Prognostics for the Maintenance of Distributed Systems

Pauline Ribot, Yannick Pencolé and Michel Combacau
LAAS-CNRS, Université de Toulouse
7 avenue du Colonel Roche, F-31077 Toulouse, France
{pribot,ypencole,combacau}@laas.fr

***Abstract*—This paper addresses the problem of the maintenance of a distributed system of heterogeneous components. We propose a generic health monitoring architecture that encompasses the available prognostic methods and provides a common support for the maintenance decision on a distributed system. The output of this architecture takes into account the distributed nature of the system by not only providing component prognoses but also higher level function prognosis.**

I. INTRODUCTION

In the classical case, preventive maintenance is only based on reliability analyses that do not take into account the stress factors really influencing each component of the system during its own life. By taking into account real stress factors that occur on a component, it is possible to measure huge effects on the remaining useful life of a component. Among stress factors are included the faults and their consequences that can occur on a component or on any components in its neighbourhood.

Prognostics is the capability to predict the *remaining useful life* (RUL for short) of components or systems in service: the RUL is defined as the time at which the system will not successfully perform its function anymore and will have to be replaced [1]. Model-based prognostics [2], [3], [4] is a technically comprehensive modelling approach often used for component failure prognostics. Such a method relies on a continuous physics model of the component degradation and provides an accurate prognosis by identifying the possible stress causes. However, such methods cannot handle the distributed and heterogeneous nature of integrated systems.

In this paper, we propose a general on-line supervision architecture for supporting the maintenance decisions.[1] This architecture is generic as it has to handle the fact that the components of the system are heterogeneous which mean that several prognostic methods can be used depending on the available models and the available sensors. We thus propose a common representation as a prognosis output for any type of components.

II. HEALTH MANAGEMENT ARCHITECTURE FOR DISTRIBUTED SYSTEMS

A. Maintenance of distributed systems

The maintenance efficiency of systems is an important economical and commercial issue. The main difficulties result from the choice of maintenance actions. A bad choice can lead to a maintenance with an over cost that is not acceptable [5], [6]. Because of the increase of involved technologies (pieces of hardware, software) and the different interactions between components (communications by message passing or physical interactions), the decision of a maintenance action is very complex and requires a diagnostic and prognostic analysis. Our aim is to develop a prognostic architecture for a distributed system in order to improve the efficiency of preventive maintenance for complex systems. In this sense, a distributed system can be split down into a set of subsystems, each subsystem implementing a function. As a function also relies on subfunctions, any subsystem is also composed of a set of subsystems.

For instance, let us consider a system composed by a power supply subsystem (three power supply components PS_1, PS_2, PS_3), an electrical transport network EW, an on/off switch SW and a functional device FD (a lamp, a motor...). The subsystem PS_1, PS_2, PS_3 implements the function *power_supply*, EW implements the function *power_transmission*, etc.

Maintaining such a system basically consists in replacing components that are unable to perform their function by new ones. Maintenance activities are costly for several reasons. The first one is that they usually require to stop the system that cannot be used anymore during the maintenance phase. The longer the maintenance phase is, the more costly it is. It follows that the maintenance phase must be reduced to the strict minimal operations, that is the replacement of the correct components. This requires that the maintenance actions must be decided relying on an efficient and complete analysis of the health of the system when it is operating. The second reason of a high cost in maintenance is in case of emergency. If a component suddenly fails and the system fully breaks down, it automatically requires some unscheduled maintenance actions which are more costly than scheduled maintenance. To partly avoid this issue, prognostic methods are used in order to perform preventive maintenance. Preventive maintenance basically consists in replacing components during a scheduled maintenance phase that are not faulty yet but that will inevitably become faulty before the date of the next scheduled maintenance phase.

In our case, the system is composed of heterogeneous components (pieces of hardware, software) which means that

---

[1] This work is partly funded by the research project ARCHISTIC on the maintenance of aeronautical systems in collaboration with AIRBUS and the National Engineering School of Tarbes, FRANCE.

the available knowledge about each component for prognostics may be very different. Our objective is to provide a prognostic architecture that covers all these situations by finally providing the same prognostic representation for every monitored component.

