Life Cycle Simulation Applied to a Robot Manipulator
– An Example of Aging Simulation of Manufacturing Facilities –

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Abstract

Evaluation of the aging process of manufacturing facilities is essential for life cycle facility management, which includes such activities as design for reliability and maintainability and maintenance planning. For this purpose, we have developed a life cycle simulation system for robot manipulators. The developed system can simulate the wear of gears and bearings of joints as component deterioration and evaluate the resultant positioning error of an end-effector as functional degradation. The system is applied to assembly robots of a car parts manufacturing plant. The simulation results correspond to the failure history of the robots fairly well.

Keywords: Life cycle management, Deterioration evaluation, Robot manipulator

1. Introduction

To make best use of the potential capability of a manufacturing facility throughout its life cycle, we have to manage all processes related to the facility life cycle in an effective way. In order to facilitate Plan-Do-Check-Action management cycles, it is important to evaluate expected processes in advance based on models constructed from the design data and to feed forward predicted information for purposes of planning and control. It is also necessary to feed back experienced information to a case-base which can then be used for the prediction in the subsequent management cycle, as shown in Figure 1.

From the maintenance point of view, facility aging process is just such a process to be evaluated. It is necessary to predict potential deterioration of components induced by operational and environmental stress and to evaluate resultant functional degradation for the purpose of design for reliability and maintainability and for maintenance planning. For the evaluation of potential deterioration and failures, methods for reliability analysis such as FTA and FMEA have been widely used. Recently model-based methods have also been studied in connection with life cycle management [3][4]. These are either methods of qualitative evaluation or they are based on statistical data which represent only characteristics of the facilities on average. However, the failure characteristics of facilities are dependent on how they have been used. To carry out a proper evaluation corresponding to each particular case, it is necessary to have a method which enables quantitative evaluation of the aging process of the facility when it operates in a particular environment and performs a particular task.

We have, therefore, developed a life cycle simulation system for this purpose. In the following, we will introduce the concept of life cycle simulation, then, describe the life cycle simulation system for robot manipulators. We will also explain an application example of the developed system to robot manipulators in an assembly line of a car parts manufacturing plant.

