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National Aerospace Laboratory NLR

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Summary

The International Space Station (ISS) is a high tech research and development facility in low earth orbit. The key factor is availability. In part, the availability of a robotic system is warranted by the redundancy philosophy applied in its design. Nevertheless, surfaces will degrade, wear will occur and the performance will suffer. And some day, an upgrade becomes inevitable. SW upgrades can be uploaded with limited effort, but still require preparation and verification. Some spare parts will be available on orbit, but other parts are stored on the ground, yielding quite long repair times. Predictive maintenance helps to plan ahead, and make sure the system availability remains high.

The purpose of the paper is to discuss predictive maintenance techniques based on signal analysis and analytical redundancy, to show what it would mean if they would be incorporated in the Ground Segment of a space robotic system, and to demonstrate the applicability of the techniques using a simplified model of a robotic joint.

Contents

(19 pages in total)

1 Introduction

The International Space Station (ISS) is a high tech research and development facility in low earth orbit. In late 1998, the first two modules of ISS, Zarya and Unity, were launched and coupled successfully. Robotics is a key technology in both the maintenance and the scientific operations of the Space Station. The European Space Agency (ESA) contributes to the ISS by providing, among other things, the European Robotic Arm (ERA, Fig. 1). ERA will be launched in 2001, mounted on the Science and Power Platform. ERA will help assemble and maintain the Russian Segment of the International Space Station (RS-ISS) [Kampen et al, 1995]. Other robotic systems on the ISS include the Canadian Space Station Remote Manipulator System and the Special Purpose Dextrous Manipulator, which are part of the Mobile Servicing System (Fig. 2) and the Japanese Experiment Module Remote Manipulator System.

As the number of robotic systems and their servicing capabilities grows, the users of the ISS will become more and more dependent on the adequate performance of these systems. The key factor is availability.

In part, the availability of a robotic system is warranted by the redundancy philosophy applied in its design. Most manipulators are designed to be Fail-Operational, i.e. even after a failure, the system should be able to provide full functionality. Of course, the harsh environment of space, with its high radiation levels, atomic oxygen and extreme temperatures, has been taken into account in the design of the system and the selection of materials and components. Nevertheless, surfaces will degrade, wear will occur and the performance will suffer. And some day, an upgrade becomes inevitable.

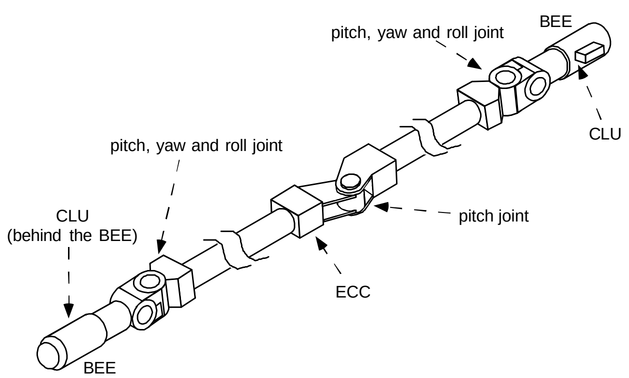

Figure 1 (The European Robotic Arm)

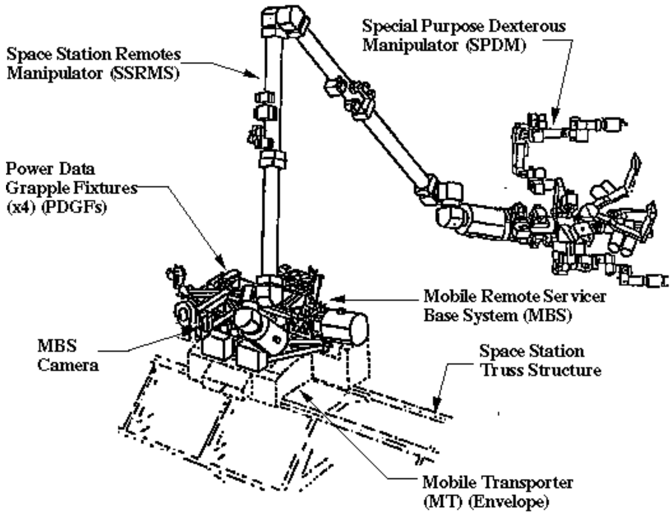

Figure 2 (Overview of the Mobile Servicing System)

