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Model based approach to life-cycle simulation of manufacturing facilities

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Abstract

For realizing effective utilization of manufacturing facilities, evaluation of various point of views in each phase of facility life cycle is essential. For this purpose, we propose a computer support system based on a model of the facility. The system, which is called *the life cycle simulation* system, can simulate the degradation of facility as it works. As essential modules of the system, we have developed a deterioration evaluation sub-system which provides qualitative estimates of the component deterioration of the facility, and a movable parts identification sub-system which can identify the parts in motion of the facility assuming that the predicted deterioration has occurred. The output of the sub-system can be used for kinematic analysis of the facility in order to identify failure modes induced by deterioration. As an illustrative example, the evaluation of a grinding robot is demonstrated using an experimental system.

Keywords

Computer models, maintenance, life cycle, deterioration, kinematic motion

1 INTRODUCTION

Today's manufacturing becomes increasingly dependent upon facilities with the advances of automation and integration of manufacturing systems. This lead to a growing concern about effectiveness of the facility, which should be evaluated from various point of views, such as functionality, reliability and maintainability. For improving its effectiveness, we have to properly manage the various activities in each phase of its life cycle.

In this study, we direct our attention to a maintenance activities of the facility. In the past, maintenance was regarded as a reaction to the occurrence of failure. Even through condition-based maintenance is concerned, most efforts have been directed at diagnostic issues, that is, identifying what happened or what is happening. However, in order to carry out the effective maintenance over the facility life cycle, it is necessary to take a proactive approach. If you do not know what to expect, you can hardly prepare for it. Only by predicting potential problems, can you devise countermeasures, such as improving design or planning for preventive maintenance.

For implementing the proactive maintenance strategies, we need an effective computer support for predicting problems which would occur in the facility. For this purpose, we propose a concept of a life cycle simulation which is executed based on a model of the facility, called a facility model. As essential modules for the life cycle simulation, we have developed a deterioration evaluation system which predicts potential deterioration of the facility components, and a movable parts identification system, which is used to extract the parts participating in kinematic motion from the facility model and to construct a model for kinematic simulation so as to evaluate functional failure induced by expected deterioration.

In Chapter 2 and 3, we will describe the concept of the life cycle simulation and the facility model respectively. Then we will present the method of evaluating deterioration and identifying movable parts in Chapter 4 and 5. In Chapter 6, an experimental system is explained and illustrative examples are demonstrated.

2 CONCEPT OF LIFE CYCLE SIMULATION

To take the proactive maintenance approach, we need to be able to evaluate the state of the facility in any phase of its life cycle based on the best available information at each point in time. For this purpose, we need to have access to any evaluation tools and information provided in

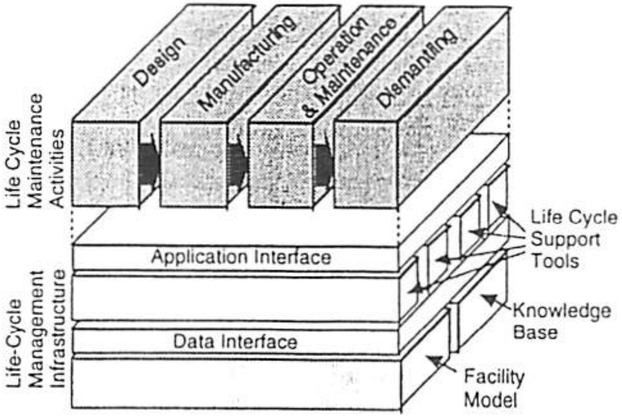


Figure 1 Life cycle facility management infrastructure

each phase of the life cycle. For example, it is essential to know the real operating situations and the problems experienced in the past in the design phase for the purpose of design for maintenance. On the other hand, it is necessary to have exact design information for the maintenance planning in the operation phase.