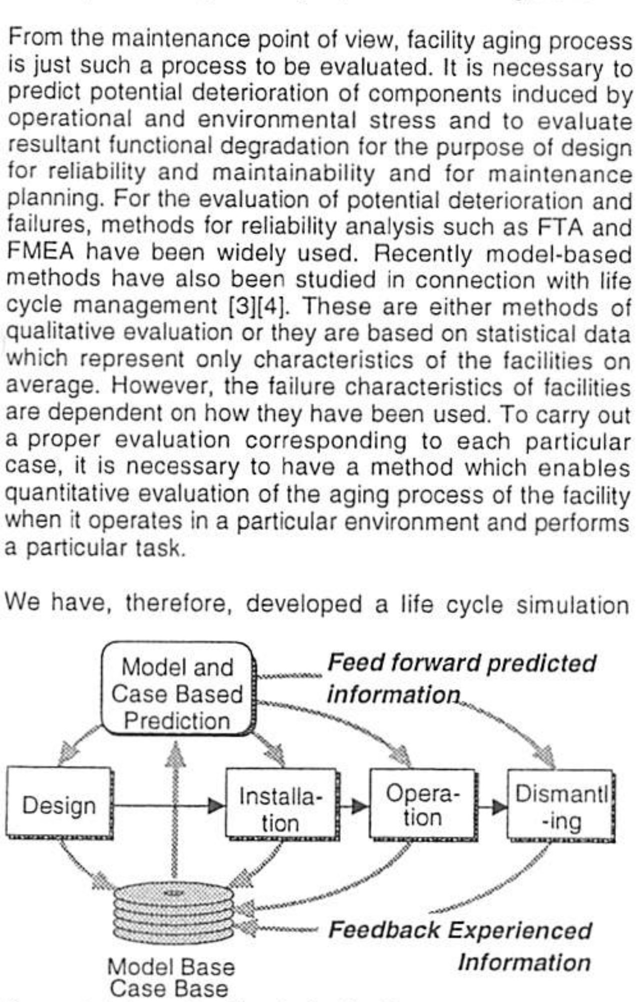

Figure 1 Information flow in facility life cycle management

2. Concept of Life Cycle Simulation

Life cycle simulation is an essential tool for facility life cycle management. Its function is to estimate aging processes of facilities as they perform specified tasks with specified conditions. In the simulation, operational and environmental stress acting on components of the facility is evaluated and their deterioration processes and resultant functional degradation are simulated. Life cycle simulation can be employed in various phases of the facility life cycle. In the design phase, for example, it is effective for reliability and maintainability design. In the operation phase, it is useful for maintenance planning and also for task planning in which excess stress can be avoided so as to extend the maintenance interval.

Figure 2 shows the general procedure for life cycle simulation [5]. First, behavior of the facility under given operational and environmental conditions is evaluated in terms of various operational parameters, such as torque, speed and temperature. The results are used to evaluate the stress exerted on components of the facility during the operation. Then, deterioration of the components which could be induced by the exerted stress is

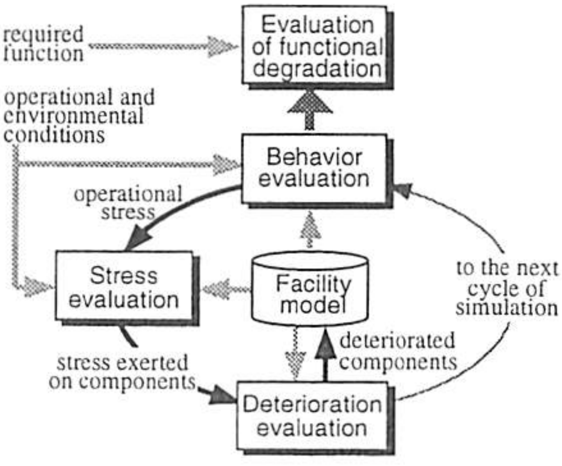

Figure 2 General procedure of life cycle simulation

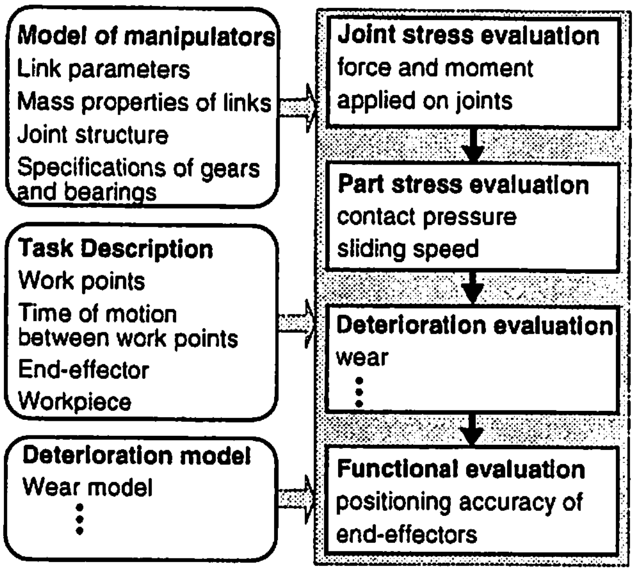

Figure 3 Procedure of life cycle simulation of robot manipulators

evaluated, and the resultant changes in the properties of the components are estimated. The results are reflected in the facility model. Based on this "deteriorated model", behavior of the facility is evaluated again and the resultant functional degradation of the facility is assessed in reference to required functions. By repeating the aforementioned procedure, progress of the degradation of the facility as the operation continues is simulated.