SW upgrades can be uploaded with limited effort, but still require preparation and verification. Some spare parts will be available on orbit, but other parts are stored on the ground, yielding quite long repair times. Predictive maintenance helps to plan ahead, and make sure the system availability remains high.

To the authors' knowledge, analysis of data from the Canadian Shuttle robot arm is done by trend analysis and by tuning parameters by hand to match measured data with the simulator data, which is labour intensive work.
The purpose of the paper is to discuss predictive maintenance techniques based on signal analysis and analytical redundancy as a tool to be able to detect deviations from the nominal behaviour quicker and more efficient. In addition, this paper will show what the context is for such tools (facility) would be incorporated in the Ground Segment of a space robotic system, and to demonstrate the applicability of the techniques using a simplified model of a robotic joint.

2 Predictive maintenance techniques

The purpose of predictive maintenance is to determine what and when maintenance should be done, before the system performance degrades to a failure which would prevent a successful completion of the mission or even cause safety problems.

Maintenance scheduling is often based on reliability assessments. However, the average life cycle does not need to say much on the actual state of a component or unit. Especially when the uncertainty or variance in the reliability figures are large, a clear possisbility exists for replacing a component to soon (without need) or too late (a real failure occurs during a mission). The variance of the reliability figures of components in space are relatively large, because only few parts may be produced (thus eliminating obtaining reliability figures by test), and space conditions can vary considerable (like temperatures). In case of a space robot the use of signal analysis and analytical redundancy methods (observer based and identification based) are considered, just because detailed models are available.

Signal Analysis Signal Analysis methods are based on the monitoring of signal trends. Typical quantities that are used are the magnitude of signals, mean values, maximum and minimum values, variances, trends, correlation coefficients etc. A failure is detected if one of the signal trends exceeds a predefined threshold. Signal Analysis methods are relatively straightforward and common practice.

Observer-based Observer based methods use the mathematical model to compare real-life measurements with the predicted outcome of the model. By means of statistics it is determined whether the deviation is significant. By configuring a number of observers the methods can be used for diagnosis. The observer method chosen is based on the parity equations [Frank, 1996], because the measurement noise is expected to be relatively small.
The following system equations are used in the formulation of the parity space method:

$$\begin{aligned} x_{k+1} &= A\,x_k + B\,u_k + E\,d_k + K\,f_k \\ y_k &= C\,x_k \end{aligned} \tag{2-1}$$

where x denotes the state vector, u the control inputs, d the disturbances, and f the failures. In the formulation of the method no distinction is made w.r.t. the “size” of the failure. The failure term f can represent both a small degradation for which a controller is robust, or a severe failure causing safety problems when using the system. The term f represents both component and actuator failures. Component failures can be modelled as perturbations of the matrix A, and

actuator failures can be modelled as perturbations of the matrix B. For instance, f =)A*x$_k$*f'(k), where f'(k) is zero before the failure occurs, and 1 during/after the failure.
Note that the method can be generalized to include sensor failures.