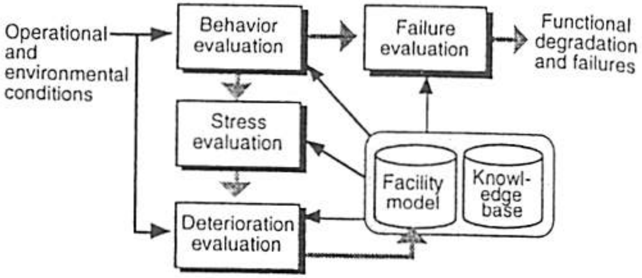


Figure 2 Life cycle simulation

For fulfilling these requirements, we propose an integrated information system which is called a life cycle facility management infrastructure. Figure 1 shows the architecture of the system. The system has two types of common data bases: a facility model and a knowledge base. The facility model maintains all information associated with the facility life cycle. In the knowledge base, generic knowledge, independent of an individual facility, is stored. Such generic knowledge includes deterioration mechanisms, theories and practices. Various tools which support maintenance activities based on the facility model are implemented in the system. They are accessible to any phase of the facility life cycle.

We have been developing a system for simulating the degradation of the facility as it continues to work. It is a essential part of the life cycle facility management system. We call it a life cycle simulation system. The process of the simulation is shown in Figure 2. First, the system evaluates behavior of the facility under given operational and environmental conditions 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, the system evaluates deterioration which could be induced by the exerted stress and other factors existing in the component. Here, deterioration means a physical and/or chemical process occurring on a component of the facility, such as wear, fatigue, and corrosion. The change in the properties of the facility due to deterioration is reflected in the facility model. Based on 'the deteriorated facility model,' the behavior of the facility is evaluated again. The results are assessed in reference to required functions and potential failure modes are predicted. At the same time, the stress exerted on the components is estimated based on the newly evaluated behavior. By repeating the afore mentioned procedure, the change in the facility as the operation continues can be simulated.

3. FACILITY MODEL

The facility model for life cycle management system should represent the basic information of the facility such as parts, assemblies and its hierarchical structure. It should also have the capability of representing various additional information, such as design intention and information related to maintenance. As a base of the model structure, we have adopted the assembly structure of the facility (Sodhi, 1994, Sugimura, 1994). We used an object oriented data structure as shown in Figure 3 (Takata, 1995).

The model consists of *assembly items* and *assembly relations* between the *items*. Notations in the figure are based on EXPRESS-G (NN, 1992) where an attribute is shown as a thin line with its name on it and marked with a circle at the value end. A thick line shows a class hierarchical relation, with a circle attached to the sub-class side.

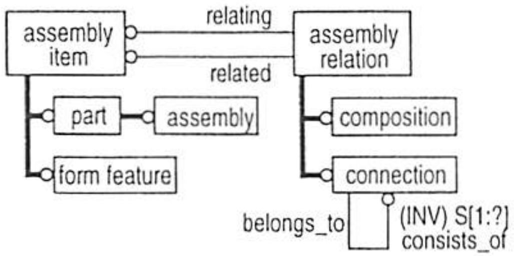


Figure 3 Structure of the facility model

An *assembly item* represents a physical substance in the facility. *Assembly items* are classified into *part* and *form feature*. A *part* is an individual physical substance. We consider an assembly a kind of *part* that can be divided into multiple *parts*. This concept allows us to represent the hierarchical structure of the facility in a flexible manner.

Form feature is a group of geometric elements that carries some functions or behavior. Note that it does not necessarily belong to a single *part*. An assembly feature is a *form feature* that mates with another *form feature* of a different *part* or sub-assembly to make an *assembly*, such as holes/pins and grooves/extrusions. For allowing users to focus their attention on any level of hierarchy, neglecting the lower levels of assembly structure, we provide the access function for the model to get *form features* from *assembly items* at any level. If the *item* is an *assembly*,

