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Analysis of the Energy Efficient Usage Methods of Medium and High Payload Industrial Robots in the Automobile Industry

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Abstract

In this paper, various approaches of the energy efficient use of the industrial robots are analysed and the potential energy savings are estimated. There has been evaluated an influence on energy consumption of implementation-close methods like robot's speed, acceleration and process point approximation variation. The novice brake management and robot "Energy team" principle is presented.

Keywords

Industrial robots, robotics, path planning, energy efficiency, brake management

Introduction

Over the last decade the electricity prices in many industrial countries have been increasing, in some countries like Germany the wholesale prices have fluctuated with a factor 2.3 since year 2000 [2]. Similar trend can be observed in the crude oil price evolution [2]. Most of the European countries within the frame of Kyoto protocol have committed to reduce the CO_2 emission of 8% until 2012 in reference to 2008 [3]. These are the basic reasons that have led to a series of energy efficient measures in many manufacturing companies.

Automotive industry is a large energy consumer; a significant part of total volume takes the electrical energy consumed by robotics. Dependent on manufacturer, during the vehicle's lifecycle 15-28% percent of its required energy is being consumed in production phase. Electrical energy consumed by robotic applications in production in average is about 8% [4]; therefore an energy efficient use of robotics has a high impact on the production costs and total CO_2 emission of the whole vehicle's lifecycle.

In further chapters there will be analysed some of the most substantial approaches towards the energy efficient use of industrial robots, like usage strategy, technical modifications and *add-on* possibilities and cost-effective trajectory planning; their energy savings potential will is estimated either as a proportion of the total consumption or in energy units. The research is being done at Mercedes-Benz plant in Sindelfingen, Germany.

1 Description of the robot

According to ISO an industrial robot is an automatically controlled, reprogrammable, multi-purpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications [7]. The most typical industry robot has 6 degrees of freedom, from which the axis 1 to 3 are used for position of tool centre point (TCP), but axis 4 to 6 – for the orientation as shown is Fig. 1.

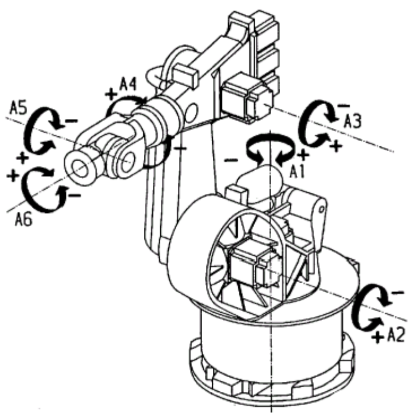

Fig. 1. Sketch of typical industrial robot

The original equipment manufacturers (OEM) of the robotics in the last decade have done a significant research increasing the precision, repeatability, speed of the robots; there have been developed various modelling tools [8]. The energy efficiency in automation industry and robotics has become in focus only in the recent years [1].

Apart from many other machines, industrial robot's power consumption can be characterised as very dynamic - a power of a regular 6 axes 200kg heavy payload industrial robot has a range from 0.5kW in stand-by mode up to 20kW at peak. It is highly dependent from particular robot type, application, tool, work piece, movement trajectory, usage strategy and many other factors, altogether building a complex set of influence variables.

2 Planning and usage strategy

Because of the largest market share, among all, the 150kg-250kg payload range heavy load 6axes industrial robots today are the most low-priced ones [8], which is a reason why they are often chosen also for applications that do require far lighter load.

A recent measurement of energy consumption between Kuka KR16 and KR210 evaluating identical process points with the 16kg load and identical cycle time showed that the KR210 required in average 2.2 times more energy. Because the proportion of the own weight of the larger robot is much higher, accordingly the consumption results higher. However, because there are no explicit software tools available that might evaluate such comparison, it is hard to examine the proper choice of robot type in the plant planning stage, based on energy consumption of the actual work. Knowing the precise consumption of the particular robot and its task, the relation between initial investment and actual work costs would be easier to determine. The exact energy savings are determinable only knowing the specific application, but, according to series of comparisons, the optimal robot choice may result in energy savings in extreme examples of about 50-65%.