B. *Prognosis and diagnosis*

Another challenge facing prognostics for distributed systems is to enhance the exploitation of current diagnostic results for a more precise prognosis. When a fault (also called anomaly in [7]) occurs on a component, its functioning mode is degraded and its RUL tends to drastically decrease and does not follow the nominal ageing law anymore: this is for instance the case when a crack occurs in a rotor blade of an helicopter [4]. From a system point of view, if a fault occurs on one of its components, it may also have some effects on the other components and modify their ageing law as well. For instance, a problem in one of the power supply PS_i can provoke high voltage that may have some consequence either on the wire EW and even on the functional device FD.

There is thus a direct link between the prognostic approach and the diagnostic approach which is illustrated by Figure 1.

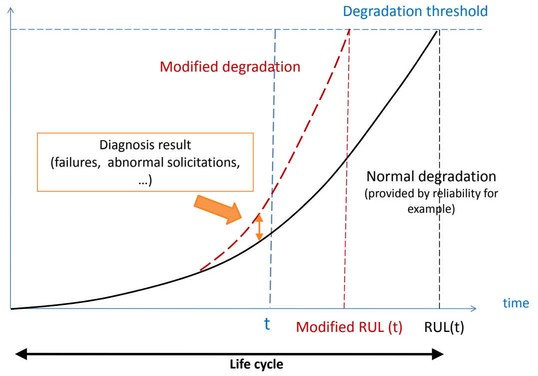

Fig. 1. Prognostics and maintenance

To take into account the relationship between faults and the age of the components, it firstly requires to establish an ageing law that depends on the faults and their consequences. This knowledge is described into *life models* [8]. To solve this issue, data from bench tests are required. The faults for which a life model is available are called *anticipated faults*. Secondly, it is necessary to detect whether faults have occurred at a given time when the system is effectively operating. To solve the second issue, it is necessary to take into account the current diagnostic results in the prognostic approach to get the current prognosis.

C. *Health Management and Maintenance Architecture*

Our generic architecture for the health management and the maintenance of the distributed system is presented in Figure 2.

This architecture is mainly divided into two modules. The first module is the health monitoring module. It is in charge of monitoring the system when it is operating. The second module is a decision support module: it is in charge of deciding for action maintenance relying on the outputs provided by the health monitoring module [8].

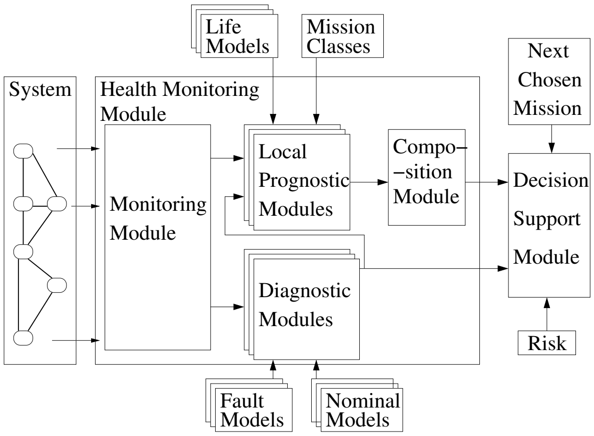

Fig. 2. Health Management and Maintenance Architecture.

1) Health monitoring module: This module is composed of four types of submodules. The monitoring module contains the sensors and all the communication protocols between sensors and the other modules in order to get the necessary observations for the diagnostic and the prognostic modules. The diagnostic modules are in charge of performing fault diagnosis on the system.

A local prognostic module is in charge of providing a current prognosis about a component of the system (see Section III). It relies on a set of life models of the component and a specification of mission classes. A mission class describes a set of possible missions that the system can realise: each class describes the expected stress conditions induced by any of its mission on the component if such a mission is effectively realised. Finally, a composition module provides prognoses of subsystems (see Section IV).

2) Decision support module: This module is in charge of providing maintenance recommendations. The description of this module is not under the scope of this paper.