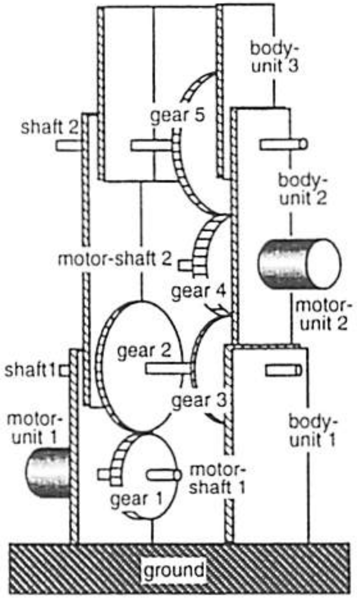


Figure 4 Robot manipulator

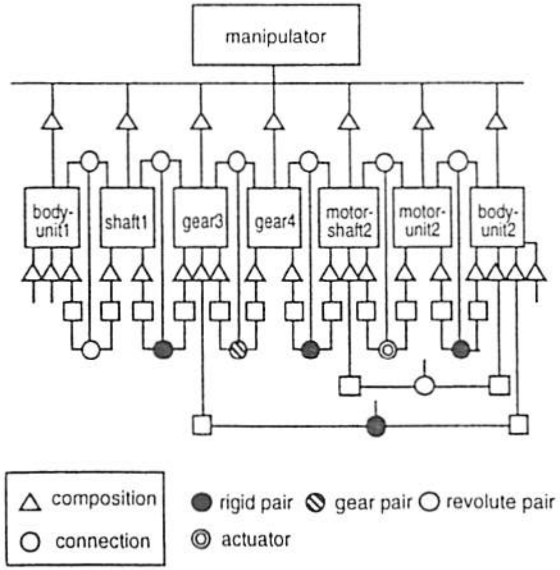


Figure 5 Model representation of robot manipulator

form features of the *parts* that are mated with those outside the *assembly*, are identified by the function.

Two types of *assembly relations* are identified to represent assembly structures. *Connection* is an *assembly relation* between two *items* that have no inclusion relations with each other, e.g., a *part* to a *part*, an assembly feature to an assembly feature. As hierarchical information, *connection* has a pointer to the *connections* in which it participates. For example, a *connection* between two parts may consist of several *connections* between assembly features. They have a pointer to the parent *part*-to-*part connection*.

Composition is an *assembly relation* between an *assembly item* and another *assembly item* that consists of it. *Composition* has a transformation that represents the position and orientation of the child *item* in the coordinate space of the parent *item*.

Both *assembly items* and *assembly relations* can have technical information in addition to configuration structures. *Connection*, for example, contains technical information that represents the type of the *connection*, such as a sliding pair and a revolute pair. This is effective in performing various simulations and analysis based on the model.

As an example of the facility model, a model of a robot manipulator shown in Figure 4 is represented in Figure 5. Note that Figure 5 is an instance-level diagram. Attribute names have been omitted. *Connections* and *compositions* are represented as circles and triangles. The entire model is not represented because of space limitations. The hierarchy of *assembly items* are arranged vertically.

4. MODEL BASED DETERIORATION EVALUATION

4.1 Modeling of the deterioration processes (Takata, 1994)

Mechanisms, such as fatigue, wear, and corrosion, which induce deterioration at certain areas of parts or assemblies are called deterioration mechanisms. The resultant deteriorated states are distinguished by deterioration modes. The deterioration mechanism is caused by a certain set of conditions which we call causal factors. They are classified into four categories: 1) Inherent characteristics such as geometry, material and surface finish. 2) Exerted stress such as mechanical stress, thermal effects and electro-magnetic effects. 3) Relative motion. 4) Operating environment such as in a gas, in a liquid, or in particles.

Although there seems to be an infinite number of phenomena recognized as deterioration of the facility, we can identify a certain set of deterioration mechanisms which are basic and common for many types of facilities (Dasgupta, 1991). We call them fundamental deterioration mechanisms.

In many cases a chain of multiple fundamental deterioration mechanisms are related to failure. For example, fatigue failure could be initiated by a notch created by corrosion. In this way, one of the causal factors of a deterioration mechanism could be provided by other deterioration mechanisms. There is also a case where some of the causal factors are provided by mechanisms other than deterioration mechanisms, which we call causal factor formation mechanisms. An example of this type of mechanism can be seen when the rotation of a shaft with a radial load creates cyclic stresses which lead to fatigue at a stepped part of the shaft. The chain of deterioration mechanisms and causal factor formation mechanisms is termed a deterioration process. Figure 6, for example, schematically represents the deterioration process of fatigue for a spindle.

