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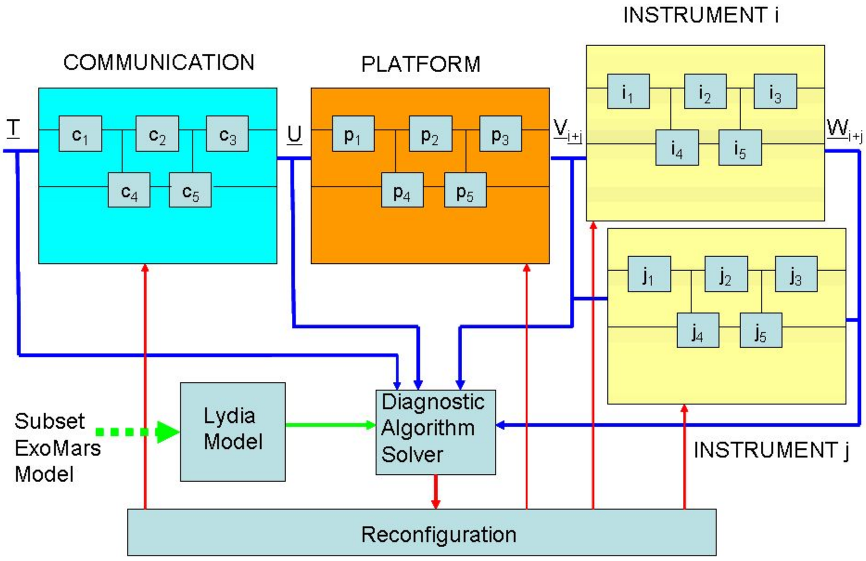
National Aerospace Laboratory NLR

Executive summary

Automated on-board model-based diagnosis during planetary mission and teleoperation



Problem area
The infrastructure for operating instruments on robotic platforms for planetary missions needs to be robust to allow remote operations. One way of improving robustness is to add a diagnostic subsystem which is able to support the control.

The diagnostic reasoning subsystem includes both knowledge about the communications and the robot system operating in the planetary environment. The project "TELEoperations and Model-based Supervision for instruments for planetary exploration" (TELEMOS) aims to develop and test this concept.

Description of work
An overview is provided of the project by introducing Model Based Diagnosis, the toolset used, the cases being studied and the tested.

Results and conclusions
The first phase of the project has been completed and the planned activities are introduced.

Applicability
Application is foreseen in harsh environments for teleoperation.

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This report is based on a presentation held at the 10th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ESTEC, 11 - 13 November 2008.

Automated on-board model-based diagnosis during planetary mission and teleoperation

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Automated on-board model-based diagnosis during planetary mission and teleoperation

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[1] Science & Technology

This report is based on a presentation held at the 10th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ESTEC, 11 - 13 November 2008.

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Summary

The infrastructure for operating instruments on robotic platforms for planetary missions needs to be robust to allow remote operations. One way of improving robustness is to add a diagnostic subsystem which is able to support the control. The diagnostic reasoning subsystem includes both knowledge about the communications and the robot system operating in the planetary environment. The project “TELEoperations and Model-based Supervision for instruments for planetary exploration” (TELEMOS) is part of the Pre-qualification ESA Programme and aims to develop and test this concept.

The project takes the LYDIA (Language for sYstems DIAgnosis) modelling language as a started point for describing the diagnostic rules. A corresponding rule-based engine developed by S&T will be used for implementation. As part of a first phase the descriptive languages for modeling the on-board command and control are being reviewed for use in automation for the instruments and interfacing to the robot platform. The link between the rule-based engine and the executive control is part of the research. Experience with instrument scheduling for Columbus Payloads and instrument scheduling for planetary operations on robot platforms is compared.

To enhance the Technology Readiness Levels and to validate various appraoches a teleoperation simulation setup is being developed. The integration and interfaces of the diagnostic reasoning are described. The test setup will be based on a hybrid setup containing both software and hardware robotic elements. The communication modeling is done using the Satellite Toolkit. A number of cases for a Mars mission are analyzed and the proposed validation approach is presented with conclusions on the proposed approach.

