Design and manufacture of a full size Breadboard Exomars Rover Chassis

Author(s):
Lee, C.G-Y.; Dalcolmo, J.; Klinkner, S.; Richter, L.; Terrien, G.; Krebs, A.; Siegwart, Roland; Waugh, L.; Draper, C.

Publication Date:
2006

Permanent Link:
https://doi.org/10.3929/ethz-a-010043415

9th ESA Workshop on Advanced Space Technologies for Robotics and Automation
ASTRA 2006

28 – 30 November 2006 at ESTEC,
Noordwijk, the Netherlands

DESIGN AND MANUFACTURE OF A FULL SIZE BREADBOARD EXOMARS ROVER CHASSIS

Lee, C G-Y[(1)], Dalcolmo, J[(1)], Klinkner, S[(1)], Richter, L[(2)], Terrien, G[(3)], Krebs, A[(4)], Siegwart, R[(4)], Waugh, L[(5)], Draper, C[(5)]

[(1)]von Hoerner & Sulger GmbH, Schlossplatz 8, 68723 Schwetzingen, Germany
Email: lee@vh-s.de

[(2)]Utopia Consultancies, Germany

[(3)] BlueBotics SA, PSE-C, 1015 Lausanne, Switzerland

[(4)] ETH Zurich, Tannenstrasses 3, 8092 Zurich, Switzerland

[(4)] ***Astrium UK Ltd, Gunnels Wood Road, Stevenage, Hertfordshire, SG1 2AS UK***

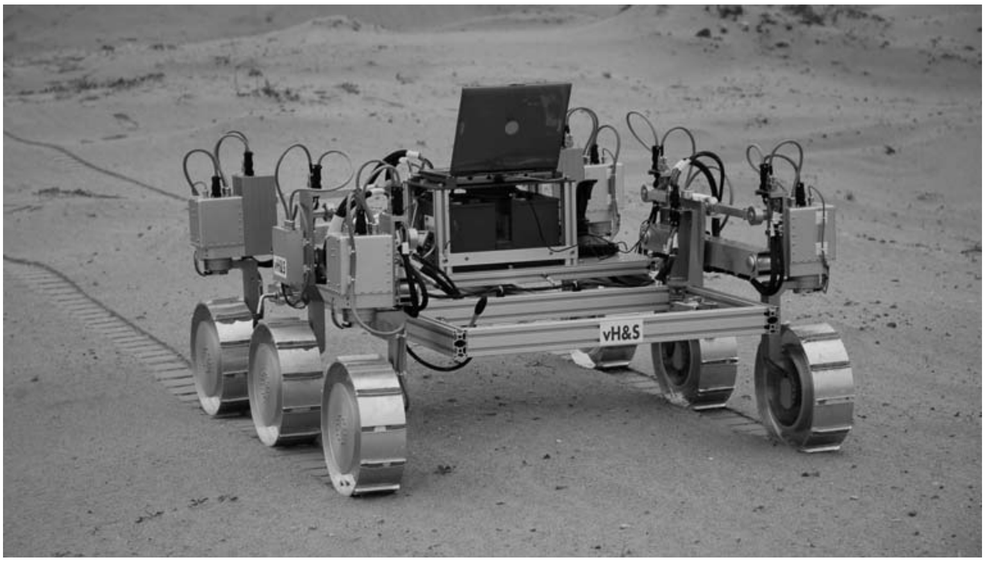


Figure 1 Exomars Breadboard Rover Chassis (a.k.a. Bridget)

1. INTRODUCTION

This paper describes a full size breadboard rover which was commissioned by Astrium UK Ltd and built by a consortium of companies and institutes led by von Hoerner & Sulger GmbH. The primarily intention was to build a full scale rover in order to investigate the capabilities of the suspension and traction system for use on a future EXOMARS rover. It will also be used to study additional rover system components such as the navigation system or a drill. The scale of the rover chassis allows valuable experience to be gained not only in the performance of these systems but also from practical aspects such as accommodation of these components and AIV aspects related to the handling of a full scale vehicle.

