

Robotic Arm for Beagle2 Mars

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ABSTRACT

The Beagle2 program is a British lead effort to land on Mars as part of ESA's Mars Express mission, due to be launched in June 2003. The primary aim of Beagle2 is to search for evidence of life and a key element in this task is the robot arm, which is equipped with a multi-functional tool (PAW) as an end effector. The robot will be used to examine rocks and take samples for processing on-board the lander. This paper briefly describes the Beagle2 mission and then discusses in more detail the design and operation of the robot arm.

1. INTRODUCTION TO THE BEAGLE2 MISSION

Beagle2 is due to be launched with ESA's Mars Express orbiter on a Soyuz-Fregat launch vehicle in June 2003. After six months cruise, the complete probe is ejected from Mars Express 5 days before impact on Mars. During this coast phase, Beagle2 is totally passive, spinning slowly about its axis in order to minimise thermal gradients and to provide stability at the point of entry into the Martian atmosphere.



Figure 1 Beagle2 leaving Mars Express

Once atmospheric entry is commenced, the lander is decelerated from 5.75km/s (20,000kph) to zero in just five minutes. This function is carried out by the Entry Decent and Landing System (EDLS), which involves aerodynamic braking, followed by parachutes and finally airbags for the impact with the surface. This impact occurs at 30m/s (105kph) and generates an initial shock of as much as 200g despite the protection of airbags. In fact the second impact can be just as severe as the first. The final 1m drop from the airbags, when they are released, results in another impact with the surface at 3.1m/s (11kph). This gives rise to shocks of up to 350g within the lander. Having settled on the surface the lid is opened and the solar arrays are deployed. Finally after confirmation that there are no obstacles to arm deployment, the hold-downs on the PAW and robot arm are released, such that the arm can be raised into the operational position.



Figure 2 Beagle2 dropping from airbags

The primary landing site for Beagle2 is the ISIDIS basin, which is situated 1 1°N, 270°W. The targeted operational life is 180 Martian sols (days)

2. ROBOT ARM DESIGN CONSTRAINTS

Beagle2 is a particularly demanding program: mass and volume are particularly restricted due to limitations imposed by Mars Express. Specific design requirements are discussed in the following sections. The robot arm specific requirements are summarised in section 2.2.

2.1 General

• Mass:

The probe mass is constrained to a maximum of 60kg by Mars Express. The lander mass is then limited to only 30kg and if this mass is exceeded then a safe landing on Mars cannot be guaranteed. This means that all equipment on Beagle2 has tight mass targets. The current arm mass is 2.4kg, against a requirement of <2.7kg

• Power:

Power is also limited due to the mass constraint. This means that the solar array area and battery size are limited, which means all equipment has been designed with the aim to limit power consumption. The proposed drive method for the arm is to move each joint separately. The maximum joint power consumption is currently predicted to be 1 W.

• Volume:

Space is at a premium within the lander. The intention has been to maximise the science return from Beagle. This has meant that the arm configuration is not ideal, but clearly compromises are required in such a complex program as Beagle2. This is clearly shown in figure 3.

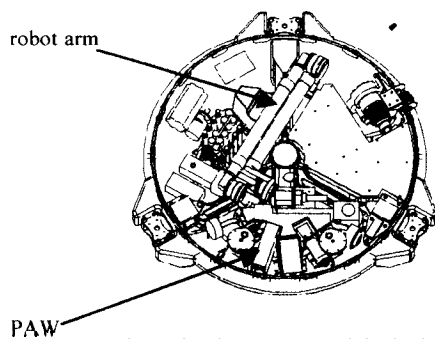


Figure 3 robot arm stowed in lander

- Redundancy:

Due to the mass constraint the decision has been taken to minimise the redundancy within Beagle2. In fact it has only been implemented in systems where failure would result in total mission loss (eg. pyrotechnics within the EDLS). In the case of the arm there is no redundancy.

- First Vibration Mode:

This has to be greater than 80Hz in order to prevent cross coupling with the probe main modes. The arm currently has a first mode of 180Hz.

