30330 Image Analysis with Microcomputer

Project report

by

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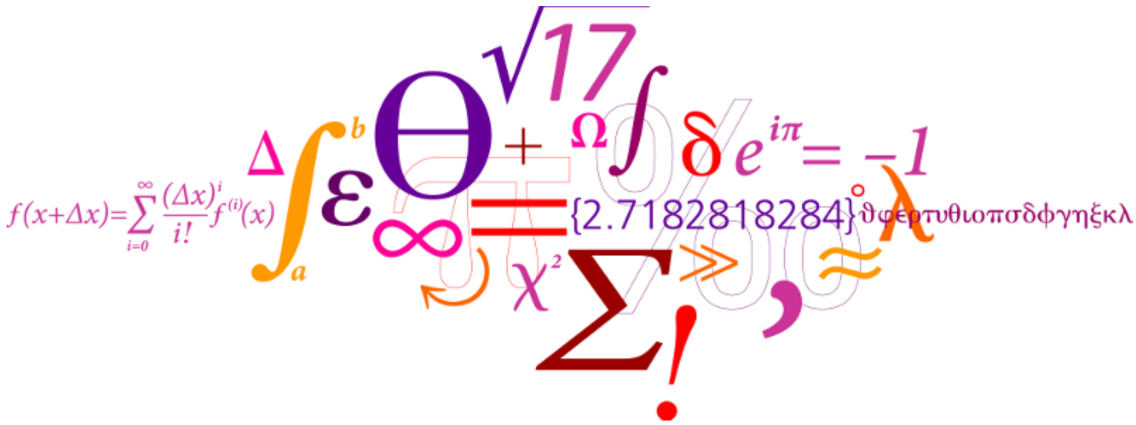

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1.1 Problem formulation

In this report, we assume that we would like to send a rover on Mars, capable of communicating with Earth. Self-powered by solar panels, it will land at latitude 50° where it could get enough sunlight to recharge its lithium batteries. It is provided with an arm whose hand is replaced with a camera (see figure 1.1). The latter will be used by scientists to observe relevant rocks to study. In order to accomplish this mission, once a stone is designed, the camera must be able to keep it in focus, despite the wind, the movement of the robot or any other perturbation. This implies a real time image analysis to be able to rectify the position of the camera. As a robust method is needed to maintain the stone in front of the arm, the identification of patterns should be completed by carrying out a 3D map of the surface. A luminous source should then be added to the rover to be projected on the surface containing the rock and detected by the camera.

This luminous source must be powerful enough to outshine the sunlight during the day, notwithstanding that the energy needed to make it work has to be negligible compared to the amount provided to the rover. Moreover, the characteristics of the camera need to be perfectly adapted to Mars, as once the rover has landed on the red planet, it would be impossible to adjust it.

Will it be feasible to design such an embedded system, composed of a camera, a luminous source and algorithms, capable of keeping a rock in focus thanks to a 3D map, for an application on Mars soil?

Figure 1.1: Curiosity Rover with an embedded camera on a arm [5]

1.2 Problem delimitation

In order to design the rover's camera which will be used to study rocks and to implement a robust algorithm to carry out a 3D map of the rock's surface, different characteristics of Mars and of the target need to be specified. However, as all of them cannot be taken into account, some simplifications and choices will be assumed.

Mars delimitation

Plenty of missions on Mars have been realized and a great deal of data has already been gathered. Nevertheless, even if some of them will be used to designed our system, others will be simplified or even ignored. The first simplification concern the atmosphere of Mars. Indeed, even if its composition is now well know, it will be assumed that the dirt on the surface Mars plus the different layers of the atmosphere absorb, or scatter, 10% of the solar energy. Moreover, the influence on the image acquisition that the dirt between the target and the camera could have will not be taken into account. The second reduction cover the temperature. Indeed, even if it can reach -143°C during winter, 27°C during summer and have around 60°C variations between daytime and nighttime[6], we will assume that the CCD sensor works well all the time.

