similar fixing.

2. The PTU pan axis is oriented vertically.

3. The PTU tilt axis is oriented horizontally, and is parallel to the camera optical bench.

4. The cameras are mounted on a single optical bench, pointing “forward”, with their optical axes parallel. The optical axes are perpendicular to the tilt axis.

5. When calculating the position of a target from a single camera image (forward calculation), the target is assumed to be lying on the ground plane.

Cartesian co-ordinates are defined in a right-handed system relative to the rover chassis. The origin point is at the intersection of the pan axis of the PTU with the ground plane. Positive X is forward, in the direction of travel; positive Y is left when facing the positive X direction (“port”) and positive Z is vertically upwards.

Pan and tilt are defined such that (pan=0, tilt=0) is along the positive X axis. Positive pan is clockwise as seen from above; positive tilt is upwards from the horizontal (see figure 5).

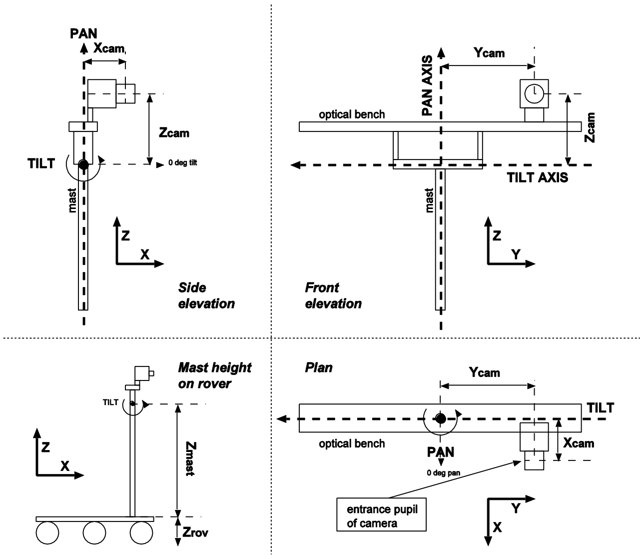

Figure 5. PTU kinematics parameters

5.2 PTU kinematics parameters

The kinematics parameters are described below. The “position” of a camera is considered to be its centre of perspective, which is usually the entrance pupil of the optical system. This may not correspond to an obvious position on the physical body of the camera.

X_{cam} Distance of camera forward from tilt axis

Y_{cam}	Distance of camera left of pan axis
Z_{cam}	Distance of camera above tilt axis
Z_{mast}	Height of tilt axis above rover deck
Z_{rov}	Height of rover deck above ground plane
X_{pt}	Distance of tilt axis forward from pan axis

The kinematics parameter X_{pt} allows for a displacement of the tilt axis relative to the pan axis. However, this offset has not been required with the units modelled so far, and it is not shown in figure 5.

5.3 Forward kinematics

The following camera parameters are required in order to compute the pan and tilt angles of a target relative to the optical axis of the camera:

p_x, p_y	Image (pixel) co-ordinates of target centroid, relative to centre of image (origin in centre, right-handed system: positive X is left, positive Y is up)
p_s	Camera sensor pixel size (assumed square)
f	Camera lens focal length

Using these, the horizontal and vertical angles of the target relative to the camera optical axis can be found by:

$$\delta pan = \arctan\left(\frac{p_x \times p_s}{f}\right)$$

$$\delta tilt = \arctan\left(\frac{p_y \times p_s}{f}\right)$$

The position of the target in Cartesian co-ordinates is first found relative to the current pointing direction of the PTU (with the current pan direction defining the X-axis), and then transformed by rotation about the origin to rover chassis co-ordinates.

Figure 6 shows the geometry for calculating the X co-ordinate of the target object using following equations:

$$h_{cam} = Z_{mast} + Z_{rov} + Z_{cam} \,.\, \cos(tilt) + X_{cam} \,.\, \sin(tilt)$$

$$d_{cam} = X_{pt} + Z_{cam} \,.\, \sin(-tilt) + X_{cam} \,.\, \cos(tilt)$$

$$d_{camRock} = \frac{h_{cam}}{\tan(-(tilt + \delta tilt))}$$

$$d_{rock} = \sqrt{d_{camRock}^2 + h_{cam}^2}$$

$$X_{rock} = d_{cam} + d_{camRock}$$

Calculation of the Y co-ordinate of the target is shown in Figure 7 and proceeds as follows:

$$Y_{camRock} = d_{camRock} \,.\, \tan(\delta pan)$$

$$Y_{rock} = Y_{cam} + Y_{camRock}$$

Finally, the Z co-ordinate of the target is set to zero (assumption 5 in section 5.1). The co-ordinates are then rotated about the Z-axis (pan axis) by the current pan angle to obtain Cartesian co-ordinates relative to the rover chassis:

$$Z_{rock} = 0 \qquad Z'_{rock} = Z_{rock}$$

$$X'_{rock} = X_{rock} \,.\, \cos(pan) - Y_{rock} \,.\, \sin(pan)$$

$$Y'_{rock} = X_{rock} \,.\, \sin(pan) + Y_{rock} \,.\, \cos(pan)$$

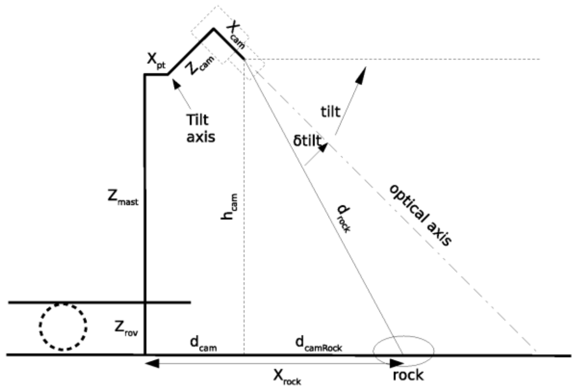

Figure 6. Calculation of X distance to target

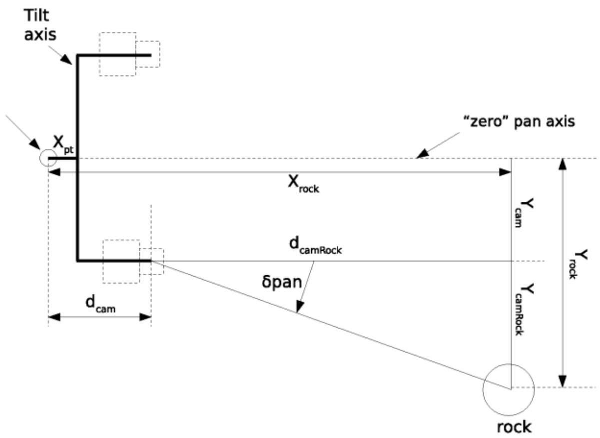

Figure 7. Calculation of Y distance to target

5.4 The PTU calculations

The PTU calculations involve computing the necessary pan angle to align the "zero" pan axis (direction of pan = 0, tilt = 0) with the target, then adjusting the pan angle to point the desired camera at the same spot. The tilt angle is computed separately. It is assumed that the optical axis of the camera is to be aligned with the target. The general case solution (align target with arbitrary pixel of image) is not addressed here.

Calculation of the initial target pan angle proceeds as follows (see figure 8):