The responsibilities for the design and manufacture of the rover were split up as follows:

- **von Hoerner & Sulger GmbH**: System design, suspension and main chassis, electrical system, project management.
- **Bluebotics SA**: wheel and steering drives, motion control hardware
- **ETH Zurich (formally EPF Lausanne)**: motion control software and user interface
- **Utopia Consultancies**: wheels (rigid & flexible)

The rover design reflected the shape and form of the proposed EXOMARS rover at the time. However, pragmatic decisions in the use of materials and off-the-shelf hardware had to be made in order to keep to a reasonable cost for the rover whilst maintaining flexibility for its future use.

2. TOPLEVEL DESIGN

The main design requirements of the rover chassis are based on the output from Astrium UK's Exomars/Pasteur Phase A mission study during which von Hoerner & Sulger GmbH had led the chassis study team. It was decided that the rover dimensions would be as per study whilst not keeping to flight model worse case mass of 240kg. This was done so as to allow cheaper materials to be used and so that the rover can withstand heavier loads with the greater gravity of Earth. However a careful comprise had to be made in the mass scaling so that the flexible wheels did not become so stiff that they were totally unrepresentative of the flight wheel. It was decided to aim for a chassis mass of less than 150kg (including batteries and electronics) with a maximum fully laden mass of 300kg.

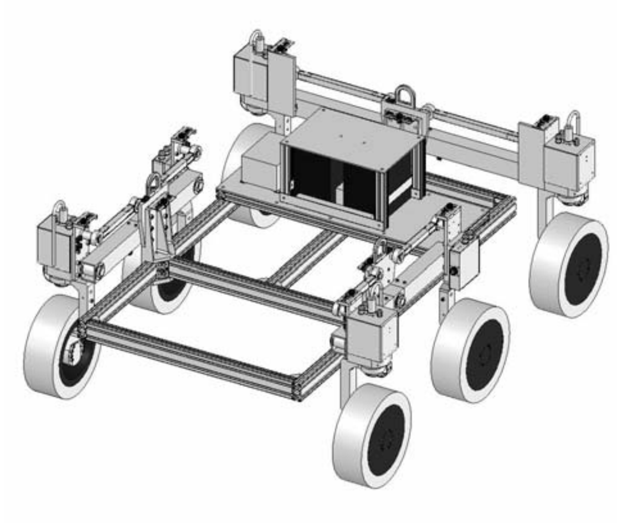


Figure 2 CAD model of breadboard design (RCL-E)

However at the time of the project start, ESA was considering reducing the rover mass requirement for the mission to a low value of, for example, 160kg. Despite the decision not to adhere to the study mass this change would have an impact on the rover dimensions. After due consideration, however, it was decided to remain with the original dimensions of the proposed Phase A design as although the change of mass had been announced, no exact information was available especially in relation to overall dimensions and mass.

The original phase A study proposed a 6 wheel rover with a RCL-C type configuration as the mission baseline as it was a good compromise between complexity (and mass) and its performance in terms of stability and body movements during obstacle negotiation. However, further comparison with miniature hardware rover models conducted for Astrium UK by ETHZ identified an undesirable characteristic which under certain conditions the outside wheels would effectively lift the centre wheel off the ground. A more complex control algorithm could be use to provide a solution to this problem but this is highly undesirable due to extra risk and resource it would entail. For this reasons plus the fact that RCL-E offers a reasonable mass advantage in a flight design, it was decided to proceed with a RCL-E type chassis configuration for the breadboard design.

The change of chassis type meant that some of the rover dimensions had to be extrapolated from the type C study design. This is due to the rear lateral suspension unit that the type E chassis possesses which is not present in the type C chassis. The extrapolation was performed by retaining the original rover wheel base and maximising the main chassis (the base plate connected to each suspension unit) to fill the area in between. The distance that the main chassis protruded in front of the wheel was taken from the phase A study so that it would be consistent with possible accommodation of a robotic arm or drill unit.

The sizing of the suspension components were based on the wheel diameter which was also taken from the Phase A study and the requirement that the chassis must over come a step obstacle of 30cm. This broadly defined the ground clearance and leg length.

The main dimensional specifications of the breadboard are summarised in Table 1.