Target delimitation

Regarding the target, that is to say the part of the rock being studied, it is supposed to :

- be vertical;
- not exceed 2*2 meters

- have an area between 0.1 and 1 square meters;
- have a relief less than meters.

Camera delimitation

Then, regarding the camera which is designed during this study, it is presumed to :

- be between one and two meters far from the target;
- be right in front of the target, that is to say that the angle between the normal of the target's surface and the focal axis of the camera is 0°;
- be able to capture the image of a target of 2 meters height maximum.

The different characteristics of target and the camera are represented figure 1.2

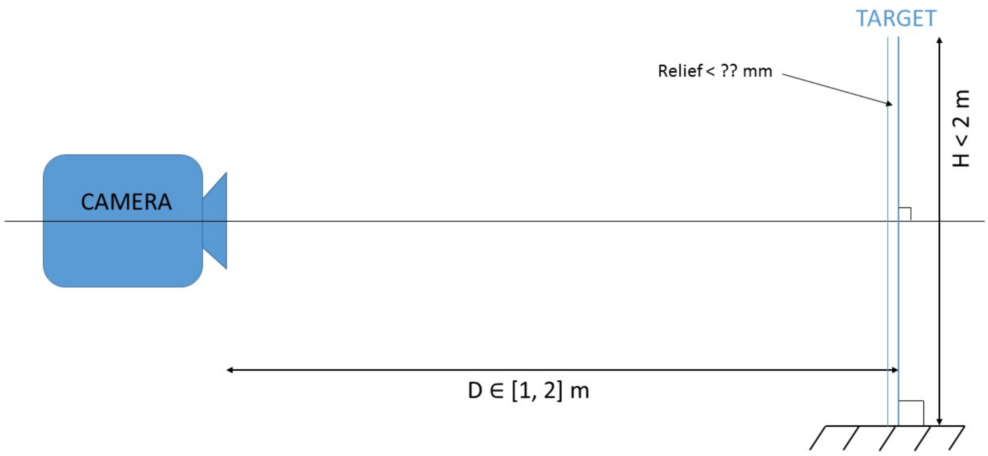

Figure 1.2: Schema of the scene

Part 2

Theory Section

2.1 Mars Features

2.1.1 Albedo

Mars surface is covered by sand and volcanic rocks. The first purpose of this project is to allow scientists to examine these rocks through the camera. To achieve it, it is needed to know their characteristics, especially their albedo. As a reminder, the albedo is the fraction of incident light which is reflected from a surface. We can assume that the power reflection of Martian rocks is the same than on Earth. Then, to cover a wild range of rocks, the albedos of a black and of a white stone would be considered. Charcoal, as a dark rock, is a powerful absorber of the sun radiation, with an albedo around 0.05. On the contrary, chalks are poor absorbers and their albedo reach 0.45 according to [3]. In the following parts of the report, it will be taken for granted that Martian rocks have an albedo between 5 and 45%.

Part 3

Development

3.1 Scene Analysis

In order to design the camera and find its characteristics, a scene analysis have to be carried out. Our study is based on the MER (Mars Exploration Rover) cameras properties [4]. To begin with, we choose an image sensor.

3.1.1 CCD

The Charge Coupled Device (CCD) is commonly more sensitive to light than its counterpart, the CMOS (Complementary Metal Oxide Semiconductor). Moreover, in the near infrared CCD appears to have a better response. Since Mars has a reddish color, it seems more accurate to select the CCD detector.

As scientists will need to discern the details of rocks, the resolution should be around the megapixel. Taking into account the cost, which will increase with the resolution, and the time of computation for an image with too many pixels, 1024 x 1024 seems to be an acceptable compromise.