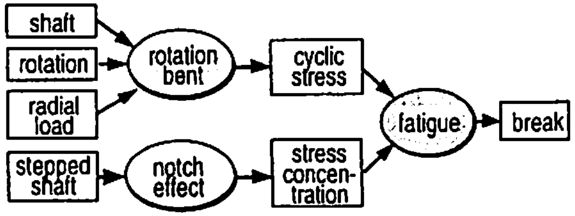


Figure 6 Example of the deterioration process

4.2 Method of deterioration evaluation

The qualitative deterioration evaluation is based on the facility model and a deterioration data base. The result is represented in terms of potential deterioration processes which may occur at particular parts of the facility (Takata, 1994, 1995).

Deterioration data base

The deterioration data base contains the fundamental deterioration mechanisms and the causal factor formation mechanisms. They are expressed in terms of a set of causal factors and the resultant deterioration modes or causal factors. This data base can be prepared independently from individual facilities.

Facility model

The structure and properties of a facility are retrieved from the facility model. The properties are represented in terms of values of attributes defined in assembly items and relations. The model has a mechanism to inherit the values of attributes from those of higher level items in the hierarchy, unless they are explicitly defined at their level.

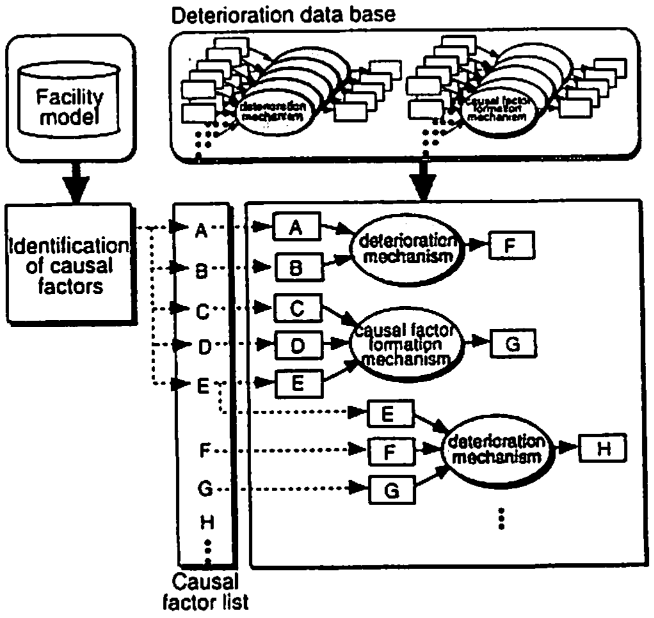


Figure 7 Inference mechanism of deterioration processes

Inference of deterioration process

Inference is conducted for every form feature of every part defined in the facility model, since different form features have different causal factors even in the same parts. Figure 7 illustrates the inference mechanism. The causal factors associated with a particular form feature are identified from the facility model and placed in a causal factor list. They are selected from the attributes of the form feature itself, the related form feature connection and the parent parts. Then, mechanisms whose causal factors match with those in the casual factor list are searched in the deterioration data base. The output of the selected mechanisms are appended to the casual factor list and the other mechanisms are searched again taking the newly appended causal factors into account. Finally, the deterioration process(es) is (are) formed by the selected mechanisms.

Inference of range of effects of deterioration

In the above procedure, the effects of causal factors and deterioration modes are considered within the specified form feature. However, there are causal factors and deterioration modes which also have effects on other form features or parts. The following three cases were identified: 1) Some types of deterioration, such as loose bolt fastenings, have ranges of influence involving multiple parts or part connections. 2) Effects of causal factors, such as vibration and heat conduction, propagate from one part to another. 3) Effects of deterioration change environmental causal factors of other form features or parts. For example, leakage of coolant due to a damaged seal makes a bearing wet. In the system, the first and the second cases are dealt with. Inference algorithms were developed for the first case. For the second case, the propagation rules for the corresponding causal factors were defined.