III. CHARACTERISATION OF PROGNOSTIC FUNCTION

The prognostic function of a component has to provide a failure probability over all its life; this function thus depends on a set of parameters that represent the stress factors over all its life. Due to its flexibility, the Weibull model can be used to represent this failure probability of the component [9] [3]. The prognostic function provides Weibull probability densities from which the decision support system estimates the remaining useful life (see Section II-C).

A. *Weibull model*

The Weibull model is often used in the field of reliability and life data analysis [4] to define a probability density function (pdf for short). It is a parametrised probability distribution that is able to reproduce the behaviour of other statistical distributions such as the exponential distribution and the normal distribution. In the sequel of this paper, the problem is restricted to the useful life period of any component of the system. A Weibull pdf models the useful life period by fixing the value of the shape parameter $\beta = 1$, so that the Weibull model represents an exponential law.

The RUL evaluation consists in determining the time t_p for which the failure probability has reached a given threshold Pr

$$RUL = t_p \quad / \int_0^{t_p} f(t)dt = Pr$$

where Pr is a probability deriving from the risk level suitable with the next mission.

B. Effect of an unexpected stress on the Weibull distribution

A stress on a component can be generated by the occurence of a failure or an abnormal or unexpected solicitation from other parts of the system. The RUL can be shortened if the component is highly and frequently solicited. But the RUL may also get longer if a component is less stressed than expected.

The parameter η of the Weibull pdf can be determined by a function of the *stress factors* extracted from the set of available life models:

$$\eta = f(EF, DR, I, MC)$$

where, EF are the environmental factors, DR is the diagnosis result, I represents the interactions between components and MC is the class of future missions before the next maintenance phase.

Interactions between components may induce some stress. If a component is abnormally solicited (or stressed), it can have an impact on other components in its neighbourhood. An extended FMEA should be used to quantify these interactions.

Some future stress can also be estimated by knowing the future missions (for instance energy required for the next missions, frequency of use of the functional device FD in the next missions). The future missions are sorted into missions classes according to the stress (low/medium/high frequency of use for instance) they induce. To each mission class corresponds a stress level, thus a value of η. The prognostic function of a component computes a set of Weibull probability density functions with different values of η for the different mission classes.

IV. COMPOSITION OF RULS

The concepts introduced by the previous section are about a component. Now, the challenge is to compute a global RUL for a specific subsystem [10]. This composition relies on functional dependencies in the subsystem.

A. System modeling

The formalisation of the composition mechanisms of RULs is based on a description of the functional dependencies of the components within a system function. To write the formalisation of the RUL combinations, definitions of components and systems are given.

Definition 1 (component): A component C_i is a hardware or software entity implementing a basic functionality Fu_i, characterised by a nominal RUL, and whose environment influences on this RUL are quantifiable.

Formally, the RUL and the functionality Fu_i associated to a component C_i are defined by two mappings Rul and Fc on the set of components $Comp = \{C_1 ... C_m\}$.

$$\begin{cases} Comp \xrightarrow{Rul} \mathbb{R}^+ (\text{set of positive real numbers}) \\ C_i \xrightarrow{Rul} Rul(C_i) \end{cases}$$

$$\begin{cases} Comp \xrightarrow{F_c} \{Fu_1 ... Fu_m\} \\ C_i \xrightarrow{F_c} F_c(C_i) = Fu_i \end{cases}$$

For maintenance purposes, a component is the atomic entity that can be taken into account. Now, we extend the definition of a system as follows.

Definition 2 (system): a system S_i is composed by a set $Sys^{(m)}$ of m components C_k and by the system functionality SFu_i that it implements:

$$S_i = < Sys^{(m)}, SFu_i > .$$

A system S_i has functional requirements and provides a high-level functionality SFu_i to its environment. In this way, a system can be viewed as a super-component, and a system can also be defined as a set of subsystems whose role is to implement a higher-level functionality.

The functionality SFu_i provided by a system S_i can be defined as an extension F_s of the previously defined mapping F_c. $P(Comp)$ denotes the power set of $Comp$.

$$\begin{cases} P(Comp) \xrightarrow{F_s} \{SFu_1 ... SFu_n\} \\ S_i \xrightarrow{F_s} F_s(S_i) = SFu_i \end{cases}$$

Similarly, the RUL for a system can be defined as an extension of the mapping Rul previously defined on the components. Figure 3 illustrates all the relationships that have been previously defined.