To obtain the parity equation the system is rewritten in the following form, where for illustration purposes the past is limited to 2 samples:

$$\begin{bmatrix} y_{k-2} \\ y_{k-1} \\ y_k \end{bmatrix} = \begin{bmatrix} Cx_{k-2} \\ CAx_{k-2} \\ CA^2x_{k-2} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ CB & 0 & 0 \\ CAB & CB & 0 \end{bmatrix} \begin{bmatrix} u_{k-2} \\ u_{k-1} \\ u_k \end{bmatrix} + H_2 \begin{bmatrix} d_{k-2} \\ d_{k-1} \\ d_k \end{bmatrix} + H_3 \begin{bmatrix} f_{k-2} \\ f_{k-1} \\ f_k \end{bmatrix} \tag{2-2}$$

By subtracting the deterministic part and eliminating the autonomous part by pre-multiplying with the kernel of the observability matrix (V), the following residual is obtained:

$$r = V\left(\begin{bmatrix} y_{k-2} \\ y_{k-1} \\ y_k \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 \\ CB & 0 & 0 \\ CAB & CB & 0 \end{bmatrix} \begin{bmatrix} u_{k-2} \\ u_{k-1} \\ u_k \end{bmatrix} \right) = V\left(H_2 \begin{bmatrix} d_{k-2} \\ d_{k-1} \\ d_k \end{bmatrix} + H_3 \begin{bmatrix} f_{k-2} \\ f_{k-1} \\ f_k \end{bmatrix} \right) \tag{2-3}$$

There exists still some design freedom, so r* = w r is chosen such that the effects of noise are as small as possible, and the effects due to the faults are as large as possible. The leads to minimizing the following equation:

$$P(w) = \frac{\left\| w^T V H_2 \right\|}{\left\| w^T V H_3 \right\|} = \frac{w^T V H_2 H_2^T V^T w}{w^T V H_3 H_3^T V^T w} \tag{2-4}$$

Solving for w, this can be considered as a generalized eigen value problem: $VH_2H_2^TV^Tw = \lambda VH_3H_3^TV^Tw \Leftrightarrow Aw = \lambda Bw$

This problem can be solved with the MATLAB function EIG(A,B). Choose from the solutions the smallest eigenvalue and its corresponding eigenvector. The latter is w.

Now note that the left hand side of equation (2-2) leads to the measurable residual:

$$r^* = w^T V\left(\begin{bmatrix} y_{k-2} \\ y_{k-1} \\ y_k \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 \\ CB & 0 & 0 \\ CAB & CB & 0 \end{bmatrix} \begin{bmatrix} u_{k-2} \\ u_{k-1} \\ u_k \end{bmatrix} \right) \tag{2-5}$$

of which all elements are known.

Identification based Identification techniques aim at deriving a mathematical model from actual (input-output) measurements of an (unknown) dynamical system (plant). Since the identified mathematical model may provide (additional) insight on the (changing internal) system behavior, a long term interest exist in using identification methods in fault detection and diagnosis, see e.g. the state-of-the-art paper of P.M. Frank [Frank, 1996]. The major drawback that has hampered a widespread use of identification in Failure Detection and Isolation (FDI) is the nonlinearity of the numerical (parameter) optimization methods (even for the estimation of the parameters of a linear time-invariant systems). Subspace Model Identification (SMI, [Verhaegen, 1994]) schemes overcomes this drawback. The formulation of the identification problem allows a numerically very reliable solution, and (compared with other methods) only relatively short datasets are needed.

In the Systems and Control Engineering Group of the Delft University of Technology a particular class of reliable SMI tools have been developed and tested in numereous industrial applications. A free copy of Version 1.0 of a toolbox developed in the course of the research activities can be obtained via http://lcewww.et.tudelft.nl/~haver/smi/smi.html.
The subspace identification scheme is in fact a two-step method. Firstly the A and C matrices are estimated. Given the A and C matrices, B is determined.

The basic step in the above mentioned SMI tools is the derivation of the extended observability matrix

$$\Gamma_s = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{s-1} \end{bmatrix}$$

from an input-output data batch $\{u_k, y_k\}$. When this data batch is derived from the fault-free system, we denote the corresponding observability matrix by Γ_{s^0}. The use of this approach in failure detection, new sets of input-output data batches (transmitted from the space station on regular time instances) are processed to determine a new matrix Γ_{s^i} and the detection is done by investigating the angles between this new matrix and Γ_{s^0}, which is a completely new approach.
The angles between subspaces are related to the singular values of “product” of the two subspaces: the cosine of the angles are equal to the singular values.