5 IDENTIFICATION OF MOVABLE PARTS

To prepare appropriate methods to maintain a facility, it is necessary to predict what will happen to the behaviors of a facility when some of its parts fail. When we perform kinematic analysis of facility with failed parts for that purpose, a nominal kinematic model developed at the design phase may not be useful. For example, small parts such as bolts may not be explicitly represented in the model but those small parts could deteriorate and break, which may lead to the facility's malfunction. On the other hand, it is not economical nor realistic to analyze the whole facility model because it includes numbers of parts that may not contribute to the motion. So we should first identify the parts that can participate in the motion under the specific situation. In the following, we describe how to identify parts that are able to move using the facility model with information on failure. The method is based on kinematics and no friction is assumed.

The strategy is, starting from the actuator where the motion is generated, to repeat calculating the transmission of the motion by following the connection of parts in the facility model. If the motion is reached to the fixed end that does not allow the transmitted motion, the original motion is found unfeasible. Otherwise all the parts on the path from the actuator to the end will move and should participate in the kinematic model on which more detailed analysis (such as by Kramer (1992) or Haug (1989)) would be made later.

Transmission of motion

In our system, two types of motion are represented: translation and rotation. Translation is represented by a vector of its velocity. Rotation is represented by the center of rotation and a vector of the angular velocity.

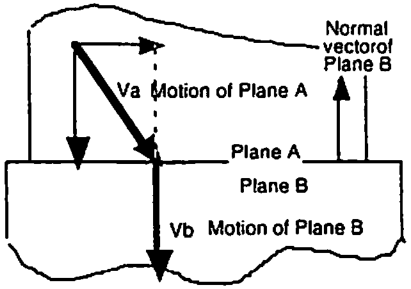
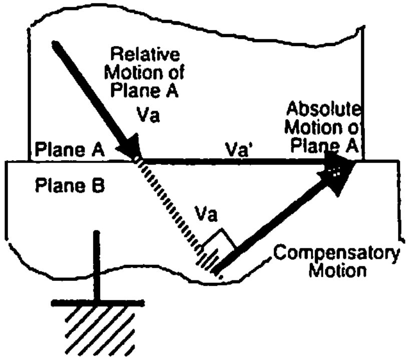


Figure 8 Transmission of translational motion for planar pairs



Figures 9 Compensatory motion for planar pair

Motion of an object is transmitted to another object through their physical contact. Transmission differs depending what type of connection is formed by the contact. In kinematics such connection of objects is called a kinematic pair (Duffy, 1980, NN, 1995). In our facility model, kinematic pair is represented by *connections* between a pair of features in contact. We currently have implemented three types of kinematic pairs that include a planar pair, a gear pair and a revolute pair.

For instance, in planar pairs, the translational motion of the input feature *A* with velocity *Va* is transmitted to the output feature *B* as shown in Figure 8. As no friction is assumed, the transmitted motion of feature *B* has the velocity *Vb*, that is the components of *Va* perpendicular to the contact plane. When the motion of feature *A* is rotational motion the transmitted motion of feature *B* is the same rotational motion. Similarly, we have analyzed and implemented the transmission of gear pairs and revolute pairs.

Propagation of motion

The motion is generated at the actuator, which is the single source of motion represented by a feature relationship, as relative motion between two features that compose the actuator. The motion of the feature is transmitted to the part it belongs to. It is transmitted from the part to all its features. Then, the motion of each feature is transmitted to its connecting feature as described above. Thus the motion is propagated to all the related parts by repeating this process.

A series of parts and features generated by this process is called a path of transmission. As a part has multiple features, paths have branches to make a tree with the actuator as its root. When the motion is not allowed at any point in the tree, the motion is unfeasible. The tree is called fixed in which all the parts are not movable. When the different motions from different trees coincide at a point, motions are also considered to be fixed.