Finally, the last element to consider is the pixel size. A trade-off have to be found between having a higher resolution (smaller pixels) and more sensitivity (larger pixels). All the camera of the MER mission were conceived with a pixel size of 12 x 12 μm for a resolution of 1024 x 1024. It was decided to comply with that value.

For the next parts of this report, we will use the data sheet of the FTT1010M CCD image sensor as a basis for our calculations which will require CCD details.

3.1.2 Field of View

According to the book [1], the Field of View (FoV) "is the angle of the cone of directions encompassed by the scene that is being images". This solid angle is needed to compute the focal length the camera should have.

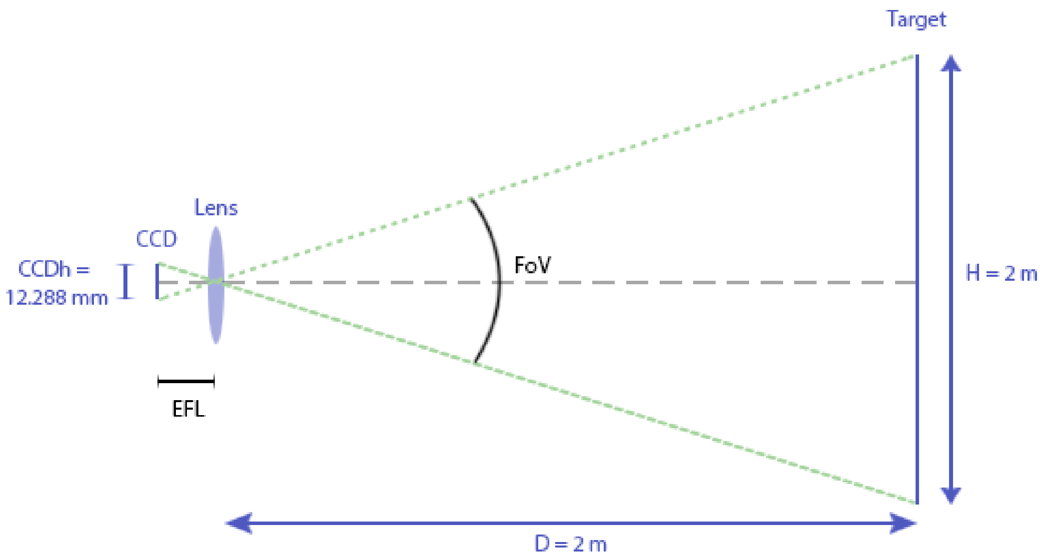

Figure 3.1: Field of View and Effective Focal Length

A simple relationship between the distance lens-target, the size of the target and the FoV can be deduced from the detailed diagram 3.1:

$$tan(\frac{FoV}{2}) = \frac{1}{2} \times \frac{H}{D}$$

We derive and get

$$\frac{FoV}{2} = atan(\frac{1}{2} \times \frac{H}{D})$$

Numerically, with our problem delimitation, the Field of View is equal to $26.6° \times 26.6°$.

3.1.3 Focal Length

Thanks to the previous diagram, the Effective Focal Length (EFL) can also be determined:

$$EFL = \frac{1}{2} \times \frac{CCDh}{tan(\frac{FoV}{2})} = 12.29\ mm$$

where $CCDh$ is the image section of the CCD according to the data sheet.

In order to get the real focal length, we choose $rf = 1\ m$ for the distance of focus of the camera.

$$f = \frac{1}{\frac{1}{rf} + \frac{1}{EFL}} = 12.14\ mm$$

3.1.4 Aperture

To determine the diameter of the aperture, several criteria have to be accounted for. If the diameter is too small, the sharpness of the image will decrease due to the diffraction effect. In fact, at large aperture, the diffracted light is negligible compared to the total amount of light entering the system. On the other hand, we should also consider the Depth of Field (FoV). We need to insure that it is big enough to allow us to see the whole target on the image. The relationship between the DoF and the diameter is inversely proportional. That means that if we increase the diameter, we will lessen it. The Circle of Confusion (CoC), linked to the DoF is also a factor to take into consideration for the choice of the diameter. According to Wikipedia [7] It corresponds to “an optical spot caused by a cone of light rays from a lens not coming to a perfect focus when imaging a point source”. The smaller the CoC is, which corresponds to a better focus, the bigger is the DoF, and also the smaller is the diameter.