As an appendix a summary presentation is included presented at the report is based on presentations held at the 10th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ESTEC, 11 - 13 November 2008 and an earlier presentation at the 2nd NPP Symposium Planetary Exploration & Extra-terrestrial habitats for life, Velthoven, 19-20 March 2008.

Contents

Abbreviations

ASTRA	Advanced Space Technologies for Robotics and Automation
CAN	Controller Area Network (bus)
CCD	Charge Coupled Device
CCSDS	Consultative Committee for Space Data Systems
CLUPI	Close-up Imager
ECSS	European Cooperation on Space Standardization
EGSE	Electrical Ground Support Equipment
FDIR	Failure Detection, Recovery and Isolation
FMECA	Failure Modes, Effects and Criticality Analysis
FRM	Functional Reference Model
HPL	Humbold Payload
HP3	Heat flow Physical Properties Package
ICD	Interface Control Document
ICEU	Instrument Control and Excitation Unit
LIBS	Laser Induced Breakdown Spectroscopy
LMC	Life Marker Chip
LYDIA	Language for sYstem DIAgnosis
MBD	Model Based Diagnosis
MBR	Model Based Reasoning
NPP	Nationaal Planeet Platform
OHU	Optical Head Unit
PEP	Pre-qualification ESA Programmes
PPL	Pasteur Payload
RAMS	Reliability Availability Maitainability and Safety
S&T	Science and Technology B.V.
SCOS	Spacecraft Control and Operations System
SEIS	Ultra broad band seismometer
SESP	Simulation for European Space Programmes
SOIS	Spacecraft Onboard Interface Services
SPDS	Sample Preparation and Distribution System
SPEX	Spectropolarimeter for Planetary Exploration
TELEMOS	TELEoperation and MOdel-based Supervisie of Instruments for planetary missions
TM/TC	Telemetry/Telecommand
TRL	Technological Readiness Level

AUTOMATED ON-BOARD MODEL-BASED DIAGNOSIS DURING PLANETARY MISSION AND TELEOPERATION

ABSTRACT

The concept is explored for model-based diagnosis to support teleoperation of instruments in planetary missions. Architectures are reviewed and options for integration of tools are analysed. A toolset is described which has been selected for the implementation and integration with a test environment. A number of cases related to instrumentation for Mars exploration are introduced.

INTRODUCTION

The infrastructure to operate instruments on robotic platforms for planetary missions needs to be robust to allow remote operations. One way of improving robustness is to add a diagnostic subsystem that is able to support remote and automated control. The project "TELEoperation and MOdel-based Supervision for instruments for planetary exploration" (TELEMOS) aims to develop the concept, increase technology readiness and gain experience in testing. This paper introduces the project which is part of the Pre-qualification ESA Programs (PEP) in the Netherlands*.

The first section introduces the concept, the second section contains a review of model-based diagnosis and the third section introduces the toolset. A number of cases are discussed and the corresponding test bed being developed is introduced at the end of the paper.

CONCEPT OF MODEL-BASED DIAGNOSIS AND TELEOPERATION

A model-based supervision component is foreseen which monitors teleoperation and takes corrective actions when relevant. The diagnostic reasoning subsystem implementing supervision includes models about the communications, the automated instrument and the platform operating in the planetary environment (Fig. 1).

* The work is funded via the Netherlands Agency for Aerospace Programmes NIVR through contract nr. PEP 61730N.