Table 1 Summary of the main specification from the Exomars Rover breadboard

Name	**Exomars Breadboard**	**RCL-C Value**	**Comment**
Step height	30cm	30cm	
Speed	140 mh^{-1}	100 mh^{-1}	
Front wheel to rear wheel distance	1182 mm	1181.5 mm	centre to centre, rover on flat horizontal ground
Right wheel to left wheel distance	1070 mm	1070 mm	centre to centre, rover on flat horizontal ground
Ground clearance	304 mm	310 mm	Stiff wheels and no grousers.
Leg length	298 mm	N/A	From wheel centre to centre of main beam pivot
Wheel diameter	300 mm	300 mm	without grousers
Wheel width	100 mm	100 mm	
Grouser height	8 mm	5 mm	Above wheel rim
Main chassis width	750 mm	630 mm	
Main chassis length	1260mm	1460 mm	Will extend 20mm past forward edge of an unloaded front wheel.

3. SUSPENSION UNITS

The suspension concept used for the breadboard model is based on the RCL type E chassis as described by the ESROL-A study [1]. According to the study, the ideal passive suspension for obstacle negotiation is one in which there is no longitudinal displacement of the wheels positions as the rover negotiates an obstacle. Longitudinal displacement of the six wheels relative to the centre of mass will cause the loads on each wheel to vary from the ideal situation where all wheels are equally loaded. This however, ignores the effect of the rover body inclination as it changes from horizontal.

Examples of chassis which approaches such a characteristic are the EPFL CRAB chassis and the RCL concept D chassis (Exomader) which also display minimal body movement during obstacle negotiation. The drawback with both of these chassis is the complexity of the suspension linkages and the inevitable overhead of mass that this would cause in a flight design. In order to address this issue RCL concept E chassis was developed which simplifies the suspension mechanism at the expense of stability and increased body movement. The chassis E concept consists of two front longitudinal bogie units and a single rear lateral bogie units. The main chassis of the rover itself acts as part of the suspension mechanism connecting the rear and front bogies.

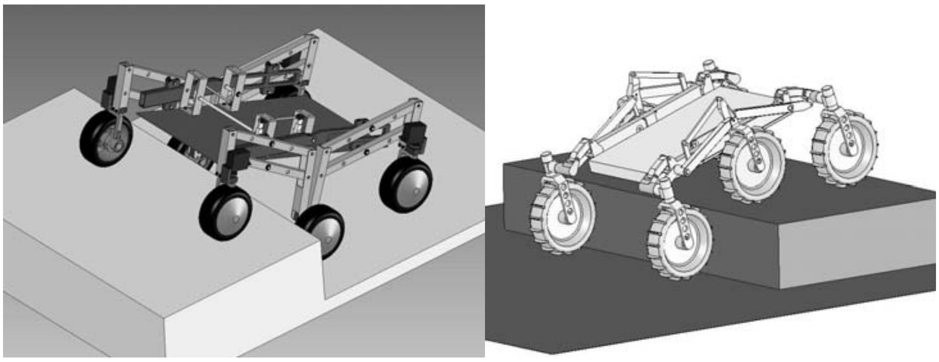


Figure 3 *(left)* CRAB chassis, *(right)* Exomader (RCL-D) Chassis

The designed suspension unit was optimised so that the longitudinal displacement of the front wheels is minimised for the given wheel size and required step climbing ability of 300mm. The final design gives a maximum longitudinal error of 3.7mm and a mean squared error of 1.7mm over the vertical displacement of a single wheel between ±150mm.

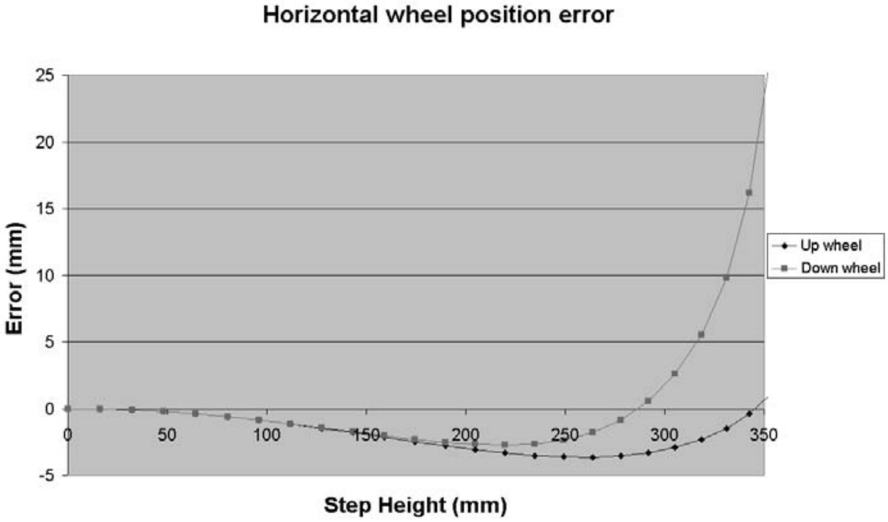


Figure 4 Horizontal Displacement versus step height (vertical difference between each wheel)