As the behaviour of the depth of field and of the circle of confusion runs counter to the diffraction one, a trade-off has to be found.

These formula are used to calculate the Diameter of Confusion (DoC) and the diffraction spot:

$$DoC = Dsr \cdot \frac{|r - rf|}{r} \cdot \frac{f}{rf - f}$$

where Dsr is the diameter of the aperture

$$DiffractionSpot = 2 \cdot EFL \cdot tan(1.22 \cdot \frac{lambda}{Dsr})$$

where $lambda$ is a wavelength of the sunlight

In the delimitations, it is assumed that the wavelengths of the sunlight belong to [400 800] nm. To settle on a diameter, the diameter of confusion and the diffraction spot were computed for diameters varying from 1 mm to 5 mm and wavelengths from 400 nm to 800 nm. The results are shown graphically in figure 3.2. As the diameter of confusion cannot be bigger than the height of a pixel, the line corresponding to 12 μm was also added to the graphic. In order to have the best trade-off, that is to say all the curves under 12 μm, we have chosen a effective lens entrance aperture Dsr equal to 1.9 mm, corresponding to $DoC = 0.0117\ mm$.

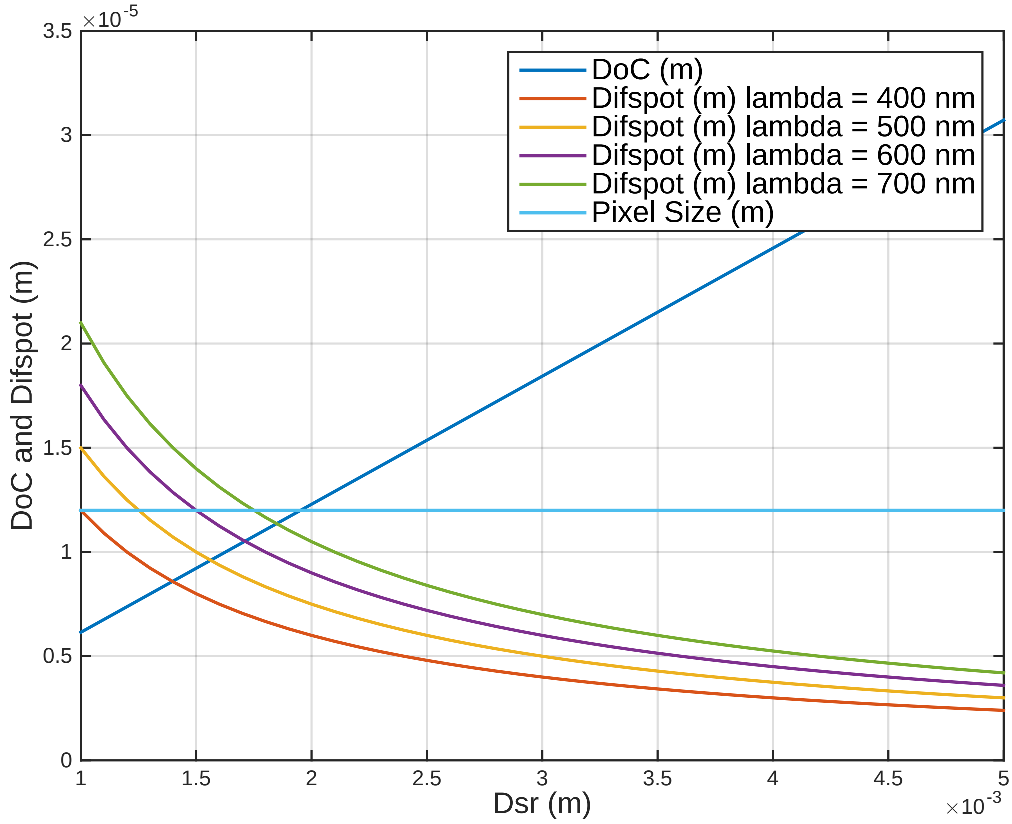

Figure 3.2: Diameter of confusion and diffraction spots as a function of the diameter