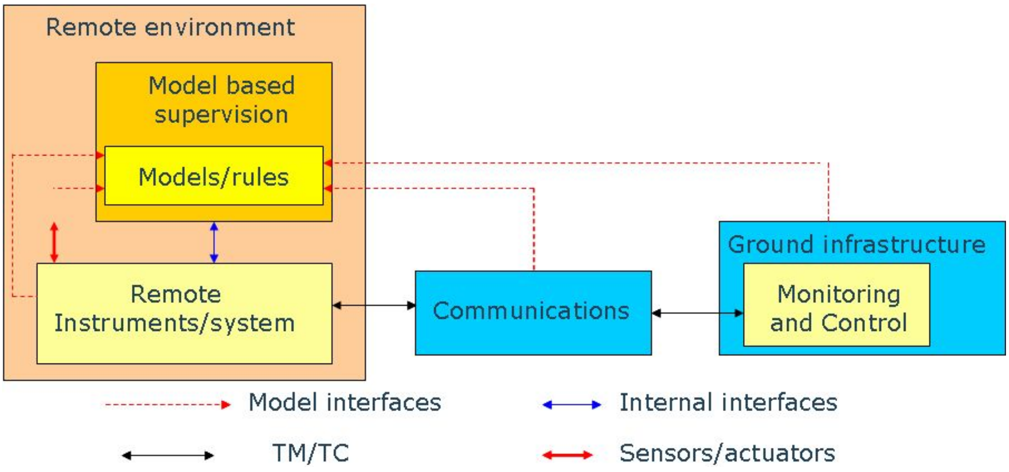

Fig. 1. TELEMOS concept integration of model-based supervision

MODEL-BASED DIAGNOSIS APPLICATION REVIEW

From space systems failures in the past a long list can be compiled: propulsion system failures, attitude control system failures, electrical failures, failures induced by the space environment, structural failures, ground system failures, operator errors and software errors [1]. Fault-diagnosis and teleoperation can be integrated in many architectures for space applications to avoid failures and allow robust operations.

The overall fault mitigation strategy analysed in the TELEMOS project is referred to as Model-Based Reasoning (MBR) or, in case of the specific application of finding the root cause of failure, Model-based Diagnosis (MBD). The expected functionality is compositionally modelled with logical constraints that are conditional upon the system health. For diagnosis a model is used to predict the output based on the known input and health state. The unknown health state is inferred from the observed inputs and outputs. This inference requires a declarative rather than an imperative model which is more common for simulation, such as used in, e.g. Matlab/Simulink. The theory of MBD was first proposed by Reiter and De Kleer [2-3] and implemented with the General Diagnostic Engine (GDE) for declarative models. Since that time, a lot of effort has been put into making MBD computationally more efficient. Different strategies have been pursued such as conflict detection, hierarchical approaches, and using different knowledge representations [4-5]. MBR has been applied in the space domain for Deep Space 1 [6] and Earth Observing One [7]. The NASA Hybrid Diagnostic Engine (HyDE) implementation[8], a follow-up of the Livingstone toolset, is a hybrid system since it is capable to deal with constraints in both discrete and continuous domains. HyDE contains a mix of a rule-based and neural network approach and was used in the Drilling Automation for Mars Environment (DAME).

The On-Board Assistant (OBA) flight element has been proposed to assume the role of an ERA MMI plus the role of an on board operator [9] with similar objectives, but in the TELEMOS project the emphasis is on ground control and on-board automation without crew involvement. Formal approaches for the control architecture development [10-12] can be used complementary. For microgravity facilities scripts and timelines executed via an on-board interpreter are typically used to co-ordinate instruments. For planetary missions it becomes more important to have a reconfigurable model-based approach to fault-diagnosis and teleoperation. ESA is co-ordinating several approaches and standards as part of space avionics software development [12]. Various ESA standards are applicable and can be linked to the approach and are closely linked to the documentation which is the basis for elaborating MBR.

IMPLEMENTATION USING MBR TOOLSET

LYDIA has been developed at the Delft University of Technology [4-5] and is an acronym for Language for sYstem DIAgnosis. Fig. 2 illustrates the basic concept applied to the teleoperation scenario. The health of a system is integrated in the input output relation of a system. Based on the real measurements, the health is derived for individual subsystems using the LYDIA subsystem model. The models are based on propositional logic, and include probability indications. This allows using problem solvers with an efficient implementation to allow near real-time diagnosis.

The project takes the LYDIA modelling language as a starting point for describing the nominal component behaviour. S&T has developed the related model-based reasoning toolset for model-based diagnosis and reconfiguration in co-operation with the Delft Technical University of Technology. LYDIA has been modelled after the NASA Livingstone toolset. The MBR toolset consists of:

- LYDIA, the modelling language.
- A generic reasoning engine based on consistency checking algorithms.
- Reasoning applications for diagnosis and reconfiguration.