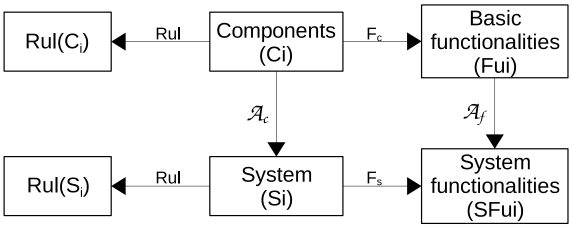

Fig. 3. RUL, components, systems and functionalities

Let us now define the RUL of a system according to these definitions.

$$\begin{aligned} Rul(S_i) &= Rul\left[F_s^{-1}(SFu_i)\right] \\ &= Rul\left[F_s^{-1}\left[\mathcal{A}_f(Fu_i)\right]\right] \\ &= Rul\left[F_s^{-1}\left[\mathcal{A}_f\left(F_c(C_k)\right)\right]\right] \end{aligned}$$

The mapping $\mathcal{A}_f$ defines the aggregation of the functional dependencies existing between a system functionality SFu_i implemented by a system S_i and the set of basic functionalities Fu_k implemented by the components C_k of this system.

Let us introduce the mapping n/m through which we will formally specify these kinds of relations.

Definition 3 (n/m): Given a system S_i with $Sys^{(m)} = \{C_j\}_{1 \leq j \leq m}$ its set of m components, each one implementing a basic functionality $F_c(C_i)$, SFu_i the system functionality and $Sys^{(n)}$ a subset of $Sys^{(m)}$ with n components.

The n/m function is then defined by

$$\begin{cases} \{SFu_i\} \xrightarrow{n/m} \{Fu_i\} \\ n/m(SFu_i) = \bigvee\limits_{Sys^{(n)} \subseteq Sys^{(m)}} \left[\bigwedge\limits_{C_i \in Sys^{(n)}} F_c(C_i) \right]. \end{cases}$$

A system S_i provides the system functionality SFu_i. We can thus define a mapping $\mathcal{A}_c$ between the system and its components by $S_i = F_s^{-1}\left[\mathcal{A}_f\left[F_c(C_j)\right]\right] = \mathcal{A}_c(C_j)$. It is then not necessary to use the mapping of system functionalities on basic functionalities to determine the functional dependencies between systems and components (see Figure 3). As for $\mathcal{A}_f$, the mapping $\mathcal{A}_c$ is written as a logical relation n/m which directly maps components to systems without taking into account the associated functionalities.

B. RUL pdf combination

According to the scheme described in Section II-C, the computation of the RUL for a component as well as for a system must take the future missions into account (stress and risk). As the RUL of a component is a monotonic increasing and positive function of the parameter η, the reasoning about the parameter η could similarly be done on the RUL. The scheme described in the sequel is valid for a given class of expected missions and must be repeated for each class of mission. For a system S_i in which SFu_i requires that all basic functionalities work properly, the η of the system S_i is given by the component of the system with a minimal η $\eta(S_i) = \underset{C_j \in S_i}{Min}[\eta(C_j)]$. On the contrary, for a system S_i in which only one functionality is required to make SFu_i work properly, the η is given by the component with a maximal η: $\eta(S_i) = \underset{C_j \in S_i}{Max}[\eta(C_j)]$. More generally, if the requirements for SFu_i to be normal can be written using the n/m function, the η of the system can be expressed as follows.

Definition 4 (composition of RUL pdf):

$$\eta[n/m(S_i)] = \underset{Sys^{(n)} \subseteq Sys^{(m)}}{Max} \left[\underset{C_j \in Sys^{(n)}}{Min} \ \eta(C_j) \right].$$

This definition points out that it is not necessary to calculate the RUL of each subset of n components to get the result. It is sufficient to consider the set of the n components whose η are the greatest and then to take the min of their η. This technique allows to compute the η parameter of each subsystem S_i and to compose them later till having the RUL for the whole system.

