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

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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).

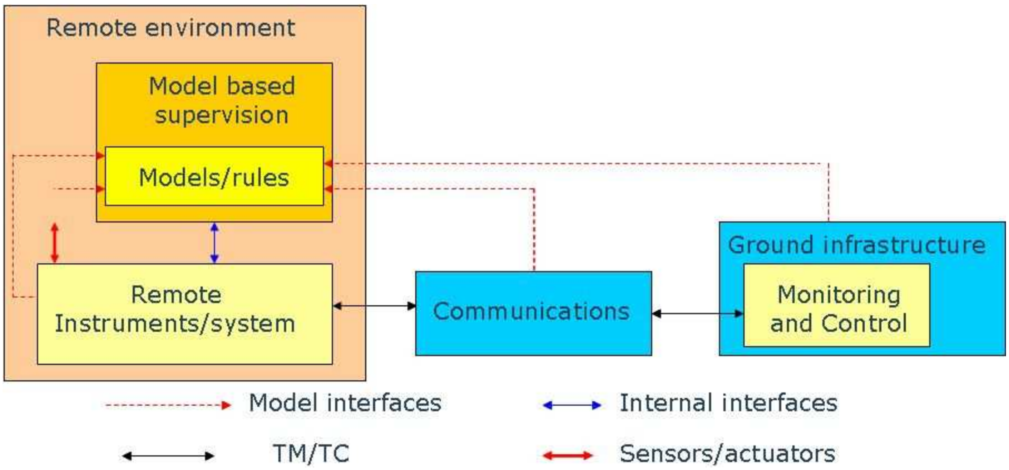

Fig. 1. TELEMOS concept integration of model-based supervision

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

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..