To better illustrate MBD we use the following example system. We model a valve as a component with an incoming and outgoing flow. For a healthy valve, the valve control variable determines the outgoing flow. A *true* control variable implies an open valve for which the outgoing flow is equal to the incoming, and a *false* control variable implies a closed valve for which the outgoing flow is zero, i.e., *false*. The propositional equations are

$$control \Rightarrow (flowOut = flowIn)$$
$$\neg control \Rightarrow \neg flowOut$$

This corresponds to the following LYDIA code

```
if ( control ) { flowOut = flowIn; }
else { flowOut = false; }
```

In non-trivial, real-world problems, observations are typically limited. For this component we assume that only the control variable and the outgoing flow are observable. The following listing shows the complete LYDIA model in which the valve behaviour is dependent on the health variable `h`. This variable represents the component health mode, for which `true` indicates a healthy component and `false` a component at fault.

```
if (h) {
        if (control) {flowOut =  flowIn;}
        else {flowOut = false;}
    }
```

As `flowIn` is not observable the only exclusive fault that can be detected is that of a leaky valve. The observations for this fault are `control = false` and `flowOut = true` which is only consistent for `h = false`. For all other observations `h = false` and `h = true` are *both* consistent, which illustrates that limited observability typically leads to limited diagnosability, i.e., multiple or ambiguous diagnoses.

The solver engine developed by S&T is the basis for MBR implementation in the TELEMOS project and has been applied in a number of industrial and ESA demonstration projects:

- Lithography machines (ESI/ASML Tangram Project).
- Health Management System for a Reusable Space Transportation System (HMS-RSTS)
- Software Architecture for Integrated Vehicle Health Management (IVHM) Systems.
- The Advanced Human Computer Interface (AHCI) project.
- Harbour Cranes (Siemens Arcadia II Project).

CASE ANALYSIS INTRODUCTION

In the following subsections a number of cases are introduced which form the basis for the developments. They allow gaining experience with the concept for communications, platform and instruments. The case development is focused on the instrument control with relevant parts of the communications and the robot platform included..

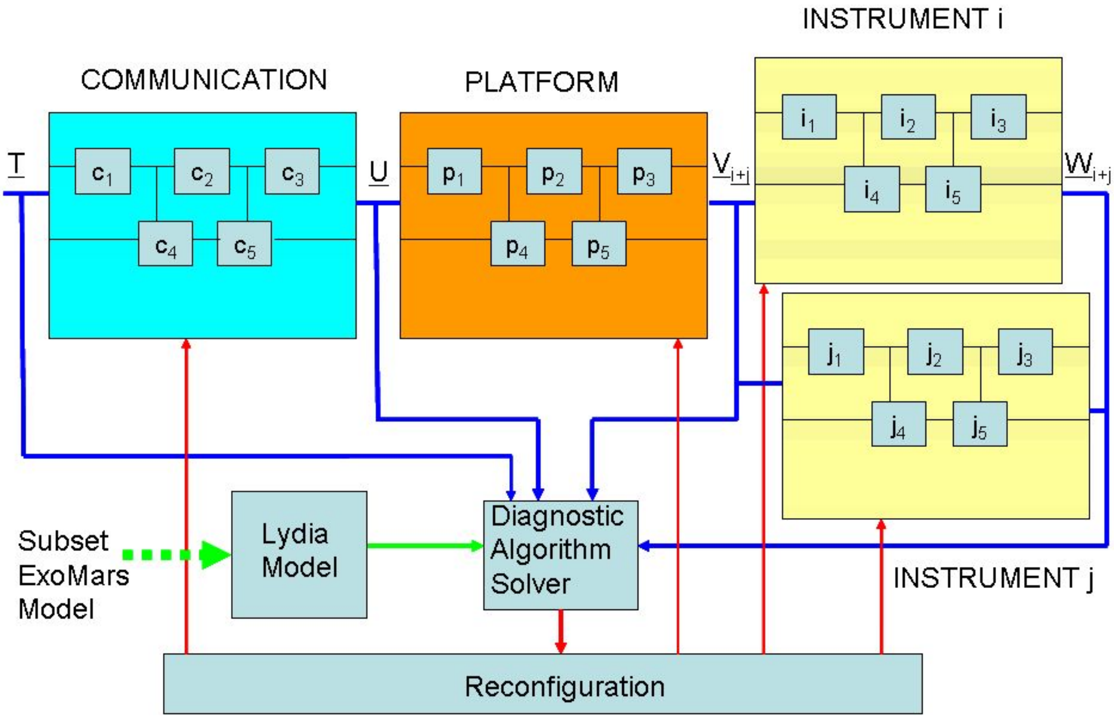

Fig. 2. Based on models of communication, platform and instruments the reconfiguration will be supported