When no abnormalities are detected in this (first) step, a second step is invoked comparing the elements of the matrix B of the state space model listed above, determined with the fault-free data and with the new incoming data.

Diagnosis was performed by matching measured datasets to datasets for known failures. This was done by calculating the cosines of the angles between the datasets.

Now, what would it mean if predictive maintenance tools based on analytical redundancy would be incorporated in the Ground Segment of a space robotic system? Which subsystems are modelled, and what is the overall system in which additional tools for predictive maintenance must be implemented. The answer is provided by taking the European Robotic Arm as an example.

3 ERA

Developed by Fokker Space B.V. under contract from ESA, ERA is a symmetric, seven degree of freedom manipulator of about 11 meters length. It can relocate to various positions (basepoints) on the Russian Segment. It can transport large objects (such as solar arrays) during the Russian Segment Assembly Phase, and exchange Orbit Replaceable Units (ORUs) as well as inspect the Russian Segment during the Operational Phase of the station [Kampen, 1995].

ERA can be controlled directly by Extra Vehicular Activities (EVA) crew members, or remotely from a laptop-type workstation by the crew members inside one of the modules of the Russian Segment (Fig. 3). The ERA program is just before the Critical Design Review. The first test results on the Engineering Qualification Model(s) are available [Hofkamp, 1998].
The control computer is integrated in the arm structure, as well as specially designed communication, power and video distribution networks. This makes ERA largely independent of other systems on board. Most of the robot's tasks are pre-programmed on ground and carried out under supervision of the crew.

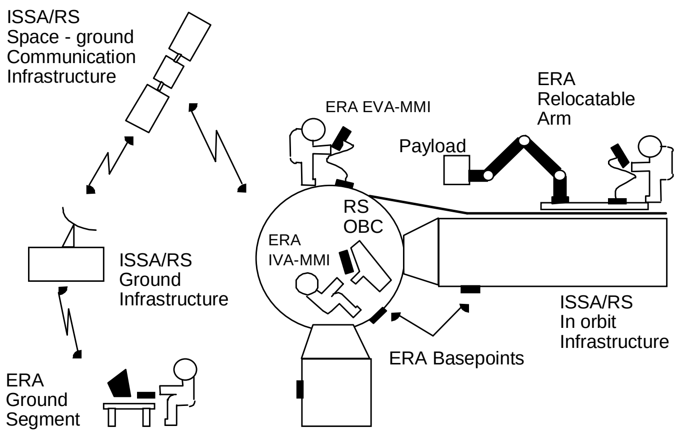

Figure 3 Elements of the ERA system

Camera and lighting units positioned on both end-effectors and on both sides of the elbow-hinge provide a view of the working area and enable automatic gripping and positioning of objects. Using the Integrated Service Tool (IST), which is an in-built screwdriver in each end-effector, ERA can mechanically actuate other mechanisms directly. The special electric connectors for data, video and power in the end-effector, enable communication with various types of equipment when these are grappled by the end effector. The same connectors also offer potential to expand ERA with intelligent tools.

The National Aerospace Laboratory NLR is responsible for the development of the ERA Mission Preparation and Ttraining Equipment (MPTE) and contributes to the design of the on-board FDIR system. In cooperation with the Delft University of Technology, NLR is also investigating the use of analytical redundancy based FDIR methods for detecting and diagnosing performance degradations. In the future, such tools may be incorporated in the MPTE, in the framework ERA Evolution [Heemskerk, 1998].

4 MPTE and ESF

The MPTE is used for mission planning, training, on-line mission support and mission evaluation.

Within the current MPTE a number of displays are available for performance monitoring, like control errors. These will be used for signal analysis based predictive maintenance. Analytical redundancy based predictive maintenance tools could be incorporated in a future upgrade of the ERA MPTE. These techniques make use of detailed models of a the system under consideration. Within ERA, these models are incorporated in the ERA Simulation Facility (ESF).