3. Life Cycle Simulation System for Robot Manipulators

3.1 Simulation procedure

Based on the concept explained in the previous section, we have developed a life cycle simulation system for robot manipulators. The system obtains a specification of the manipulator, descriptions of tasks, and deterioration models from the database and performs the simulation in the four steps: stress evaluation on joints as well as parts, deterioration evaluation, and functional evaluation, as shown in Figure 3. The model of a manipulator represents link parameters in terms of the Denavit-Hartenberg notation and mass properties of links in terms of weight, centers of gravity and density. The shape of each link is approximated by a cylinder. In this system, we consider wear of gears and bearings of joints as component deterioration. Specifications of reduction gears and bearings, and their arrangement in each joint, are described in the model.

Tasks are represented in terms of a series of work points and periods of time of motion between work points. Each work point is specified by a position and an orientation of the end-effector and force and moment applied on the end-effector. Weight and the center of gravity of the end-effector should be specified. If a workpiece is grasped at a work point, those of the workpiece should be also specified.

3.2 Stress evaluation

Based on the model of the robot and the task description, the force $\vec{F}_{ji}=(Fx_{ji}, Fy_{ji}, Fz_{ji})^T$ and the moment $\vec{M}_{ji}=(Mx_{ji}, My_{ji}, Mz_{ji})^T$ acting on the j-th joint at the time t_i are calculated by taking gravity and inertial force as well as the loads applied on the end-effector into account [1].

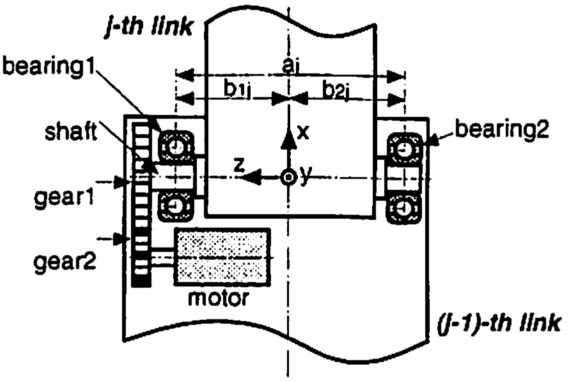

Figure 4 Structure of joints

With regard to the stress on gears and bearings, we assume the structure of joints as shown in Figure 4. Although one pair of gears is indicated in the figure, the system can deal with multistage reduction gears. Using $\vec{F}_{ji}$ and $\vec{M}_{ji}$, stress on the k-th gear and bearing is calculated in terms of contact load on a unit width of a tooth surface or a bearing surface, Pg_{kji}, Pb_{kji} [N/mm] as follows.

$$Pg_{kji}=\frac{Mz_{ji}}{r_{kj}\cdot\eta_{kj}\cdot t_{kj}} \tag{1}$$

$$Pb_{kji}=\frac{1}{t_{kj}}\sqrt{\left(\frac{a_j-b_{kj}}{a_j}Fx_{ji}+\frac{My_{ji}}{b_{kj}}\right)^2+\left(\frac{a_j-b_{kj}}{a_j}Fy_{ji}+\frac{Mx_{ji}}{b_{kj}}\right)^2+\left(\frac{Fz_{ji}}{2}\right)^2} \tag{2}$$

where r_{kj} is the radius of the pitch circle and η_{kj} is the ratio of contact of the gear. t_{kj} is the width of the tooth surface or the bearing surface. a_j is the distance between the bearings on the both side of the joint and b_{kj} is the distance of the k-th bearing from the origin of the joint.

3.3 Deterioration evaluation

We assume that wear rates of the gear and the bearing wg_{kji}, wb_{kji} [mm/s] are proportional to the contact load Pg_{kji}, Pb_{kji} and the relative sliding speed Vg_{kji}, Vb_{kji} [mm/s] [2].

$$wg/b_{kji}=kg/b_{kj}\cdot Pg/b_{kji}\cdot Vg/b_{kji} \tag{3}$$

where kg_{kj} and kb_{kj} are constants which depend on environmental conditions and types of gears and bearings.

The progress of backlashes of gears and the bearing clearances is estimated by summing up $wg/b_{kji}\cdot\Delta t$ through the whole task, where Δt is the time interval specified in the simulation.

