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Methodology for creation a reference trajectory for energetic comparability of industrial robots in body shop

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Abstract

The high amount of industrial robots in body shop allows significant energy savings, e. g. by the use of appropriate robot sizes for certain applications or energy efficient types of robots. Based on an extensive cluster analysis of several body-in-white systems and with the development of a special reference trajectory a new resource has been established to compare robots of different sizes or fabricators. Building on these results decisions for the choice of robots can be made in production planning to reduce energy consumption by the use of energy efficient robots. Furthermore, the expected energy consumptions of a robot can be estimated in advance.

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1. Introduction

For years now, the reduction of energy consumption has been an essential objective in the reduction of environmental damage and also in keeping down costs. At the start of this development, emphasis was placed primarily on products with energy-efficient uses and applications, but over the past few years since that starting point, the focus of new developments has shifted towards saving energy in the production of these products.

In addition to the mechanical engineering and tool construction industries, another pioneer for these developments in Germany is once again the automotive industry, which is now taking the next logical step from creating energy-efficient products to ensuring the energy-optimized production of vehicles. These days, producing a medium-sized car requires approx. 3.5 MWh of electric energy [1], which equates to the annual electric energy consumption of an average German household.

When implementing measures designed to increase energy efficiency, it is both crucial and practical to consider the entire process chain. Otherwise savings at one point in the chain would be undermined by the resulting extra outlay required at other points. Obviously though, consideration must first be given to those processes with the highest energy consumption. These are often processes that also make a large contribution to value added [2]. In vehicle construction, the processes with the highest energy consumption are primarily the press shop and the painting process [3], but car-body construction has been identified as a key production step with high energy consumption.

Car-body construction is characterized by a wide range of assembly and handling processes. In order to ensure that the different thermal and non-thermal joining processes are carried out in accordance with quality requirements, it is necessary that the components to be joined and the joining tools be moved quickly and positioned securely. These types of complex motional processes are predominantly carried out by 6-axis industrial robots, large numbers of which are responsible for the major part of car-body construction. Studies have shown that these robots have an average annual energy consumption of 8 MWh [4], and over 500 robots are used for car-body construction in each vehicle-production plant.

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Under economic-efficiency criteria, there is now a demand for the most energy-efficient robots, i.e. robots with the lowest energy consumption for comparable process parameters such as cycle time and accuracy.

For many users, it would certainly be desirable to have an indication of energy efficiency similar to the one proposed by the EU [5] since the mid-'90s, which has been in place in Germany since 1997 for household appliances such as refrigerators or washing machines [6]. However, because of robots' significantly more complex mechatronic structure and different fields of application compared to that of kitchen appliances, it is not possible to transfer this type of method to the vehicle-production industry. A simple solution for reference trajectory has been proposed by VDMA by using the ISO-Cube, which has been originally established for determination of accuracy of robots [7, 8]. This trajectory describes a cube inside the robots working range and has no industrial relevance [9, 10]. Therefore, the objective here is to create a trajectory that makes it possible to compare different robots in terms of their energy-efficiency, thereby providing the opportunity of increasing energy-efficiency in their fields of application. The very complexity of the task meant that it was initially limited to 6-axis industrial robots in the field of automotive body construction. This proposed method of path generation for a reference trajectory for energetic comparability of industrial robots can then be transferred to other fields and other robot types.

2. Cluster analysis

6-axis industrial robots can be classified based on various criteria. Aside from the load-capacity range, i.e. the maximum mass that can be moved on the robot flange, the robots also differ in terms of the size of their work space. In general, it can be established that robots with high load capacities also have larger work spaces, though robots with the same load capacity can also be given larger work spaces by making structural changes, e.g. by extending individual robot arms. These structural changes are often accompanied by a reduction of the permissible load capacity. Obviously, robots with different load capacities will have different levels of energy consumption for different movements. Moreover, electrical measurements have shown that the energy consumption is also influenced by the specific application of the robot. Accordingly, the acceleration values required when starting up an individual robot axis cause a substantially higher energy consumption than that caused by steady movement along a trajectory [11]. There is therefore a distinction between applications that involve several short movements, e.g. spot-welding, and those with predominantly steady movements, e.g. movement of components between two positions in the work space.

For these reasons, it is necessary to develop a suitable reference path that appropriately takes into account the different robot variables (load capacity and work space) as well as the specific application. In order to achieve this objective in the field of car-body construction, an analysis was carried out on over 1,000 robot archives from a major German car-manufacturing company. Each archive contained several (approx. 10 – 20) individual programs from robots manufactured by KUKA and FANUC. The objective was to carry out a movement analysis of the robots, i.e. to determine the path lengths, positions in the work space, speeds, accelerations and movement types and to perform statistical processing of this data.

The programmed paths are always the trajectories of the defined tool tips. However, the reference path is run without this tool during an energy evaluation, meaning that all values had to be converted to the coordinate system of the robot flange (flange coordinate system).

One such coordinate system H is given as a function of another coordinate system G via a translation $V = [X\ Y\ Z]^T$ and rotations of angles A, B and C about the z, y and x-axis respectively of G. If the rotation matrix in relation to the a-axis by the angle φ is $D_a(\varphi)$, then the translation operator $T_{G,H}$ from G to H for a point P_G is calculated from G by means of

$$T_{G,H}(P_G) = \left(D_z(A) \cdot D_y(B) \cdot D_x(C)\right)^{-1} (P_G - V) \qquad (1)$$

Accordingly, the inverse translation from H to G for a point P_H is calculated from H by means of

$$T_{G,H}{}^{-1}(P_H) = D_z(A) \cdot D_y(B) \cdot D_x(C) \cdot P_H + V \qquad (2)$$

In order to assess the spatial location of the robot flange relative to the robot, the coordinates specified in the program code for the points reached must be converted to the ROBROOT system in the base. For this purpose, the following translations are used for the coordinate systems defined in the robot: $T_{W,R}$ from WORLD to ROBROOT, $T_{W,B}$ from WORLD to BASE, $T_{B,P}$ from BASE to tool center point (TCP) and $T_{F,P}$ from Flange to TCP. The coordinates of the zero points θ^P for system P (TCP) and θ^F for system F (flange) in system R (ROBROOT) and thus the absolute movement paths for the robot can be calculated as follows:

$$\theta_R^P = T_{W,R} \cdot T_{W,B}^{-1} \cdot T_{B,P}^{-1}(\theta_P^P), \qquad (3)$$

$$\theta_R^F = T_{W,R} \cdot T_{W,B}^{-1} \cdot T_{B,P}^{-1} \cdot T_{F,P}(\theta_F^F). \qquad (4)$$

Because some robots are also constructed on additional linear axes designed to expand the work space linearly, these additional axes were offset in order to make it possible to analyze only the direct flange movements.

Due to the large number of robot programs, the data was loaded automatically, including the separately stored movement data. The movement data was stored in a data matrix that can be easily processed in the designated programming system MATLAB.

3. Statistical analysis

The robot movement parameters determined by means of the cluster analysis were then analyzed statistically in a subsequent step depending on their load-capacity class. In cooperation with different robot suppliers as well as users of