2.2 Arm specific requirements

- Access Area:

The target of an access area of 1m² was set in order to maximise the number of rocks that could be reached on Mars. Unfortunately due to mass and volume constraints the access area is limited to 0.7 m².

- Positional Accuracy:

The target for the positional accuracy of the arm is ±5mm. The performance of the arm is dominated by the accuracy of the stereo camera pair on the PAW (currently ±2mm) and the resolution of the potentiometer used to measure joint position (±2mm). Arm structural deflection has been minimised by the use of carbon fibre tubes for the main members and by using the potentiometer to measure the joint position directly, any deflection within the drive train is compensated for by the control system. With this approach it has been possible to achieve a positional accuracy of ±5.34mm.

- PAW mass:

The arm has been designed to support the PAW mass of 2.5kg

- Position of Sample Return:

The arm is required to deliver samples back to the inlet port of the Gas Analysis Package (GAP) for on-board analysis. The location of the port has been selected with the arm configuration in mind.

- Mole Retrieval Force:

It is intended that the mole retrieval forces will be reacted by the mole launch tube. Mole retrieval forces of 50N have been measured in test. This would become an arm design-limiting load if applied directly to the arm.

- Force Applied by Arm:

All the instruments on the PAW used to examine rocks require a contact force to be applied by the arm in order to get stable readings. The arm is capable of generating the 5N required.

2.3 Environmental

- Random Vibration: (launch)

The dominant case for random vibration is in the z-axis

frequency range	level
20 - 100Hz	+9dB/oct
100 - 300Hz	3.5g ² /Hz
300 - 340Hz	-23.8dB/oct
340 - 500Hz	1.3g ² /Hz
500 - 2000Hz	-9dB/oct

- Shock:

The dominant design cases for shock occur either for the **airbag** impact case (x & y axes) or the final drop **from the airbags** (z-axis)

axis	level
x-axis	200g
y-axis	200g
z-axis	290g+ 6000rad/s ² (about C of G)

- Temperature:

The robot arm has not only been designed to survive the extremes of the Martian environment but also **sterilisation**. Currently the chosen method is to bake the unit at 125°C for 48 hours. The arm design temperatures are summarised below:

operational case	temperature limits
operational	-40° to +30°C
non-operational	-100° to +125°C

- Martian Atmosphere:

The Martian atmosphere comprises mostly CO₂ at 8mbar. This has a breakdown voltage of approximately 100V, which is of particular concern for the motors selected for the arm. The motors chosen are **Maxon** dc brushed motors with precious metal brushes. These units will be fitted with capacitors (CLL disc) to limit brush arcing (as used on Pathfinder)

- Dust:

The Martian atmosphere also contains very fine dust, blown around by the wind. Dust seals have been implemented in the arm design and breadboard hardware will be subjected to testing in order to verify the adequacy of the approach.

- Vacuum:

The probe will also be subject to the vacuum of space on the 6 month journey to Mars. The key issue for the arm will be the selection of lubricants for the motors, gears and bearings. The final choice has not yet been made but will obviously be from vacuum compatible lubricants.

2.4 Autonomy

Beagle2 will only be able to communicate with Earth via Mars Express for 15 minutes every 4 days. The approach taken for arm operations is discussed in section 3.3

3. DETAIL DESIGN

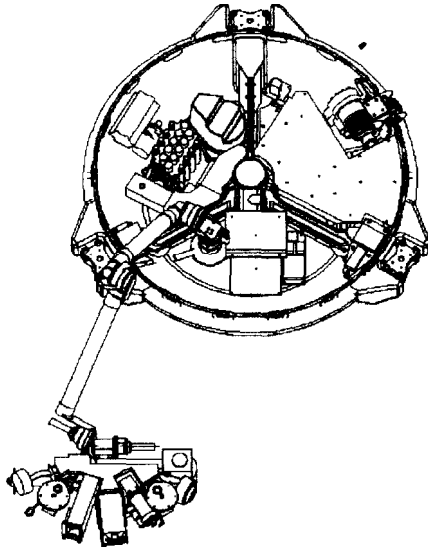


Figure 4 Arm Deployed

3.1 Mechanical Aspects

The robot arm (shown in **figure4**) is a **5-degree** of freedom anthropomorphic manipulator, with the PAW permanently attached to the wrist. Each joint comprises a dc brushed motor driving through a 100:1 harmonic gearbox. Joint position is detected by a potentiometer mounted directly to the output shaft.