3.4 Functional evaluation

In this system, the function of a manipulator is evaluated in terms of positioning accuracy of an end-effector at each work point. With regard to gear backlashes, the system evaluates whether the backlashes of gears affect rotational accuracy of the joint motion at each work point by considering the direction of the rotation of the joint and the gravity force. The rotational error of the j-th joint at the p-th work point due to gear backlashes is denoted by δz_{jp}^{g}.

Regarding bearing clearances, the system calculates the translational and rotational errors of the shaft of the joint due to bearing clearances taking the directions of the force and moment acting on the joint into account. They are denoted by $\left(dx_{jp}^{b}, dy_{jp}^{b}, dz_{jp}^{b}\right)$ and $\left(\delta x_{jp}^{b}, \delta y_{jp}^{b}, 0\right)$.

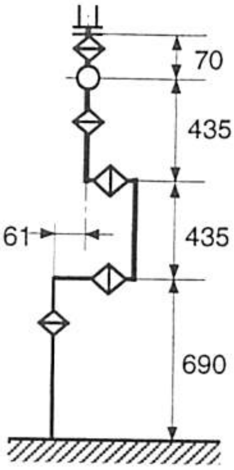

Figure 5 Structure of the assembly robot

Table 2 Failure history of the assembly robots

station	time	location	failure
lever assembling 1	1994. 12	wrist	excess clearance
	1995. 11	wrist	adjustment
	1996. 11	wrist	wear of gears, excess clearance
lever assembling 2	1994. 6	wrist	excess clearance, noise
	1995. 10	wrist	excess clearance
	1995. 12	wrist	wear of gears, excess backlash
sub-unit assembling	1993. 12	3rd joint	wear of gears, excess backlash
	1994. 7	3rd joint	excess backlash, positioning error
	1995. 11	1st joint	wear of gears, excess clearance
	1996. 4	1st joint	wear of gears, excess clearance
stamping	1993. 7	6th joint	wear of gears, excess clearance
	1994. 4	unknown	overhaul
	1994. 9	4th, 5th joint	wear of gears, excess clearance
	1995. 12	5th joint	wear of gears, excess clearance
	1996. 5	6th joint	wear of gears, excess clearance
	1996. 10	2nd joint	wear of gears, robot did not work

Both results are combined in the form of the error matrix of the j-th joint at the p-th work point as follows.

$$E_{jp} = \begin{bmatrix} 0 & -\delta z_{jp}^{g} & \delta y_{jp}^{b} & dx_{jp}^{b} \\ \delta z_{jp}^{g} & 0 & -\delta x_{jp}^{b} & dy_{jp}^{b} \\ -\delta y_{jp}^{b} & \delta x_{jp}^{b} & 0 & dz_{jp}^{b} \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

When omitting the higher-power terms, the transformation matrix representing the positioning error of the end-effector at the p-th work point is expressed as follows.

$$E_p = \sum_{j=1}^{6} \left(A_{1p} \cdot A_{2p} \cdots A_{j-1,p} \cdot E_{jp} \cdot A_{jp} \cdots A_{6p} \right) \tag{5}$$

where A_{jp} denotes the transformation matrix between the (j-1)-th and j-th joint at the p-th work point.

4. Application of Life Cycle Simulation to Assembly Robots

4.1 Description of assembly tasks and a robot manipulator

A case study was conducted taking an example of an automatic assembly line in an automobile parts manufacturing plant where a number of assembly robots are used. The robot manipulators are articulated type robots with 6 degrees of freedom. The joint structure and link lengths are shown in Figure 5.

We have investigated three kinds of assembly tasks at the following assembly stations.