To reduce the part count, the rear lateral suspension unit uses the same components as the front units except with longer beam members to accommodate the rovers width. Using the same parts meant that the rear suspension unit is not optimised to minimise the lateral movement although this movement is now perpendicular to the direction of motion and thus less critical. More critical, as it effects the wheel's foot print, is the slight deviation from vertical that is seen by the wheel leg. The maximum values for both of these parameters occurs at the 300mm limit of the step requirement where the vertical displacement is 12.8mm and the leg is less than 3.5° from vertical which was considered a good compromise between the two.

4. WHEEL AND STEEERING DRIVES

The rover has 10 drive units in all: four steering drives in the corner wheels plus six wheel drives. For economy and schedule, all motor drives are based on the same design and differ only in accommodation between the wheel and steering units. Each drive were built from off-shelf-components comprising of a 1800:1 harmonic drive coupled to a Maxon EC45 motor. This configuration provides a peak torque of 70 Nm at a maximum speed of 2.5 rpm. For the wheel drives this equals a speed of 150 metres per hour.

The use of a single harmonic drive with the motor allows for a compact drive unit that can be accommodated in a low profile leg and thus minimising the possibility of interference with any obstacle the rover is surmounting. The steering drive is situated at the top of the leg and accommodated with the electronic controllers required for all the drive on the leg. An additional potentiometer is included to each steering mechanism to provide absolute measurement of the steering angle.

5. FLEXIBLE WHEELS

During the Phase A Study of the rover chassis it had been highlighted that the use of a flexible wheel would be beneficial to vehicle performance and efficiency in several ways:

- for a properly designed flexible wheel, the larger (and longer) ground contact footprint will lead to less slip and higher thrust as compared to a similarly sized rigid wheel, resulting in better drawbar performance (and thus improved slope climbing capability)
- overall motion resistance of a properly designed flexible wheel is lower than that of a similarly sized rigid wheel, resulting in smaller losses or, equivalently, a better mileage (energy to be spent per distance driven).

Obviously, development of a flexible wheel for space has its own challenges and is intrinsically more involved than development of a rigid wheel that has been the default choice for unmanned planetary rovers thus far. However, an all-metallic flexible wheel had been conceived and sized in the Phase A effort due to its significant benefits as just outlined, and was favourably received by ESA.

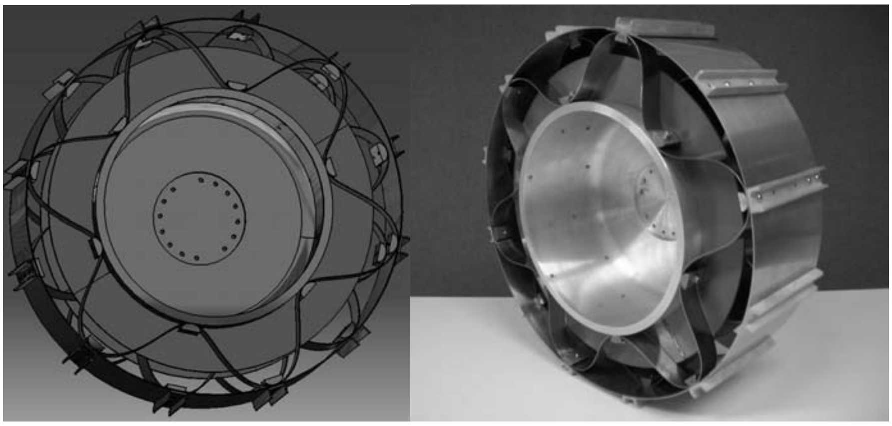


Figure 5 Flexible wheel: CAD model (left) and as manufactured (right)