ESF is a high-fidelity dynamic simulation of ERA arm operations and motion. ESF consists of a set of powerful real-time models, embedded in the commercial package EuroSim. The ERA Simulation Facility ESF is developed in parallel with the ERA flight design. In the early stages of the project, ESF was used to design the ERA motion control algorithms. In this phase, the motion control software was simulated and its performance evaluated. Today, the emphasis is on verication of the flight software. The flight software is connected as software or hardware-in-the-loop to ERA simulation models. Finally, all the models in ESF will be validated against tests on the real arm, and the validated ESF becomes the core element of the MPTE [Couwenberg, 1998].

Manipulator dynamics model: The core model within ESF is a model of the manipulator arm dynamics. The model is based on a recursive method of solving dynamics equations comprising an open-chain of flexible and rigid bodies as described in [Ellenbroek, 1994]. To simulate the contact motion, the open-chain dynamics model has been augmented with a contact model and a constrained manipulator tip motion model to enable closed-chain dynamics.

Actuator model: The ERA shoulder, wrist and elbow contain seven rotational joints driving unit. The joint dynamic bahaviour is described in the Actuator model. This model features a flexible gearbox between the motor and joint axis, including hysteresis characteristics. Furthermore friction and stiction on the out-going joint axis are taken into account.

Sensor models: In each joint, a resolver and an encoder measure the motor speed and joint angle. The key characteristics of the resolver and encoder models in ESF are quantification of the output signal and noise. To measure the arm tip behaviour with respect to the environment, ERA has a proximity sensor and a torque/force sensor. The proximity sensor is part of the end effector camera subsystem, determing the pose relative to an illuminated dot pattern. The torque/force sensor is part of the end-effector subsystem, it measures via strain gauges, the force and torque vector exerted on the end-effector. The ESF torque/force sensor model transforms and quantifies the in the manipulator dynamics model determined spring deformations.

Joint control model: Each ERA joint has its own closed-loop controller. The ESF joint control model features a functional model of the embedded joint control software in copied C source code.

Communication models: ERA contains two databuses transmitting commands and status between ERA subsystems and the host computer on the Russian Segment. Within ESF, both HW and SW communication models for the MIL1553 Remote terminals and Bus Controllers are available, enabling both HW in the loop tests and SW tests.

Onboard software model: The ESF Onboard software model is a functional model of the ERA motion control software implemented in C source code. It is used for non-real-time design simulations without the need for HW models of the central computer or databus communication.

Hardware-in-the-loop: A HW Model of the ERA Central Computer can be connected to the ESF via the MIL1553 bus interface. In this HILT configuration the functionality of the flight software is verified against the requirements. In combination with a HW EMMI or IMMI the configuration is used for end-to-end tests with a man-in-the-loop (cosmonaut), and will eventually be the basis for the MPTE.

EUROSIM: EuroSim is a complete real-time simulation environment, supporting the user through all phases of the simulation life cycle [Brandt, 1994]. EuroSim contains by graphically interactive tools to support simulator development, test preparation, test execution (simulation), test analysis and facility management.. The user can operate the complete facility through ‘pointing & clicking.'

5 Results

In this paper we summarize the results of applying two anlytical redundancy based methods to a simple linear model of one joint of ERA (Fig. 4): observer based and identification based.
Although the dynamica of a space robot are non-linear, first of all a linear model was considered, to get in a cost-effective way a good feeling and understanding of the (dis)advantages of the methods. Moreover, if the methods would not work for the linear model, little is to be expected for the non-linear case.