ExoMars Analytical Drawer generic application analysis

The Enhanced ExoMars mission will typically support 23 instruments. For the Rover 12 instruments are planned (the Pasteur Payload) and for the Lander 11 instruments are planned (the Humboldt Payload). For each instrument a data package needs to be provided related to fault -diagnosis as part of the Preliminary Design Review. The data package for each instrument is expected to include a Design report, a Software User requirements document, a FMECA report, an Instrument Risk analysis and a draft FDIR report. The Failure Modes, Effects and Criticality Analysis (FMECA) builds upon the Reliability Block Diagrams to assess the impact of different component failure modes. According to generic interface requirements, each instrument shall provide on-board failure detection capabilities based on more than one sensor. All mission critical functions shall be monitored by at least two independent parameters, to be determined on a case-by-case basis. This implies that each instrument will have several sensor outputs to be used for fault-diagnostics.

For ExoMars dedicated requirements are imposed on the failure detection algorithms. They are partly related to avoiding excessive communication traffic and to allow setting of parameters from ground. So in the model shown in Fig. 2 dedicated requirements are imposed on the reconfiguration. The on-board system requires that the time between the occurrence of the failure and the manifestation of the irreversible consequences is estimated for catastrophic and critical failure consequences. The propositional language used in LYDIA does not allow directly reasoning about time. It is possible to add additional states for some timing aspects. In addition the reasoning can be part of the further processing and reconfiguration. In case of a time-critical hazard, which may affect mission objectives and from which autonomous recovery and continuation of nominal operation is not possible, the affected instrument shall have to be configured into a Safe Mode to await Ground Control intervention.

The ESA Functional Reference Model FRM developed in the context of robotics has been based on the three hierarchical layers, mission, task, and action, with forward control, nominal feedback, and non-nominal feedback for each layer. For instruments related concepts can be used. The hierarchical approach which has been required for ExoMars instrument control can be implemented. Each instrument is required to have knowledge of the actual health status of all its hardware units which allows analysis at instrument level. The analysis can be propagated at the level of instrument co-ordination. If the knowledge is integrated in the telemetry, the observability of parameters in the internal interfaces is a basis for partitioning. Using LYDIA, two approaches can be considered. A hierarchical solver is available for the disjunctive normal form which is faster in run-time based on introducing an additional model compilation step. Another approach is to use a divide and conquer approach in which the drawer system is split into a healthy and unhealthy part. The unhealthy part is continuously reduced until a minimal (best) correct solution is found.

ExoMars instrument co-ordination Raman spectroscopy

Another application for the concept being elaborated is the co-ordination of instruments operations. Typically, a global inspection is done using a camera or microscope before detailed analysis using Raman spectroscopy can be done in a science activity loop:

EXP-1 **Target on position or sample obtained via drilling**

EXP-2 **Examine using external observation or microscope in case of sample being processed**

EXP-3 ***Spectrum Acquisition***

- **a. Initialisation**
- **b. Autofocus process using internal actuators**
- **c. Processing adapting parameters (exposure time, number of samples)**
- **d. Spectrum acquisition**

EXP-4 **Spectrum analysis**

EXP-5 **Storage and downlink**

The types of faults which can be modeled are related to the individual steps and subsets. The target position requires co-ordination with another device. In case of the internal observation this involves a microscope and in case of the external observation this includes a camera mounted at the end of a small robot arm. The basic sensor is a CCD sensor for which a Spacewire interface is assumed. Via the CAN-bus an interface is provided to the Exomars controller. The monitoring provided for in Raman is ON/OFF status (bi-level monitoring) and 2 - 3 thermistors (temperature monitor). The individual components can be modeled using the LYDIA language.