$$d_{rock} = \sqrt{X_{rock}^2 + Y_{rock}^2}$$

$$pan_{rock} = \arctan(\frac{Y_{rock}}{X_{rock}})$$

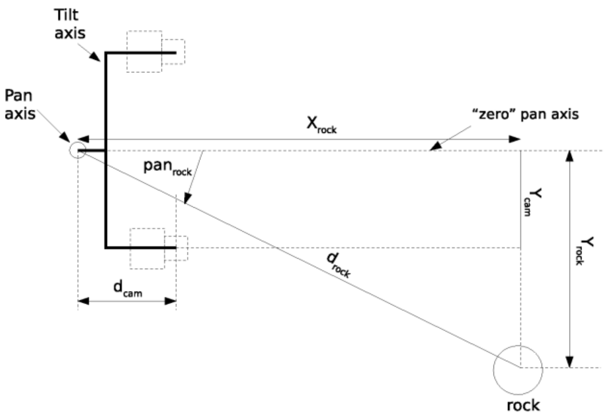

Figure 8. Calculation of initial pan angle to target

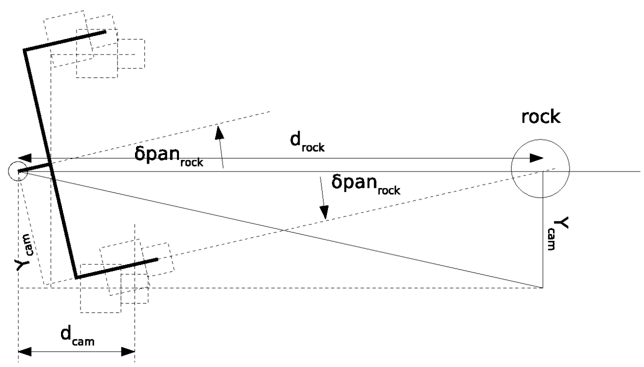

Figure 9. Calculation of camera pan adjustment

Figure 9 shows the calculation of the target pan angle adjustment by the following:

$$\delta pan_{rock} = \arcsin(\frac{Y_{cam}}{d_{rock}})$$

$$pan_{final} = pan_{rock} - \delta pan_{rock}$$

Calculation of the target tilt angle involves solving the quadrilateral shown in figure 10 for the angles α and β . Firstly we compute:

$$d_{camRock} = \sqrt{d_{rock}^2 + Y_{cam}^2}$$

The unknown sides of the figure are found by:

$$a = Z_{mast} + Z_{rov} - Z_{rock}$$

$$b = d_{camRock} - X_{pt}$$

$$c = Z_{cam} \qquad d = \sqrt{a^2 + b^2}$$

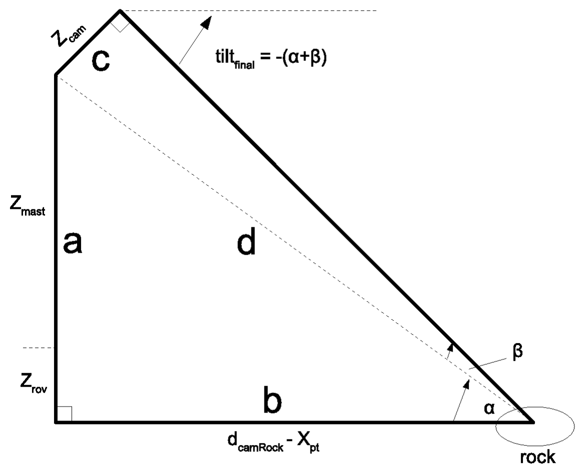

Figure 10. Calculation of final camera tilt angle

Finally the required angles are computed as follows:

$$\alpha = \arcsin(\frac{a}{d}) \qquad \beta = \arcsin(\frac{c}{d})$$

$$tilt_{final} = -(\alpha + \beta)$$

The calculation is independent of which cameras are used for the initial image and the final pointing.

5.5 Experimental Setup

The first set of APIC experimentation was carried out at the AU Planetary Analogue Terrain Laboratory (PATLab) [10]. The aim of the experimentation was to demonstrate that an automated imaging process is a viable option for extra-terrestrial exploratory missions, and such that a system could enable an increased amount of scientifically valuable data to be returned to Earth. A total of 19 rocks of varying size and shape have been used to fully test the APIC system. As the AU environment emulates the upcoming ESA ExoMars mission, it was decided that the system would be tested in an ExoMars-like configuration, with an ExoMars scenario. As such the PTU was mounted on a tripod at approximately 1.6 - 1.7 meters from the ground and the HRC was mounted centrally. The two WACs were situated with a baseline separation of 50 cm. The rocks were not moved during the experimentation, with the exception of the addition of target rocks in some images to increase target density. The aim of the experimentation was to exercise the rock detection and the three dimensional calculation carried out by the APIC system based on one camera image. In order to accomplish this, ten tripod locations were defined, beginning in close proximity to the rocks and progressively retreating for subsequent trials. During the experimentation the left WAC was used to capture the initial images. The lighting conditions of the laboratory were kept as consistent as possible, and blackout blinds were used to block out natural sunlight. Fluorescent lights were used to provide an even illumination across the terrain.

The soil simulant used in the PATLab is very fine and compacts very tightly when under pressure. This means that very clear impressions are made in areas where any pressure has been applied. These impressions (such as foot prints and countless wheel tracks) are not a feature that the system would have to deal with in a real mission environment. In order to reduce the impact of such features the terrain was raked between experiments. The raking also produced an “unnatural” pattern in the terrain, which is particularly visible in HRC images. This pattern however did not affect the APIC system, so it was ignored.