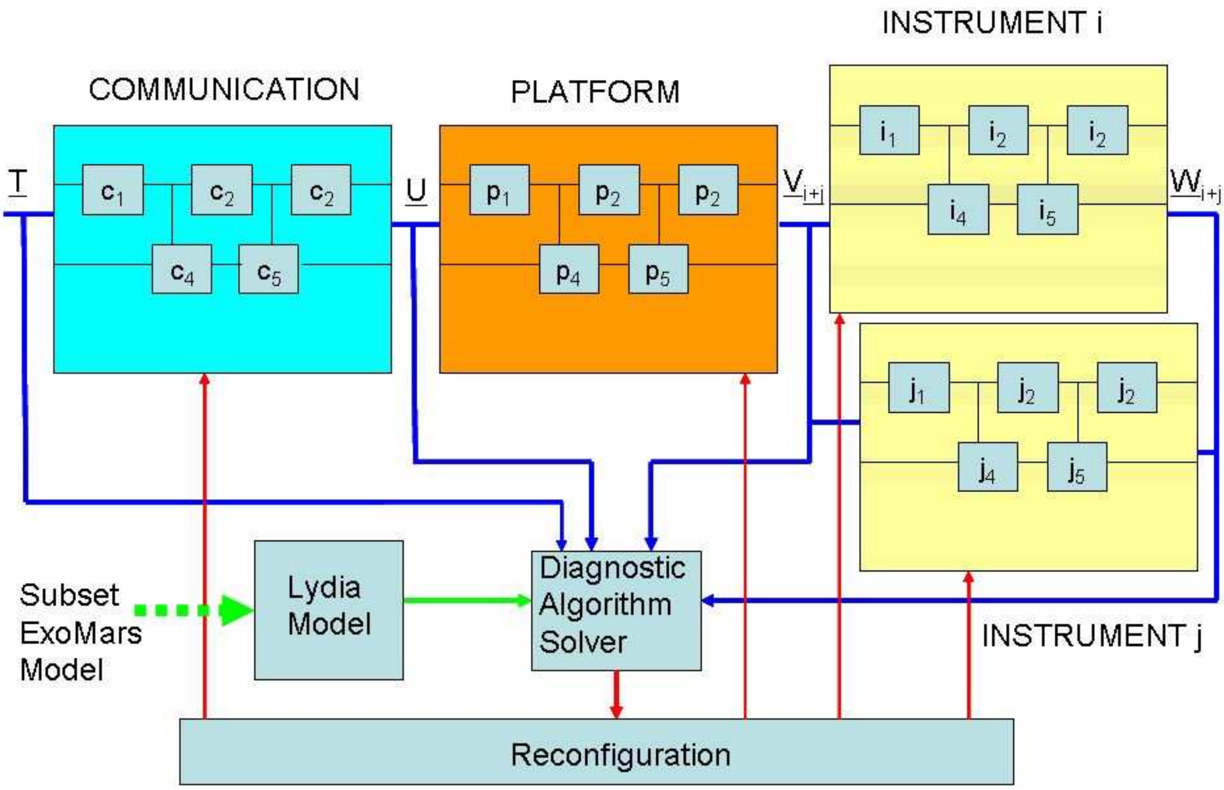

Fig. 2. Based on models of communication, platform and instruments the reconfiguration will be supported

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. 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).

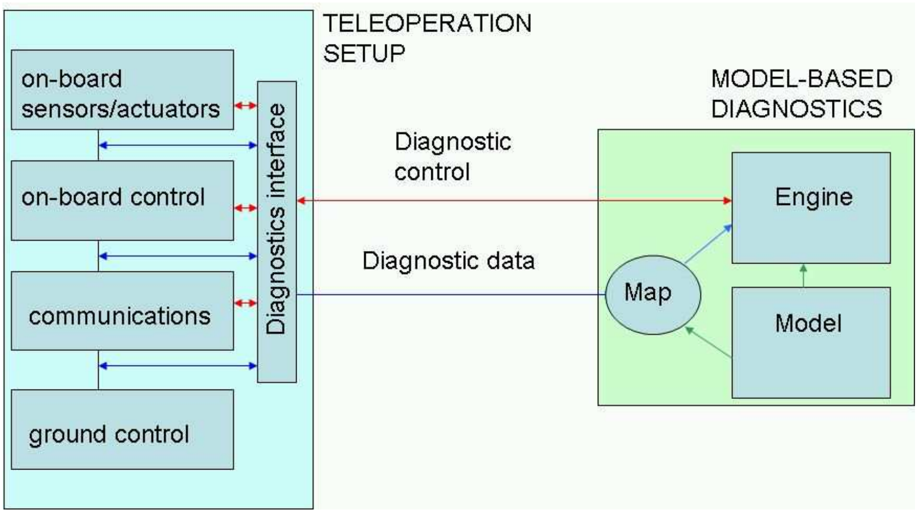

Fig. 3. The model-based diagnostics will be clearly separated from the teleoperation set-up.

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.

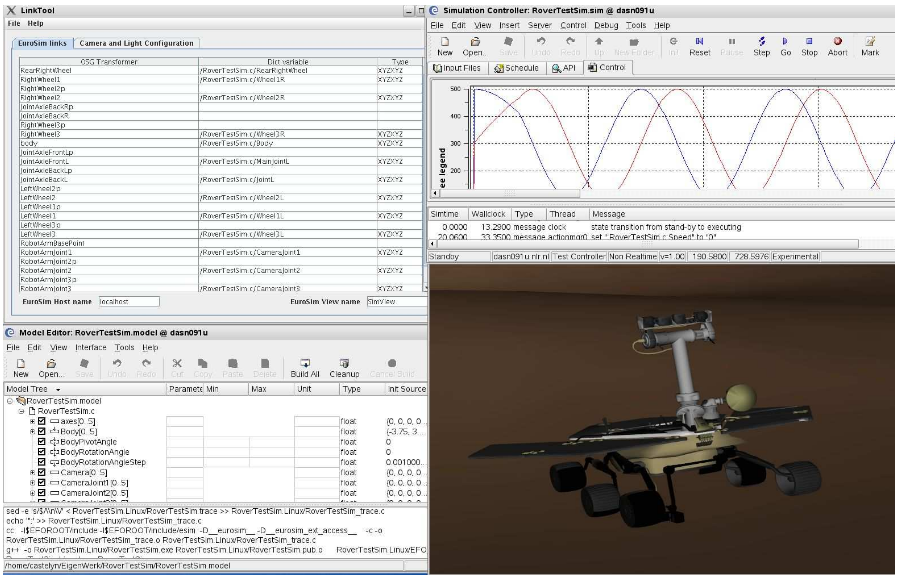

Fig. 4. EuroSim models will be interfaced via a dedicated tool to OpenSceneGraph visualisation

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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