Flying platform

ExoFly is a light-weight (20 to 200 g.) flapping wing robotic fly, which can be used for reconnaissance missions to prepare for detailed exploration and scientific observations on the surface and for the lower atmosphere [12-13]. The concept of ExoFly has been initiated at the Delft University of Technology. The ExoFly is of interest to the TELEMOS project in view of the Dutch involvement and difficult autonomous operation challenges requiring new technology developments. A ground control station will implement many of the off-board algorithms. Part of the algorithms will be based on image processing. The processing power available at the ground station can allow the inclusion of MBR components, which could address the specifics of the long round-trip delays which may be allowed for a rover, but not for a flying platform. The guidance, navigation and control needs to be reduced considerably due the size and weight limitations, stability and control properties, aerodynamic and mission considerations. A mixture of image processing algorithms can be used to determine speed, height and attitude[13]. The LYDIA language can be used to define various health diagnosis algorithms in which various Mars environment variables need to be represented as Boolean variables.

GENERIC TESTBED ENVIRONMENT

To enhance the Technology Readiness Levels of the MBR toolset and to validate various approaches, a teleoperation simulation setup is being developed. The test setup will be based on a hybrid setup containing both software and hardware robotic elements similar to another setup [14] for simulation of the operations for the European Technology Exposure Facility (EuTEF). The communications modelling will be done using the Satellite ToolKit developed by Analytical Graphics. A diagnostic engine which is part of the LYDIA toolset has been installed and is being interfaced with the environment.

The link between the diagnostic engine and the executive control is subject of further research and depends on the case to be analysed. The LYDIA C-libraries can be linked directly to the simulation environment. The toolset can also be interfaced via a Unix-pipe mechanism. A Diagnostic interface extracts telemetry data from the teleoperation setup and converts this to diagnostic data. To ensure consistency with the model, dedicated mapping and checking is needed in order to map the telemetry onto the variables used in the diagnostic model. Using the EuroSim simulation platform, models of the instruments can be integrated. The simulation will be integrated with a dedicated 3-D display using the data dictionary for the variables interfacing to the simulator (Fig. 4).

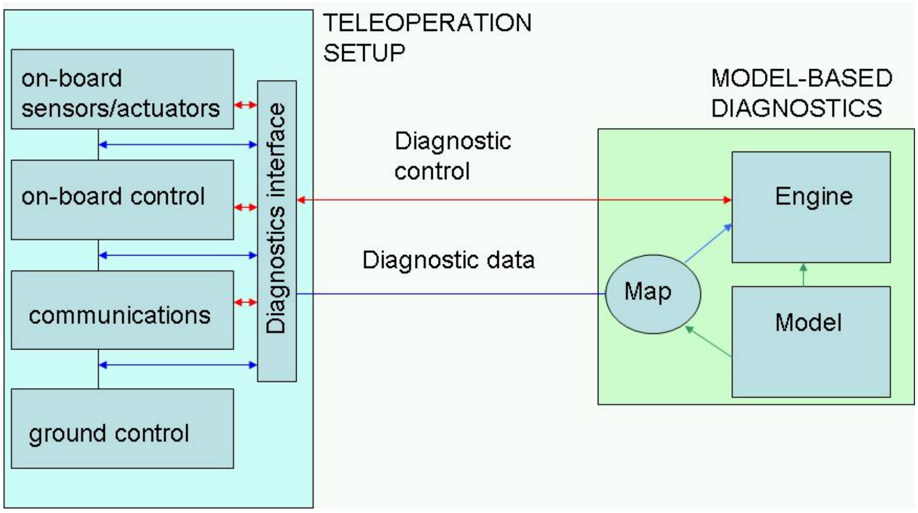

Fig. 3. The model-based diagnostics will be clearly separated from the teleoperation set-up.

CONCLUSIONS AND FURTHER WORK

The concept of model-based diagnosis has been introduced and potential applications were introduced. The TELEMOS project has three phases for which background was described: 1. Generic analysis and architectures, 2. Development and implementation case, 3. Test and demonstration. The first phase is completed and the work for phase 2 has been started. The co-ordination of a Raman spectrometer with other instruments and ExoMars Analytical Drawer subsystems has been selected for further detailed analysis. The other cases mentioned will be used to validate broader application. The application will depend on details of the designs that are currently being developed. Compared to existing approaches the limitations and potential application of the MBR toolset framework have been reviewed, but further work is needed in developing and using the test bed environment.