5.6 Results and Discussion

Experiments were conducted using Aberystwyth University’s ExoMars PanCam emulator. 10 different scenes were assessed containing a total of 152 potential science targets. Out of these, 150 were successfully identified and imaged, two rocks were missed by APIC, and no false positives were reported. The two rocks that were missed highlight a weakness of the region detection algorithm. Insufficient intensity differential was detected between these two rocks and the background region to identify a new region or to enable that region to avoid being merged with the background terrain.

This was caused by the way the rock detection algorithm avoids fragmenting regions. It is done by adapting the region’s mean pixel value according to the pixels present in that region. Therefore, as additional pixels are added it will change enabling regions to envelop small changes in intensity. This can cause a problem in detecting targets that have an edge that changes gradually in intensity. This problem could be overcome by altering the APIC threshold value, but this can introduce more problems such as the fragmentation of larger targets and the identification of multiple background objects. More accurate region detection algorithms are in existence (e.g. the Watershed algorithm [12] or possibly a more custom designed algorithm [13]), but a balance has to be achieved between high computational demands and accuracy. APIC’s current region detection algorithm adequately satisfies this balance.

Another priority during the design stage of the APIC algorithm was to limit the number of false positives detected. Any false positives generated by the system would represent a waste in down-link bandwidth. As previously noted, no false positives were identified by the current APIC rock detection algorithm, thus ensuring that only viable targets are imaged. Figures 11 and 12 represent a sample of the results from the first run. APIC has also undergone some pilot field experimentation including trails on board EADS Astrium’s Bridget rover in a sandy quarry near Stevenage and Aberystwyth's own rover at Ynyslas beach near Aberystwyth. Detailed field trials of APIC have been scheduled for later in 2010.

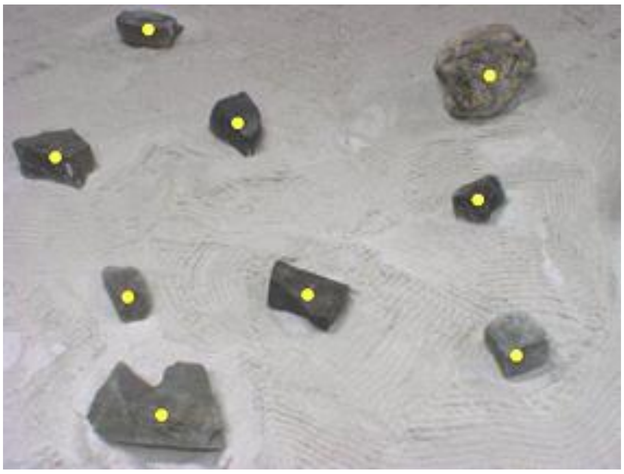

Figure 11. Input image annotated with calculated rock centroids.

5.7 CONCLUSIONS AND FUTURE WORKS

APIC's goal is to gather as many high resolution rock images as possible within a communication cycle, thus optimising mission time and reducing the need for communication with Earth. Trials of the APIC system have provided good results, showing the viability and the robustness of such a system. APIC represents advancement in rover autonomy in the sense that it is capable of selecting its own targets for re-examination.

Figure 12. 4 of the 9 HRC images output by APIC

Rock target selection, and re-examination with a different instrument, is a novel application for rover autonomy. The ability to carry this out without the production of a DEM or any three dimensional models of the rover's surroundings is also novel. The fact that APIC does not need to construct a DEM increases its suitability to run on-board a rover platform, as the production of a DEM is a computationally expensive task. APIC can also be presented as a method to increase the acceptability of autonomy. It introduces little risk to the mission, as HRC imaging is a low risk operation.

The future aim of APIC research is to assess the possibility of incorporating some more advanced image processing techniques that would enable scientific assessment of potential targets to be made, and an order of precedence to be established. This would be moving towards a more fully autonomous system; however care must be taken that the benefits of APIC are not lost by the addition of too many complex operations. Research is being conducted to identify key attributes that could provide initial clues as to a target's scientific importance. Currently four potential features have been identified: colour, spectra, reflectance and bedding. The inclusion of bedding features is based upon the assertion that bedding or lamination may be sedimentary, and could provide data about Mars's warmer and wetter past. The addition of spectra is thanks to the multi-spectral capability of the WACs allowing the targets to be prioritised based upon their mineralogy.

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