For the chassis breadboard activity, the Phase A wheel design was found to be not viable, primarily due to the higher quasi-static design wheel loads of up to 500 N to be endured by the wheel. Compared to the Phase A design - which had the wheel elasticity provided by cylindrical stainless steel leaf springs arranged around a rigid hub and held by an outer elastic ring - a new geometry of the sheet metal spring elements was chosen (as shown in Figure 5) that is capable of delivering a higher stiffness: the selected arrangement features three parallel bands of 0.4 mm stainless steel that are mounted in a sinusoidal-like fashion. Wheel diameter, including 8 mm tall grousers, is 316 mm and wheel width measures 100 mm. The design is such that at the design wheel load of 500 N the elastic wheel running surface and attached spring elements begin to make contact with rigid bump stop disks in the wheel that in turn are mounted to the rigid hub (where the I/F to the actuator housing is located), preventing further wheel deformation beyond 500 N of wheel load and thus ensure that the springs are never operated in a plastic regime if loads are temporarily higher during dynamic situations (such as incurred when negotiating obstacles).

Mass per wheel as built for the chassis breadboard is 2.5 kg, including the rigid hub with the mounting I/F. Finite Element Modelling recently conducted suggests a potential for mass savings by optimisations of the design, including the use of Ti alloy for the leaf springs and refinement of spring attachment points.

For use on the chassis breadboard, composite stiffeners have been developed as well that can be fitted to the wheels for preventing their deformation under load, permitting comparative locomotion testing of flexible vs. rigid wheels of same dimensions at approximately constant mass.

6. MAIN CHASSIS

A simple main chassis was built for the rover made out of Rexroth components which allows quick and easy modification by the end user. At the time of design, it was unknown what future requirement or form the end user had for the main chassis and so the final configuration was left open to allow for integration of additional systems and the necessary structure required to make the chassis rigid enough for operation on rugged terrain such as the tests on Tenerife.

Onto this basic frame was added a "saddle" which accommodated the system batteries, the main electronic box and the motion control computer. The saddle unit is fixed in between the main attachment points of the rear and front suspension units in a way which allows its exact longitudinal position to be modified. This feature makes it possible to alter the rover's centre of mass either to assess its effect on the terrainability performance or to reposition it when additional equipment is added to the rover.

7. ELECTRONIC SYSTEM AND CONTROL

7.1. Hardware

Each of the electronic drive controllers are connected to a CAN bus which along with a power bus, are routed around each of the suspension units and the main chassis. The power bus provides an unregulated 24V supply which powers both the motors and the electronics. The power is provided by two 12V sealed lead acid batteries giving a test duration of 2-3 hours. The system power is monitored in an electronic box which also provides the distribution point for power and data buses.

The motion controller computer is a standard laptop computer with a USB to CAN interface and external joystick.

7.2. Control Software

The control software is implemented in C++ and provides a graphical user interface and a control algorithm to coordinate the motion of the wheel and steering drives. The user interface displays basic information on the state of all the drives and system power as well as the current command settings. All information is also logged to file on disk. Control of the rover is performed with the external joystick.

The control algorithm implemented sets the rotational speed and steering angle of each wheel respecting the mechanical constraints given by the suspension mechanism of the rover. The idea is to avoid the wheels fighting each other, reducing the energy consumption and improving the terrainability and mobility [2].

Once a speed input is set, the variations on the wheel speed due to the terrain irregularities, the slippage and other disturbances, are taken care of by a wheel synchronization algorithm [3]. It updates each wheel speed independently for a better global behavior:

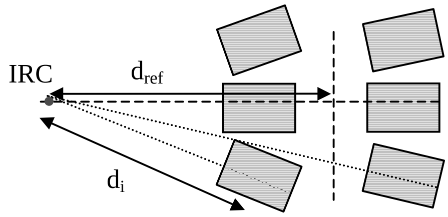
$$V_i^{t+1} = V_{nom} + \Delta V_i \qquad (1)$$

and

$$\Delta V_i = F_{syn}\left(V_{i=1:n}^{t}\right) \qquad (2)$$

where *i* is the wheel number, *n* the number of wheels and t the time.

