Reliability Improvement of Industrial Robots by Optimizing Operation Plans Based on Deterioration Evaluation

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Abstract
This paper proposes a novel method for improving reliability of manufacturing facilities by optimizing operating conditions so as to reduce deterioration of critical components and to extend the life of facilities. The method is applied to an industrial robot. For deterioration evaluation, a life cycle simulation system has been developed. It evaluates wear of joint gears, which has critical effects on the accuracy of industrial robots. Optimization of operating conditions, defined in terms of layout of the robot and in motion pattern, is performed by means of a hybrid GA, which consists of genetic algorithm and simulated annealing. The effectiveness of the method has been verified by applying the method to assembly robots.

Keywords:
Reliability improvement, Deterioration evaluation, Operation plan

1 INTRODUCTION

Reliability improvement is always a prime concern in the life cycle management of manufacturing facilities. For this purpose, various activities are conducted in terms of reliability design and maintenance. In addition, it is well recognized that planning proper operating conditions is effective for reliability improvement of the facilities. Improper operating conditions leads to so called forced deterioration of components and shortens the life of the facility. However, there have been few studies on systematic methods for determining operating conditions which take reliability of facilities into account. In this study, we propose an optimization method for operation plan of industrial robots based on deterioration evaluation.

Nowadays, industrial robots are widely used for various operations in automated manufacturing lines, for which a high degree of flexibility is required to adapt to frequent changes of products while keeping a high level of productivity. In this type of line, operations have to be switched frequently depending on the product to be processed. It is not feasible to evaluate deterioration of such facilities based on empirical data obtained from reliability tests or on operation and maintenance records. Therefore, we have developed the life cycle simulation system. It can simulate deterioration processes occurring in the facility components from moment to moment depending on changes in the operating conditions.

In the following, a strategy for optimization of the operation planning for reliability improvement of industrial robots is described in section 2. In section 3, the life cycle simulation system is explained. Then, the optimization method based on a hybrid genetic algorithm is presented in section 4. The verification of the method by means of an experimental system is described in section 5.

2 RELIABILITY IMPROVEMENT OF INDUSTRIAL ROBOTS BY OPTIMIZING OPERATION PLANS

Tasks executed by industrial robots are defined in terms of a series of motions between work points, which we call task elements. For each task element, the periods of time of motion and modes of interpolation are assigned. In the operation planning, the operating conditions for executing the task are determined in terms of a layout of the robot and a motion pattern. The layout is expressed by the position of the base of the robot in the world coordinate system as shown in Figure 1. The motion pattern is represented by the series of velocity patterns assigned to task elements as shown in Figure 2.

Since operating conditions affect the stress acting on the components of robots, and this induces their deterioration, we try to extend the life span of the industrial robots by controlling the operating conditions, while maintaining the same level of productivity.

Industrial robots are constructed by a number of joints connected in a serial manner in the sense of a reliability model. Thus, the joint with the minimum life span determines the life of the robot. In the optimization process, therefore, the critical joint with the shortest life is identified by means of life cycle simulation. Then, the operating conditions are modified in such a way that the life of the critical joint is extended on condition that the specified cycle time is maintained. With regard to motion pattern, the velocity and/or acceleration of the task elements which have significant effects on the critical joint are decreased, while those which have minor effects are increased to keep the cycle time. This procedure is repeated until no more significant improvement can be obtained. With this strategy, the life of the critical joint can be extended at the cost of the lives of less critical joints. (The critical joint is not necessarily the same joint during the optimization process. It could change depending on the modifications of the operating conditions.) As the result, the life of the robot as a whole can be improved.

3 LIFE CYCLE SIMULATION: A TOOL FOR DETERIORATION AND FAILURE EVALUATION

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

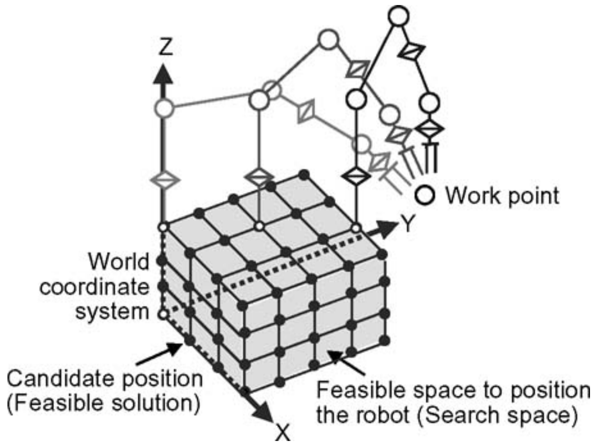

Figure 1: Layout of the robot.

facility are evaluated and their deterioration processes and resultant functional degradation are simulated.

We applied the concept of the life cycle simulation to industrial robots and developed the system shown in Figure 3 [1]: The system obtains specifications of robots, descriptions of tasks, and deterioration models from the database and performs the simulation in four steps. First, stress acting on the joints of the robot at each point in times under given operational and environmental conditions, is evaluated in terms of force and moment, taking inertia force, gravity, and load applied on the end-effecter into account. The results are used to evaluate the stress exerted on components of each joint during the operation. In this study, we consider the wear of driving gears of joints as component deterioration, because most failures of robots in manufacturing plants have been caused by wear of gears. The amount of wear of the joint gear is estimated from moment to moment by means of the slippage and the pressure between tooth surfaces at each point in time. The pressure exerted on the tooth surfaces is calculated based on Elasto-Hydrodynamic Lubrication theory [2]. Then, functional degradation induced by increase of wear of gears is evaluated in terms of the positioning accuracy of end-effectors.