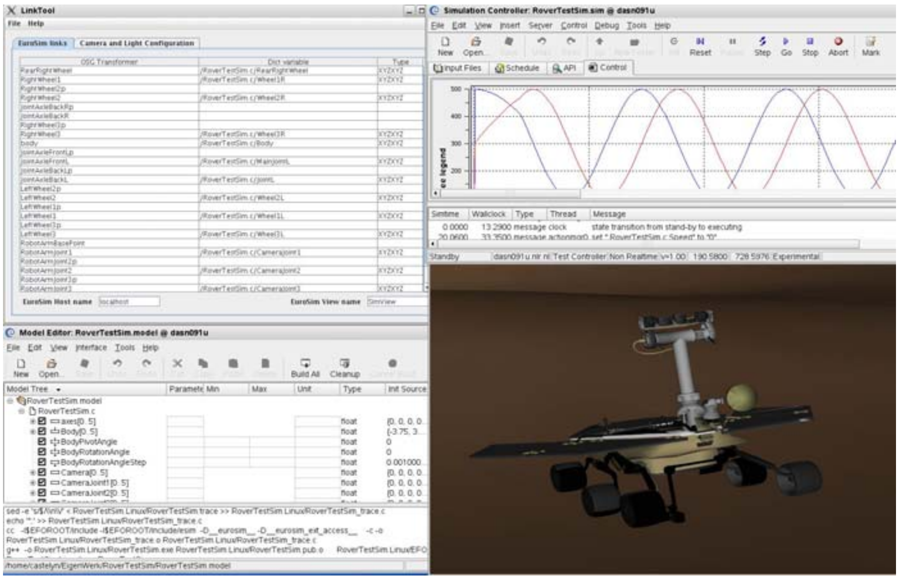

Fig. 4. EuroSim models will be interfaced via a dedicated tool to OpenSceneGraph visualisation

Acknowledgements

The NLR support of Jacques Spaa in reviewing and Ton Casteleyn in the development of the test bed environment is gratefully acknowledged.

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Appendix A Summary presentation project status

Automated on-board model-based diagnosis during planetary mission and teleoperation

s[&]t dependable solutions

INTRODUCTION

The infrastructure for operating instruments on robotic platforms for planetary missions needs to be robust to allow remote operations. One way of improving robustness is to add a diagnostic subsystem that is able to support the remote and automated control.
The project "TELEoperation and MOdel-based Supervision for instruments for planetary exploration" (TELEMOS) aims to develop the concept and to gain experience in use and testing. The work is funded via the Netherlands Agency for Aerospace Programmes NIVR through contact nr. PEP 61730N.

Project structure

- Generic analysis and architectures
- Development and implementation case
- Test and demonstration

MODEL-BASED DIAGNOSIS

Modelling in LYDIA: Language for sYstem DIAgnosis.
Literature shows compatibility with NASA/ESA developments.

Example Valve:

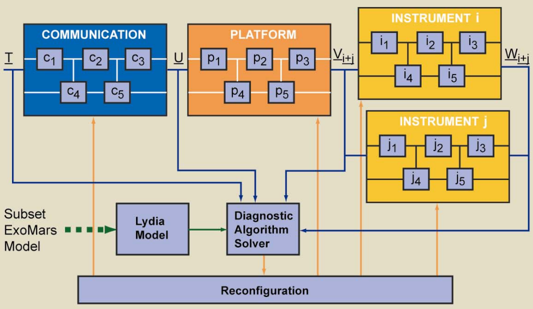
Logic → health model

$$control \Rightarrow (flowOut = flowIn)$$
$$\neg control \Rightarrow \neg flowOut$$

```
if (h) {
if (control)
{flowOut = flowIn;}
else {flowOut = false;}}
```

LYDIA Toolset implements Diagnostic Algorithm Solver.
Probabilities and observability can be specified.