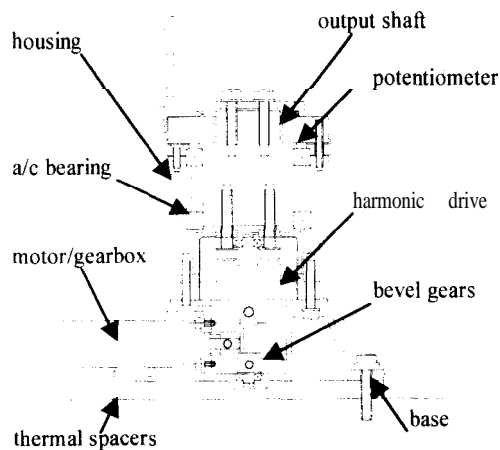


Figure 5 Cross-section through axis 1

All structural items are manufactured from titanium in order to closely match the thermal expansion of the bearings, whilst **minimising** the mass. It is also the best choice where the carbon fibre arm tubes are bonded to the end fittings. There is also a third reason for the choice: at night the robot arm **will** be exposed to the Martian night when temperatures can fall as low as -100°C . The arm will then act as a heat leak from the lander. Despite the choice of titanium thermal spacers are still required under the base of the arm.

The launch and landing loads on the arm are severe, which means that it must be held down securely until Beagle2 is safely on the ground. In order to achieve this the arm is held down using Frangibolts at the elbow and wrist. There is however an additional consideration which is that the arm spans the lander and therefore it needs to be de-coupled **from** the structure. This has been achieved by the introduction of a flexible blade at the elbow, which minimises stress build up due to thermal differentials or deflection of the lander structure, yet still restrains the arm adequately for launch and landing.

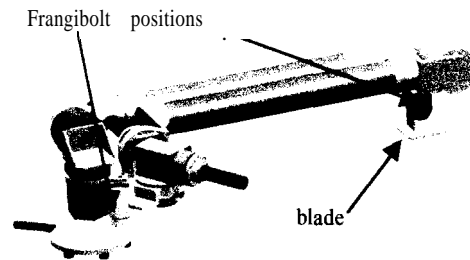


Figure 6 Arm Hold Down Positions

The **multi-functional end effector (PAW)** is a key element to Beagle2 as it comprises all the instruments to examine Martian rocks and to take samples for analysis by GAP. The PAW contains the following scientific instruments:

- a stereo camera pair for stereo imaging, arm navigation and mineralogy
- X-ray spectrometer (XRS) for age dating rocks
- mossbauer for rock mineralogy and petrology
- microscope for optical examination of the rock surface
- corer to prepare a flat surface for the XRS and mossbauer and the take samples for analysis by GAP
- mole to obtain soil samples for analysis by GAP
- wind sensor to study Martian wind speed and direction

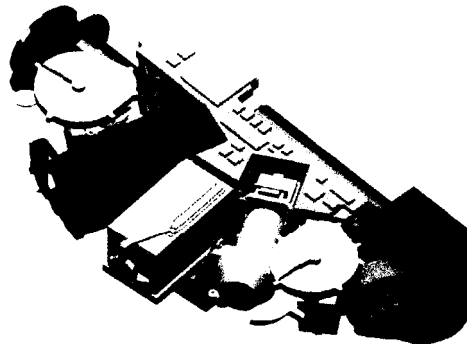


Figure 7 PAW

3.2 Mission Operations

A typical operational scenario for arm operations would be as follows:

- take three **colour** panorama using stereo cameras
- take mineralogy panorama with stereo cameras

- take stereo image of surface
- select target rock
- move close to rock (approximately 100mm)
- image rock in multi-wavebands using stereo camera
- move to target spot
- analyse rock surface composition with XRS
- analyse rock surface composition with mossbauer
- examine with microscope
- remove weathering layer with corer
- re-analyse surface with XRS
- re-analyse surface with mossbauer
- examine surface with microscope
- take sample with corer
- return sample to GAP for analysis

During the 180 sols mission life of **Beagle2**, it is expected that this sequence would be repeated three times followed by three soil samples taken by the mole.