The dynamics (Fig. 4) can be described by the following continuous-time linear model:

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{c}{N^2 \,\mathrm{Im}} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -(\frac{c}{N^2 \,\mathrm{Im}} + \frac{c}{Ison}) & 1 \end{bmatrix} x + \begin{bmatrix} 0 \\ \frac{Kt}{N \,\mathrm{Im}} \\ 0 \\ \frac{-Kt}{N \,\mathrm{Im}} \end{bmatrix} i_c \tag{5-1}$$

$$y = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & N & 0 & 0 \end{bmatrix} x \tag{5-2}$$

where x= $\begin{bmatrix} \Omega & \dot{\Omega} & \varepsilon & \dot{\varepsilon} \end{bmatrix}$ and Σ equals the angle of the motor axis, and the gearbox deformation modelled as a spring, where c equals the spring constant. Kt is the motor torque, N the gearbox ratio, Im the motor inertia, Ison the inertia of the output axis, and i_c the motor current.
Angle setpoints are realized by a PID controller (Fig. 5).
Although the identification has to be done in a closed-loop setting, at first open-loop identification was considered, because sufficient (independent) excitation was expected due to the angle setpoint trajectory. This proved to be true.

The particular failures considered include both system component failures (e.g. change in inertia of one of the axis), actuator failures (e.g. drift in the motor torque constant) and sensor failures.
As an example a drift of 1%/sec. in the motor torque constant after 7.5 seconds was introduced.
From Figs. 6 and 7 it can be seen that simple signal analysis techniques were not able to detect the degradation. The residual, shown in Fig. 8, generated by the observer-based method shows that detection is possible.

In fact, both the observer based and the identification based method did detect the degradation successfully. Moreover, all failures were detected when no noise was present.

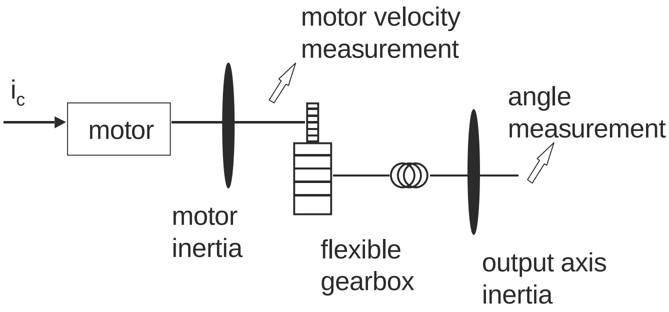

Figure 4 (Linear joint model)

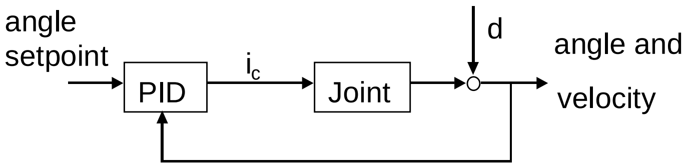

Figure 5 (Joint control context)

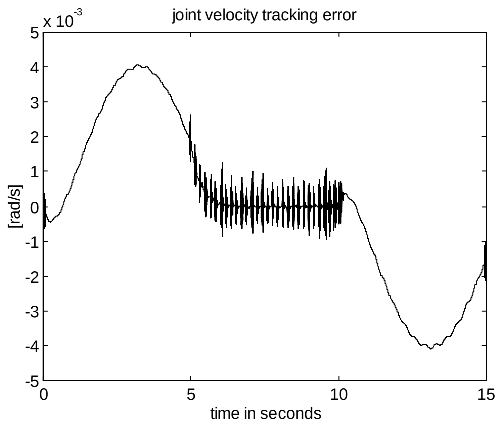

Figure 6 (Joint velocity tracking error with failure)

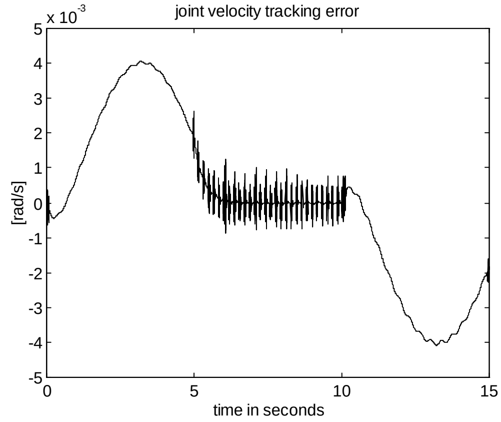

Figure 7 (Joint velocity tracking error without failure)