Table 1 Weight of end-effectors and workpieces

station	end-effector	workpiece
lever assembling	2.9 kg	–
sub-unit assembling	2.3 kg	0.8 kg
stamping	0.3 kg	0.1 kg

a) Lever assembly station 1 & 2: At station 1 and 2, an identical task is performed. The robot has a screwdriver as an end-effector, and screws the control lever on the side of the assembly while it is supported by another robot.
b) Sub-unit assembly station: a robot inserts a sub-assembly unit downward in the vertical direction.
c) Stamping station: The robot takes a stamp corresponding to a type of a product to be assembled, inks up it, and stamps the number on the assembly.

The robots performing the above three tasks are illustrated in Figure 6, 7, 8 respectively. The weight of end-effectors and workpieces are shown in Table 1. At the lever assembly and sub-unit assembly stations, heavy end-effectors are used.

4.2 Failure history

Table 2 shows failure histories of the robots which were used at these stations during a period from 1993 to 1996. Since they are summaries of what were written in failure records, the level of descriptions is not uniform. Once some of the joints failed, all joints were overhauled regardless of their conditions. The following features can be identified from the table.

a) Most of the failures were caused by wear of gears and resulted in excess clearances or backlashes.
b) At the lever assembly station, all failures occurred at the wrist. They correspond to failures of the 4th, 5th or 6th joint which are on the end-effector side.

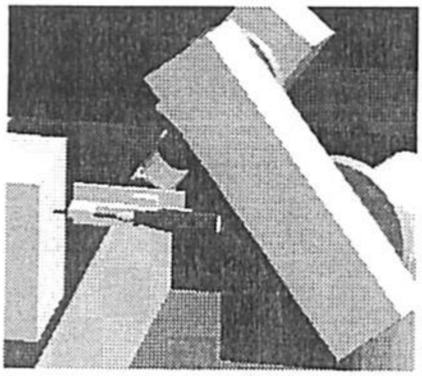

Figure 6 Lever assembling

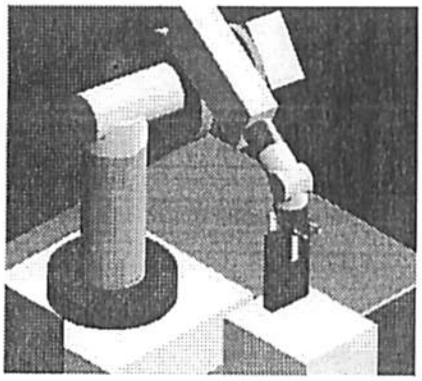

Figure 7 Sub-unit assembling

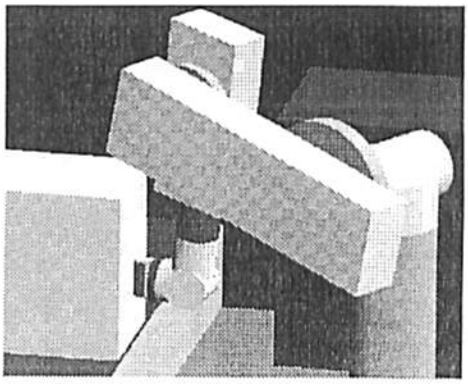

Figure 8 Stamping

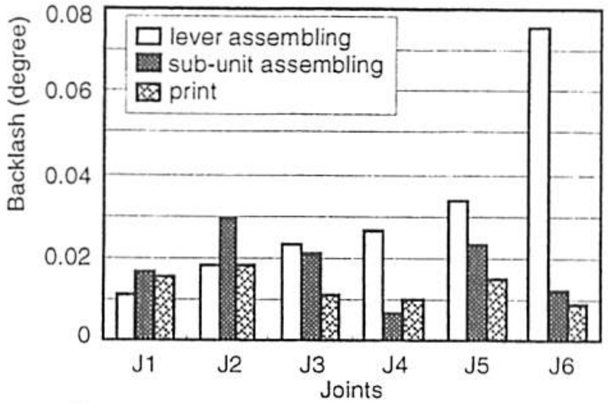

Figure 9 Results of the life cycle simulation

c) At the sub-unit assembling station, failures occurred at the joint on the base side.
d) At the stamping station, most failures occurred at the end-effector side joints, but there also was a failure at the base side joint.