The circle of confusion can be deduced:

$$CoC = DoC \cdot m \qquad where\ m = \frac{EFL}{rf}$$

and then:

$$DoF = \frac{2\frac{f}{Dsr}CoC(m+1)}{m^2 - (\frac{CoC}{Dsr})^2} = 12.29\ mm$$

That means that the roughness of the rock analysed cannot be more than $\frac{DoF}{2} = 6.14\ mm$ since we could not see the whole rock if not, and the 3D map will then be flawed.

3.1.5 Irradiance

First of all, the irradiance F of the light from the sun falling at the top of the atmosphere of Mars can be calculated as following : Conservation of energy :

$$4\pi R_{\odot}^2 F_{\odot} = 4\pi R^2 F \tag{3.1}$$

with

$R_\odot = 6,956.10^8\ m$: solar radius

$F_\odot = 6,45.10^7\ W.m^{-2}$: energy flow of the surface of the sun

$R \in [2.06644,\ 2.49228].10^{11}\ m$: distance Mars-Sun (Aphelion and Perihelion)

$$F = F_\odot \left(\frac{R_\odot}{R}\right)^2 \in [502, 730]\ W/m^2 \tag{3.2}$$

In this report, we will consider that the rover is working on a specific date and we will chose the one when R corresponds to the semi-major axis. In this case $R = 2,27936.10^{11}\ km$ and

$$F = 589\ W/m^2 \tag{3.3}$$

Moreover, we can assume that a part of the irradiance is absorbed by the atmosphere. Knowing that the atmosphere of Earth absorbs and scatters to space around 30% of the incident irradiance of the Sun[9], and knowing that the atmosphere of Mars is thinner than the one of the Earth, we will postulate that 10% of the incident irradiance is absorbed. Thus, using (3.3) the actual irradiance F_a of the light from the sun falling on the surface of Mars is

$$F_a = \frac{90}{100}F = \frac{90 * 589}{100} = 530\ W/m^2 \tag{3.4}$$

However, this irradiance is the one of surface exposed perpendicular to the sun's beams. As Mars is a sphere, the projection need to be considered. Knowing that the weather is better into the northern hemisphere of Mars[8] and the fact that a latitude between 30 an 70 degrees is favored for a landing[2], we will assume that the rover has a latitude of 50°. This latitude corresponds to an angle of 40° between the surface of Mars and the sun's beams. Moreover, suppose that the rover stop working when this angle is inferior to 10°. Thus, the irradiance F_{50} at a latitude of 50° is

$$F_{50} = F_a \sin(angleBeams) \in [92, 341]\ W/m^2 \tag{3.5}$$

with $angleBeams = [10, 90 - latitude] = [10, 40]°$.

3.1.6 Target's Radiance

Considering the trajectory of the Sun into the sky of Mars and knowing that the rock target is more or less vertical to the surface of Mars, the angle θ between the target's normal and the sun's beam is considered to be included in $[10, 50]°$. In addition, in the optimal case (when all the optimal conditions are provided to have the maximal radiance), the BRDF of the surface of the target is assumed to be 90% Lambertian and 10% Glossy while in the worst case the BRDF will be only Lambertian. In this way, the radiance of the target R_T is