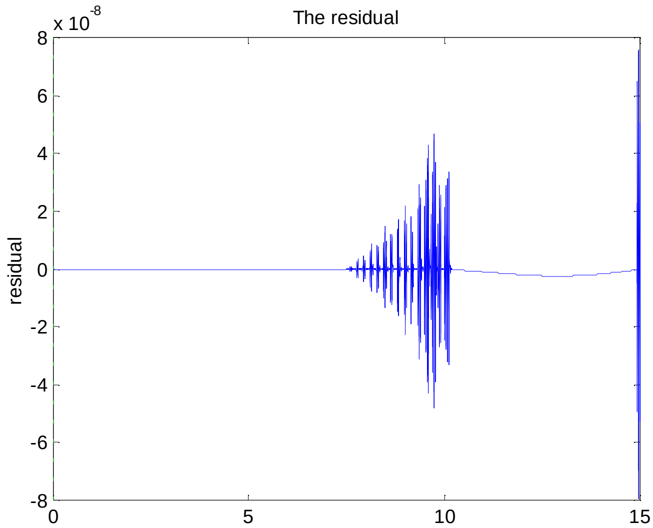

Figure 8 (Residual generated by the observer-based method)

The observer based method was more sensitive to noise then the identification based method, due to the fact that the parity space approach used is a kind of open loop method, i.e. the noise is not taken into account in the system equations. The identification based method was fairly robust against noise due to the fact that in the parameter estimation formulation noise is implicitely taken into account.

Observer based tends to be more quick in detection than identification based.

The identification based method gave fairly good diagnosis results, in contrast to the observer based method. The poor diagnostic performance of the latter was caused by the fact that no total decoupling between observers could be achieved.

The results showed also that attention must be paid to the modelling aspect (continuous time versus discrete time) in case of the observer-based method. As an illustration, suppose that like in our case the system is modelled in continuous time. Suppose that we have a component failure immediately at the start. The system model equals:

$$\dot{x} = Ax + f = Ax + \Delta Ax$$

Translating this to the discrete time domain, in which the observer based method is formulated yields:

$$x_{k+1} = e^{(A+\Delta A)\bullet\Delta t} x_k$$

This equation cannot be written in the required form for the parity space method of
$x_{k+1} = A_{nominal}\, x_k + f$, since A and ΔA are “mixed up” in the exponential.

The physical parameters appear in the system equations often as mutual multiplication or divisions. For instance, one element of the A-matrix is equal to p_1 divided by p_2, where p_1 and p_2 are the physical parameters like the motor torque constant. How to translate estimated model parameters to physical parameters for the diagnosis within the identification-based approach needs further consideration.

The ERA joints have non-linear dynamics (hysteresis, stiction). Current research work concerns the application of the signal analysis method and the analytical redundancy methods in combination with the detailed non-linear models of ERA in the ERA Simulation Facility. It is expected that a predictive maintenance facility for a space robot will use a combination of the two different techniques: signal analysis and analytical redundancy.

Note that a related subject is the tuning of the simulation models to the flight-data. The purpose of this activity is twofold: firstly, the final validation of the simulator and secondly maintaining the simulator model characteristics such that the prediction of the robot mission will reflect reality as close as possible during mission preparation.

6 Conclusions

The purpose of predictive maintenance is to determine what and when maintenance should be done, before the system performance degrades to a failure. Two techniques based on analytical redundancy, i.e. the identification and observer based FDIR techniques, gave good results for a linear joint model. For typically non-linear space robot joints, the techniques are expected to provide better (more sensitive) detection of degradation and better traceability to the cause of the degradation than signal analysis based techniques. We expect that analytical redundancy methods will augment existing and relatively simple signal analysis techniques to become a suitable basis for a predictive maintenance facility.

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