4.3 Results of the life cycle simulation

We have performed life cycle simulations of these robot manipulators and evaluated the wear of gears of their joints in terms of backlash, since most of the failures in the history were caused by wear of gears. The parameter of the wear model kg_{kj} in equation (3) was determined based on the endurance test data. Figure 9 shows the results of the simulations in which each task was repeated 5 million times. In the case of the lever assembling, the closer to the end-effector the joint is, the larger the backlash becomes. This result, which seems to be caused by the heavy end-effector, corresponds to the failure history represented in Table 1.

In the case of the sub-unit assembling, the base side joints suffer more severe wear than the end-effector side joints. Although the sum of the weight of the end-effector and the workpiece is large also in this case, they do not apply a large amount of moment to the wrist, because they are held in a way that they are suspended vertically, as illustrated in Figure 7. This could be the reason why the backlashes of the end-effector side joints are smaller than those of the base side joints, unlike the robot for the lever assembling. This result corresponds to the failure history which shows troubles with the 1st and 3rd joints in the sub-unit assembling.

In the case of the stamping station, the amounts of the backlashes are relatively uniform compared with the other two cases. This result may explain the failure history in which both end-effector side and base side joints failed.

5. Discussions

The results of life cycle simulation correspond to the failure history of the assembly robots fairly well. As already mentioned, we can make use of such results in various ways. From the view point of reliability design, for example, the result of the simulation for the lever assembling suggests the need for strengthening the end-effector side joints. The robot has actually been improved so as to strengthen the gears of the 3rd, 4th, 5th and 6th joints independently of our study. Figure 10 shows the results of the simulation when the original robot and the improved one perform the lever assembling. It is seen that the improvement was quite effective for reducing the backlashes of the end-effector side joints and for making the life spans of joints uniform.

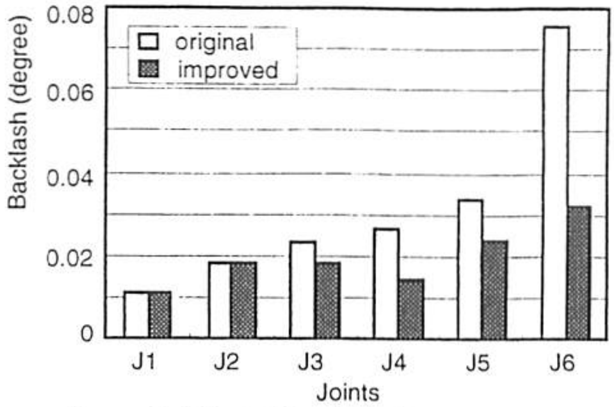

Figure 10 Effect of the design improvement

There are, however, many issues which need to be studied further. The most critical issue is the improvement of deterioration models. Since deterioration is a complicated phenomenon, we need to improve the deterioration model in such a way that various factors can be taken into consideration, such as lubrication conditions. We also need to develop deterioration models other than wear. Determining the model parameters is also an important issue. In the above case study, the simulation results have been verified only in a qualitative way. For making quantitatively accurate prediction of the life of the facility via life cycle simulation, we need to establish a procedure to obtain the data during the operation and to feed them back for improving model parameters, which can then be used in the simulation for the next management cycle as illustrated in Figure 1.

6. Conclusion

In this study, the concept of life cycle simulation has been proposed. Its purpose is to evaluate the aging process of a manufacturing facility which is used for a particular task in a particular environment. An experimental system has been developed for robot manipulators. The simulation is carried out in four steps: evaluation of stress on joints, evaluation of stress on parts, evaluation of the deterioration process relative to parts, and evaluation of functional degradation. The developed system can simulate wear of gears and bearings of joints as component deterioration and evaluate the resultant positioning error of an end-effector as functional degradation. The system was applied to the robot manipulators in an assembly line of a car parts manufacturing plant. Robots performing three different tasks are evaluated by the life cycle simulation system and the results are compared with the actual failure history. The simulation results correspond to the failure history fairly well.

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