A double Ackermann steering is used to control the steering. The principle ensures that all the wheel axes continuously intersecting at a unique point in space called Instantaneous Rotation Center (IRC). The commanded steering angle and its related speed are for an imaginary wheel situated between the front pair of wheels and provides the given IRC position for a given command. Once a new steering angle has been commanded it is also necessary to ensure that the IRC remains mutual for all wheels during the transition. A special case also exists when the IRC is in between the centre wheels. This so call “point turn” mode has been implemented but can only be entered/exited when the rover is motionless.



The use of such a steering method has consequences on the wheel speeds. They have to be proportional to the distance d_i to minimize slippage.

$$V_i' = \frac{d_i}{d_{ref}} V_i \tag{3}$$

$$V_i' = F_{ack}\left(V_i\right) \tag{4}$$

where d_{ref} can be defined as the distance between the IRC and the centre of the rover.

In the end, the combination of these to methods yields the following control algorithm:

$$V_i'^{\,t+1} = F_{ack}\left(V_i^{t+1}\right) = F_{ack}\left(V_{nominal} + F_{syn}\left(V_{i=1:n}^{t}\right)\right) \tag{5}$$

$$V_{i=1:n}^{t} = F_{ack}^{-1}\left(V'^{\,t}_{i=1:n}\right) \tag{6}$$

The wheel speeds at time *t+1* depend only on the measured wheel speeds at time *t*, $V'^{\,t}_{i=1:n}$. The current implementation of the control loop allows the loop rate to be changed between 5 and 8 Hz. The maximum rate is limited by the hardware and software implementation of the USB to CAN bus driver.

8. INITIAL TESTING

Before delivery the basic characterisation and functional tests were performed at von Hoerner & Sulger GmbH before delivery to Astrium UK site in Stevenage. Basic movements were first tried out followed by the negotiation of small obstacles and then finally operation in an sandy terrain. Images from these tests are shown in Figure 6.

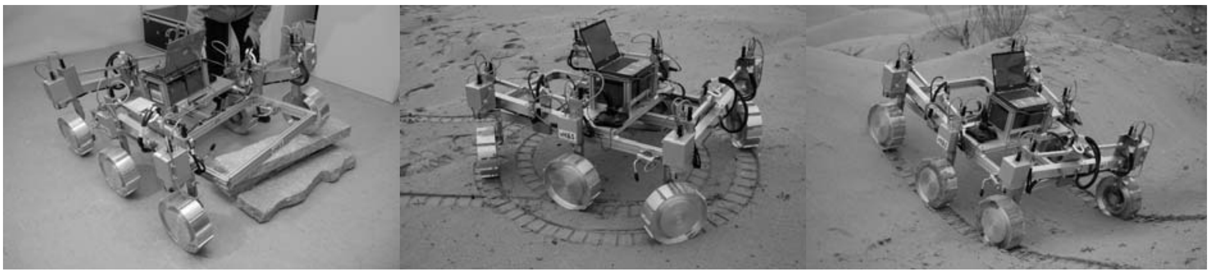


Figure 6 Manufactured rover during initial testing

9. CONCLUSION

A 125 kg full scale breadboard rover chassis model was designed based on the output of the Exomars Phase A study using the RCL chassis E concept and flexible wheels. The breadboard model used off the shelf components and materials which allows for easy modification and flexibility for future study. The rover was delivered to the customer in the first quarter of 2006.

Since delivery it has been used by Astrium (UK) for testing both in Tenerife and the UK. It has also made several media appearances for the customer and have appeared extensively in press and television in the UK and other parts of Europe.

Valuable experience has already been gained during the project which will be put to good use for the next phases of the Exomars project. Further field trials and performance test undertaken will build further on this experience.

10. REFERENCES

[1] V. Kucherenko *et al*, "*Final report – Engineering Support on Rover Locomotion for Exomars Rover Phase A (ESROL-A)*", Rover Company Ltd, Issue 1.0, December 2004.

[2] Apostolopoulos, D. S. (2001). "*Analytical Configuration of Wheeled Robotic Locomotion.*" The Robotics Institute. Pittsburgh, Pennsylvania, CMU.

[3] Baumgartner, E. T., H. Aghazarian, et al. (2001). "*Rover Localization Results for the FIDO Rover.*" SPIE 4571: 34-44.