$$R_T = \begin{cases} \frac{F_{50}\alpha}{\pi}\cos\theta & \text{optimal case} \\ F_{50}\alpha(\frac{9}{10\pi}\cos\theta + \frac{1}{10}) & \text{worst case} \end{cases} \tag{3.6}$$

with

$\alpha \in [0.05, 0.45]$, the albedo of the target**??**

$\theta \in [10, 50]°$, the angle between the target's normal and the sun's beam

Thus,

$$R_T \in [92, 340]\ W/m^2 \tag{3.7}$$

3.1.7 Target's Irradiance

Now, the irradiance of the target I_T can be calculated with

$$I_T = R_T\frac{\pi}{4}\left(\frac{Dsr}{EFL}\right)^2\cos(\alpha_{CT})^4 \tag{3.8}$$

with

α_{CT} the angle between the normal of the target and the axis of the camera

Dsr the effective lens entrance aperture

EFL the focal length

However, knowing that the camera is supposed to be right in front of the target, we have

$\alpha_{CT} = 0$

And according to (3.7), **??** and **??**, we have

$$I_T \in [0.0271, 1.1000]\ W/m^2 \tag{3.9}$$

Finally, the luminous power from the target to the camera W_{lum} is

$$W_{lum} = I_T A_T \tag{3.10}$$

with

A_T, the area of the target

According to (3.9) and **??**

$$W_{lum} \in [0.0027, 1.1000]\ W \tag{3.11}$$

3.1.8 Signal/Noise Ratio

Three different cases will be studied. In the first one, we examine the case of a target iluminated by the sun without the use of laser, the second one considers the use of lasers by night and the last one, which is the case that we need to consider for our rover, study the use of lasers by daylight. In order to calculate the Signal/Noise ratio, the different noises need to be determined. Three will be taken into account: the readout noise, the dark current noise and the noise from the sun light.

The three different cases have the readout and the dark current noise in common which are given by the datasheet of the CCD **??**.

$$\delta_{readout} = 25\ el \tag{3.12}$$
$$\delta_{dark} = ??\ el \tag{3.13}$$

3.1.8.1 First case

In this case, the signal that needs to be considered is the sun light reflected by the target. Therefore, the readout and the dark current noises are the only two which need to be considered and the noise is

$$N = \sqrt{\delta_{readout}^2 + \delta_{dark}^2} = ????? \tag{3.14}$$

Then, the number of photons per shutter time N_p corresponding o the radiance of the target is

$$N_p = \frac{1}{\lambda_{max} - \lambda_{min}} \int_{\lambda_{min}}^{\lambda_{max}} \frac{W_{lum} ts}{\frac{h.c}{\lambda}} \, \mathrm{d}\lambda \in [1.4112, 573.10].10^{37} \; photons \tag{3.15}$$

with

$ts = \; s$, shutter time
$h = 6,6263.10^-34 \; J.s$, Planck's constant
$c = 3.10^8 \; m/s$, velocity of light
$\lambda \in [400, 800] \; nm$, wavelength of the sunlight

The number of photons to the lens N_{CCD} is

$$N_{CCD} = \frac{\pi \left(\frac{Dsr}{2}\right)^2}{2\pi(r)^2} N_p \in [1.5920, 646.53].10^{30} \; photons \tag{3.16}$$

with $r = 2 \; m$, the distance between the camera and the target
the number of photons to the lens registered by the CCD Nen_{CCD} is

$$Nen_{CCD} = N_{CCD} \int_{\lambda_{min}}^{\lambda_{max}} CCDqe(\lambda).alphaLens(\lambda) \, \mathrm{d}\lambda \in [????, ?????].10^{30} \; photons \tag{3.17}$$

with

$CCDqe$, the quantum efficiency of the CCD**??**

$alphaLens$, the pass band efficiency of the lens**??**

Finally, according to (3.14) and (3.17) we obtain the Signal/Noise ratio

$$\frac{S}{N} = \frac{Nen_{CCD}}{N} = ???? \tag{3.18}$$

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