Instrument teleoperation

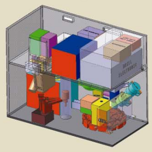


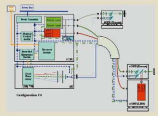
Health ⇨ Diagnostic Solver ⇨ Reconfiguration

Case studies for refinement of concept

Instrument co-ordination case

EXP-1 Target on position or sample obtained via drilling
EXP-2 External observation or microscope
EXP-3 *Spectrum Acquisition*
  a. Initialisation
  b. Autofocus process
  c. Processing adapting parameter
  d. Spectrum acquisition
EXP-4 Spectrum analysis
EXP-5 Storage and downlink

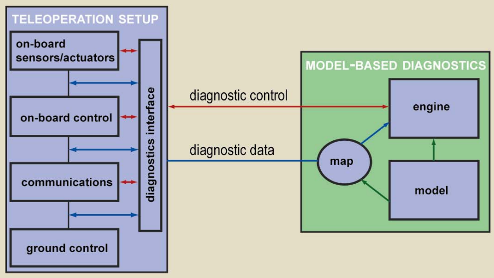




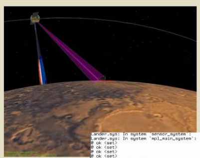
Modelling aspects: co-ordination of two instruments, science data communications, control, time dependencies, observability, health monitoring, hierarchical representation.

Other cases explored to check applicability.

Testbed

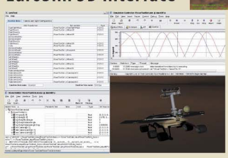


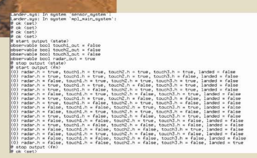
- Instrument simulation using EuroSim
- Communication simulation using STK
- LYDIA engine for diagnostics
- Mix of hardware and software
- Remote control workstation



Communications simulation

EuroSim 3D interface





LYDIA Diagnostic Solver

Development and implementation case on-going.

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Appendix B Project presentation NPP symposium

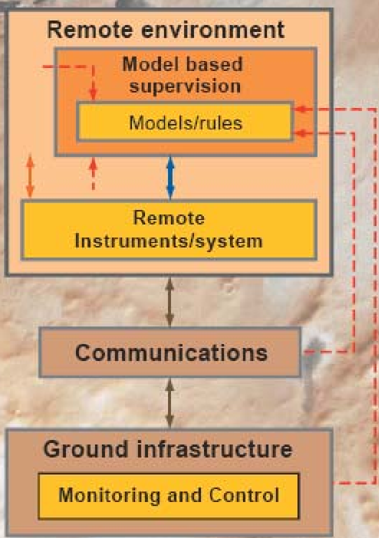
The TELEMOS project was presented previously at the 2e NPP Symposium Planetary Exploration & Extra-terrestrial habitats for life, Velthoven, 19-20 March 2008.

Model-based supervision and remote operations for planetary missions

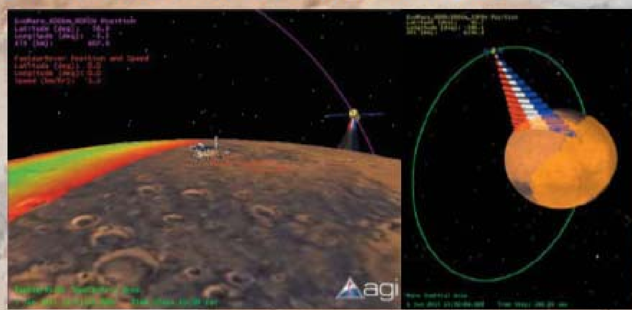
www.nlr.nl

Concept and Case Selection

Ground control to send commands to the instruments with an autonomous on-board capability for corrections, taking into account knowledge about the communication link, the status of the instrument and its environment. Dutch instrument case will be the starting point. Generic implementation for use in moving or fixed instrument platform.



Simulation and Environment



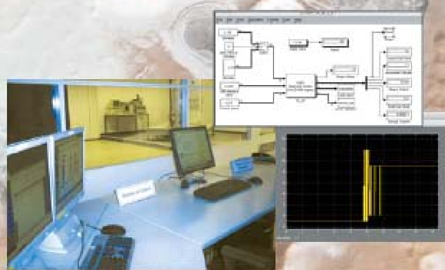
A model-based reasoning system based on Uptime tool developed by Science & Technology (S&T).

The test setup is a mix of hardware and software reusing generic simulation tools.

TELEMOS Project and Objectives

The project "TELE-operations and MOdel-based Supervision for instruments for planetary exploration" (TELEMOS) has the following objectives:

- Technology tele-operations with model-based supervision.
- Development, design, test and demonstration of expertise for remote control aspects and modeling.



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