4 OPTIMISATION OF OPERATING CONDITIONS FOR INDUSTRIAL ROBOTS BY MEANS OF A HYBRID GA

To find the optimum operating conditions, we have adopted a hybrid genetic algorithm, which combines Genetic Algorithm (GA) and Simulated Annealing (SA). In the optimization process, first, chromosomes of individuals are generated based on the genetic operations, and then the neighborhood of each individual is searched by means of simulated annealing.

A chromosome of an individual p is defined as a combination of the position of the robot and the velocity patterns of task elements, which is represented as follows.

$$p = \{x, y, z, v_1, v_2, \cdots, v_m, a_1, a_2, \cdots, a_m\} \quad (1)$$

where $\{x, y, z\}$ indicates the position of the robot and m is the number of task elements. The velocity pattern at task element i is specified by the maximum velocity rate v_i ($0<v_i\leq 1$) and the acceleration rate a_i ($0<a_i\leq 1$). The velocity rate represents the ratio between the velocity assigned to each task element and the allowable maximum velocity of the robot. The acceleration rate is defined in the same manner.

A fitness value of the individual p is calculated from the results of the life cycle simulation. The life cycle

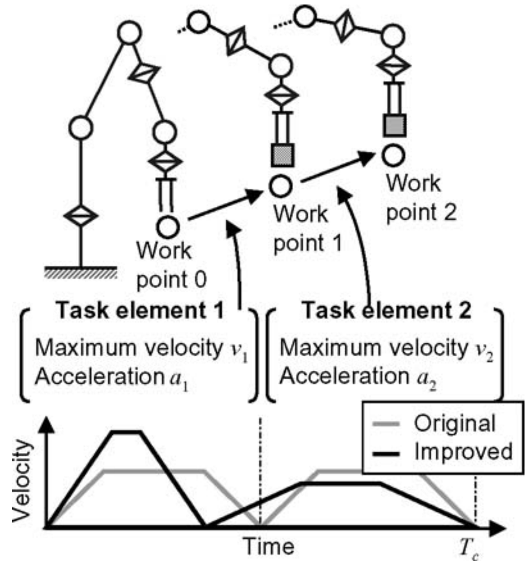

Figure 2: Motion pattern of the robot.

simulation is performed for each individual to estimate the amount of wear of each joint during one cycle of the operation. The fitness value of the individual p, denoted by F_p, is represented in terms of the maximum value among the wear of all joints, D_p, as shown in Equation (2). When execution time of the operation T_{ep}, is larger than cycle time T_c, the penalty for excess time is given by multiplying the coefficient whose initial value is r ($0\leq r<1$) as shown in Equation (2). When T_{ep} exceeds $(1+r)\,T_c$, F_p is set to 0.

$$F_p = \begin{cases} 1/D_p^2 & (T_{ep} \leq T_c) \\ \{r - (T_{ep} - T_c)/T_c\}^4 / D_p^2 & (T_c < T_{ep} \leq (1+r)\,T_c) \\ 0 & ((1+r)\,T_c < T_{ep}) \end{cases} \quad (2)$$

The individuals of the new generations are generated by means of reproduction and crossover at each optimization cycle. The probability of reproduction of an individual is defined by F_p/F_{sum}, where F_{sum} is the sum of fitness values of all individuals in the current generation. For crossover operations, a pair of individuals is chosen in the same way as in the case of reproduction. In this study, crossover is carried out at three points in the chromosome: among the position, velocity rates, and

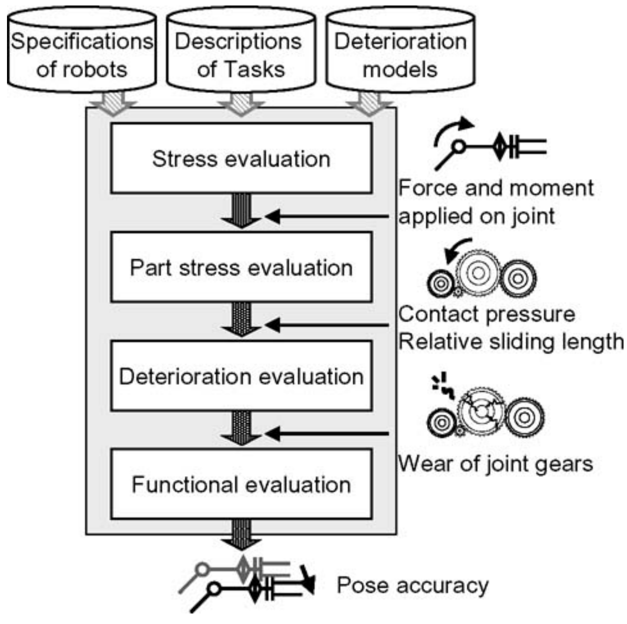

Figure 3: Life cycle simulation of industrial robot.