3.3 Operational Aspects

As previously discussed the robot arm must operate with a degree of autonomy, due to the limited communications possible with the Control Centre on Earth.

The proposed approach has been to define a series of safe points and predetermined moves, which can be pre-programmed prior to launch.

• Safe Points:

These are points within the operational range of the arm that can be returned to at any time, without risk of collision and from which the predetermined moves can be carried out.

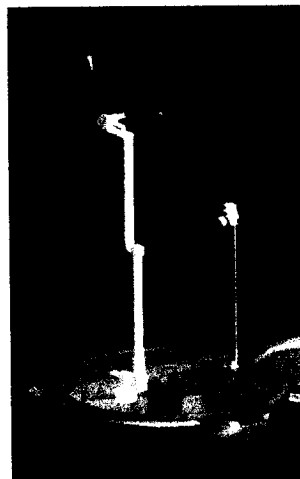


Figure 8 Safe Point 1 (arm vertical)

• Predetermined Moves:

These are moves that can be defined prior to launch and can be carried out without intervention from Earth. These would include the following:

i) arm deployment from the stowed position to a safe point.

ii) move mole to GAP inlet. The position of the inlet port is known and can be programmed from a safe point.

iii) move corer to GAP inlet. Although the final position is different to (ii), this move can also be programmed from a safe point.

iv) **Tinox** sweep- the top surface of the lander is covered with a thermal finish, which needs to be clean to work correctly. It is proposed to tit a brush to the PAW in order to allow any accumulated dust to be swept clear.

v) arm turn around manoeuvre - the arm reach is limited in some areas in the as deployed configuration. It is however possible to remedy the situation by rotating the base (axis1) by 180° and then readjusting the other joints accordingly.

vi) instrument change- there is a need to change between the different instruments. This command could be varied dependant on the current instrument in use and the next one required. The move would involve moving the arm away from contact with the rock to a safe distance then rotating the PAW before returning to continue the investigation.

vii) rock contact and mole launch- a similar approach is required for both scenarios. Having stopped the arm at a safe distance from the target, the final approach would be as follows: drive the arm slowly until contact is detected by a sensor in the PAW, then continue to drive the final joint for a predetermined time in order to obtain the desired pre-load against the surface. The arm motor is then switched off and the pre load is maintained due to the fact that the joints will not back drive at this load.

• Moves defined from Earth:

The position of target rocks and the choice of which ones to examine can only be determined from the ground. The stereo camera data will be downloaded in order to carry out stereo reconstruction. This data will then allow robot joint positions to be determined and uploaded back to **Beagle2**.

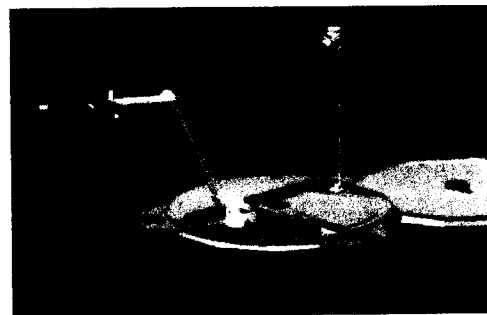


Figure 9 Safe Point 2 (arm over surface)

4. SUMMARY

A robot arm has been designed and a control strategy determined that addresses the particularly demanding challenges of **Beagle2**. The next stage is to manufacture and test the Development Model hardware in order to confirm that the design is robust enough.

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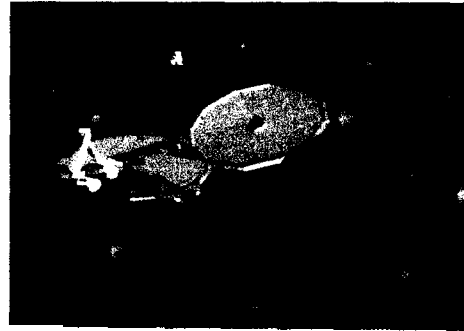


Figure 10 Robot inspecting a rock