The possibility of motion of the parts is checked by the following procedure. First, one feature of the actuator is assumed fixed and the motion is transmitted to the other feature. It is propagated as described above. Next, the second feature is assumed fixed and the motion is transmitted to the first feature. If one of the trees generated is found free and the other is found fixed, the motion is feasible. If both trees are found free, the motion is also feasible. However, because this means the mechanism is 'floating,' absolute motion against the world coordinate system cannot be decided. If both trees are found fixed, the motion is not feasible.

Compensation of motion

Even if the motion is found unfeasible using the above algorithm, there is a possibility that the actuator itself moves relative to the fixed part in the world coordinate system. The algorithm to find the possibility is as follows:

Where the tree of transmission reaches a fixed part, it calculates compensatory motion that complies with the fixed part and generates possible absolute motion from the transmitted motion relative to the actuator. For example, compensatory motion for a planar pair is calculated as shown in Figure 9. The relative motion of plane *A* is transmitted to plane *B*, but plane *B* is fixed to the ground. The only possible absolute motion of plane *A* is sliding along the contact surface. To make the absolute motion of plane *A* along the contact surface, the difference between the relative motion and its absolute motion should have a vector shown as compensatory motion in the figure. It would generate absolute motion *Va'* along the contact surface, which realizes both the relative input motion of *A* and fixed plane *B*. So if it is possible that plane *A* has the absolute motion that is the sum of the input relative motion and this compensatory motion, the motion becomes feasible. To ensure this, our algorithm transmits and propagates the compensatory motion backwards from the fixed point to the actuator and checks to see if it is feasible. For a gear pair, compensatory motion generates planetary motion around the fixed gear feature.

Though it has fairly good functions, our method has some limitations. First, it analyzes instantaneous motion and derives movable parts at a specific instance where all the information of the facility is known. To follow the behavior of the facility for some period of time, we need precise kinematics analysis with some method to handle changes in the situation.

Representation of motion with a single value brings some difficulties for handling a mechanism with loops, or generating compensatory motion. For resolving these problems, we consider that a method will be necessary to represent ranges of values and to make calculation on them. Although our method has these limitations, it derives rather easily and intuitively, a kinematic model that is sufficiently correct.

6 EXPERIMENTAL SYSTEM

The experimental system has been developed by using the object oriented expert shell G2. Elements of the facility model are defined as object classes. The deterioration mechanisms and the causal factor formation mechanism are also described as objects. The inference of deterioration is executed by production rules. The identification of movable parts is also executed by rules and procedures attached to objects.

As an example, a grinding robot whose structure is shown in Figure 4 was analyzed. First, deterioration evaluation was performed. Figure 10 shows the display of the system when potential deterioration of a bearing between body-unit 1 and shaft 1 was evaluated. The lower right part of the figure shows a corresponding part of the facility model of the robot. The upper left part of the figure indicates prediction of a potential deterioration process. The process