A final comment about the composition is that components seem not to be interacting which look contradictory: in fact, their interactions (stress propagation) have already been taken into account at the component level (see Section III-B).

C. Illustrative example

Let us consider $S_i = \mathcal{A}_c(PS_1, PS_2, PS_3, EW, SW, FD)$ with a subsystem *power_supply* whose local prognoses for a given future mission are characterized by $\eta(PS_1) < \eta(PS_2) < \eta(PS_3)$. Suppose that the global functionality implemented by S_i work only if EW, SW, FD and at least two of the power sources PS_i work, the dependencies $\mathcal{A}_c$ is then written as follows $S_i = 5/5(2/3(PS_1, PS_2 PS_3), EW, SW, FD)$.

The result of the RUL composition is that $\eta(power\_supply) = \eta(PS_2)$ and thus $\eta(S_i) = Min\left[\eta(PS_2), \eta(EW), \eta(SW), \eta(FD)\right]$.

V. CONCLUSION

This paper presents a generic framework for the development of a health monitoring architecture that supports the maintenance of distributed systems. There are several key points for implementing such an architecture. Firstly it has to take into account the heterogeneity of the components of the system. However, as the maintenance decision relies on the system as a whole, it is necessary to get the same representation for the prognosis of each component. Secondly, as life models become more and more informative, it is important to use specialised sensors for prognostics in order to measure the stress factors and provide adaptive prognosis. Some stress factors can also be deducted from faulty behaviours which means that diagnostics is necessarily an input for adaptive prognostics. Finally, maintenance decisions do not only rely on component RULs but also on the expected missions before the next scheduled maintenance phase. Depending on the expected missions, the set of required functionalities may change. Thus, the definition of RUL for functionality is required. This definition is based on a combination of the component RULs that takes the functional dependencies into account.

REFERENCES

[1] S. Engel, B. Gilmartin, K. Bongort, and A. Hess, "Prognostics, the real issues involved with predicting life remaining," in *IEEE Aerospace Conference*, vol. 6, USA, 2000, pp. 457–469.

[2] R. Valentin, M. Osterman, and B. Newman, "Remaining life assessment of aging electronics in avionic applications," in *Annual Reliability and Maintainability Symposium*, 2003, pp. 313–318.

[3] L. Kirkland, T. Pombo, K. Nelson, and F. Berghout, "Avionics health management: Searching for the prognostics grail," in *IEEE Aerospace Conference*, vol. 5, March 6-13 2004, pp. 3448–3454.

[4] G. Vachtsevanos, F. L. Lewis, M. ROemer, A. Hess, and B. Wu, *Intelligent Fault Diagnosis and Prognosis for Engineering Systems*. Wiley, 2006.

[5] C. Byington, P. Kalgren, B. Dunkin, and B. Donovan, "Advanced diagnostic/prognostic reasoning and evidence transformation techniques for improved avionics maintenance," in *IEEE Aerospace Conference Proceedings*, vol. 5, 6-13 March 2004, pp. 3424–3434.

[6] F. Camci, G. Valentine, and K. Navarra, "Methodologies for integration of phm systems with maintenance data," in *IEEE Aerospace Conference Proceedings*, 3-10 March 2007.

[7] T. Brotherton, G. Jahns, J. Jacobs, and D. Wroblewski, "Prognosis of faults in gas turbine engines," in *IEEE Aerospace Conference Proceedings*, vol. 6, Big Sky, MT, USA, 2000, pp. 163–171.

[8] C. Wilkinson, D. Humphrey, B. Vermeire, and J. Houston, "Prognostic and health management for avionics," *IEEE Aerospace Conference Proceedings*, vol. 5, pp. 3435–3446, March 2004.

[9] D. Humphrey, W. Schawlee, P. Sandborn, and D. Lorenson, "Utilization life of electronic systems - aging avionics usable life and wear-out issues," in *presented at World Aviation Congress*, Phoenix, AZ, USA, November 2002.

[10] K. Goebel and N. Eklund, "Prognostic fusion for uncertainty reduction," in *Proceedings of AIAA Infotech@ Aerospace Conference*, Rohnert Park, California, 7-10 May 2007.