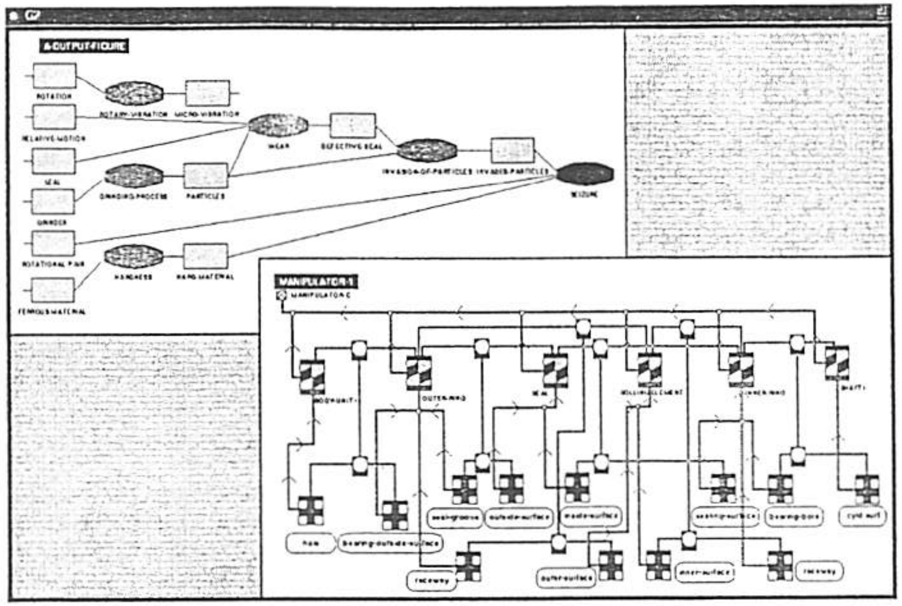


Figure 10 The output of deterioration evaluation for the grinding robot

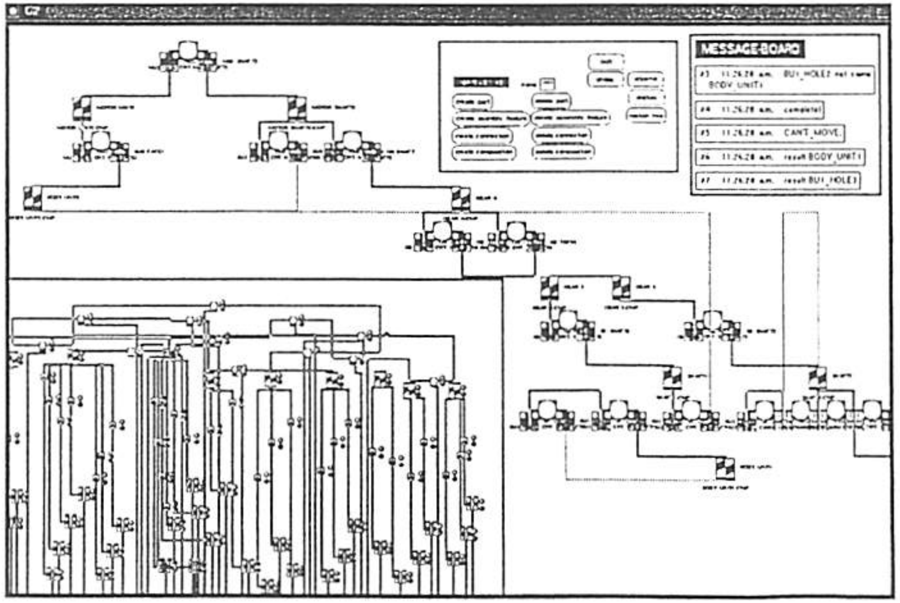


Figure 11 The output of identification of movable parts for the failed grinding robot.

shows that the seal of the bearing may be worn by grinding swarf. This leads to the invasion of grinding swarf into the bearing which may cause the seizure of the bearing.

Based on the result from deterioration evaluation, the connection of the features of body-unit 1 and shaft 1 was changed to be rigid to show the shaft got stuck. Identification of movable parts was performed based on the facility model with this information on failure. The upper part of Figure 11 shows the tree of identified movable parts. The mechanism is originally designed so that motor-unit 2 controls body-unit 3 independent of the motion of body-unit 2. With the failure of the shaft sticking, the motion of motor-unit 2 was found to generate compensatory motion and to bring the motion of body-unit 2 as well as that of body-unit 3.

7 CONCLUSION

For realizing proactive maintenance strategies, we propose the concept of life cycle simulation to evaluate the change in the facility as it works. We adopted model based approach, and proposed the model structure of the facility.

Based on the facility model, we have developed two modules of life cycle simulation system. One is the deterioration evaluation system that infers possible deterioration of facility components. The inference is performed by combining the information derived from the facility model with the deterioration mechanism and causal factor formation mechanisms which are stored in a deterioration data base.

The other module is the movable parts identification system which finds the parts participating in the motion when there is a failure in the facility. The system searches the facility model simulating the transmission of motion and generates a mechanism tree that will be used for precise kinematic analysis.

Currently we are trying to integrate these two modules with other modules necessary for completing the life cycle simulation such as the stress evaluation module and the failure evaluation module shown in Figure 2.

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