The Mercedes-Benz plant in Sindelfingen is the first one worldwide to implement the automatic shut-down and start-up of the robots during the production-free time. At the SIEMENS AG developed protocol *PROFIenergy* today enables the shutdown, leaving only the power supply necessary only for the machine's network communication.

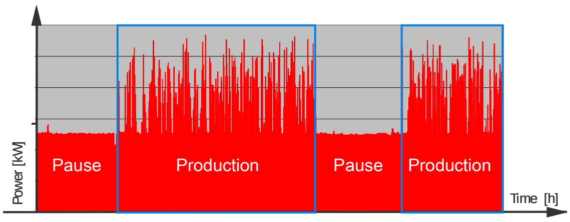

Fig. 2. A single facility's power consumption over a week

If it is assumed that the actual production over the year takes 250 working days and 18 hours per day (also used in further calculations), the savings in the rest of the time by shutting down the KR210-2000, which in stand-by mode normally requires 275 W, would save 1,17 MWh a year.

3 Potential of the recuperated energy

Industrial robots are dynamic machines, whose motors require quick starts, stops and rapid direction changes in the time frames often less than a second. Most of the robot manufacturers in their robot controllers allow recuperative motor braking, what allows reusing the *buffered* energy in the capacitors of DC-Bus, thus, when one axis is braking, others that accelerate can use that energy.

However, often is a case, when several axes brake or accelerate in the same time, and due to the limited capacitance not all potential energy may be buffered. In this case, either more power from the network is provided or the energy is dissipated in balancing resistors of DC-Bus to reduce the overvoltage as shown in Fig. 3.

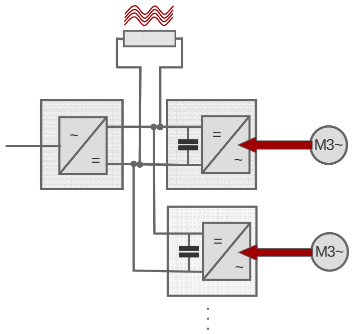

Fig. 3. Use of balancing resistors during robot's recuperative braking

The exact proportion of the dissipated energy in the resistors was obtained by simultaneously measuring the DC-bus voltage, voltage on balancing resistors and total power consumption of KR210 at dynamic program with 204 kg load. At maximum override (maximum speed and acceleration) the proportion is as high as 6% (Fig. 4), which is approximate savings when fully re-using the recuperated energy. However, it is always hardly dependent from the specific robot program.

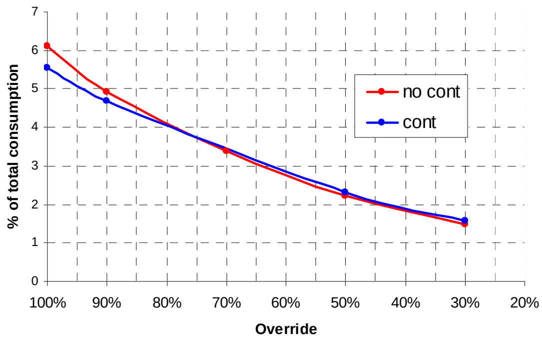

Fig. 4. Power dissipation in balancing resistors in reference to total robot's consumption

To catch up otherwise wasted energy, there are at least three ways:

- share the DC-bus among several robots, creating a robot "Energy team" (Fig. 5).
- increase the capacitance of dc-bus,
- use of reversible rectifier ,

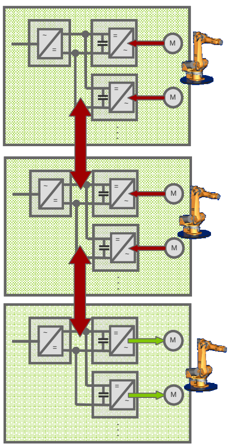

Fig. 5 Principle of robot "Energy team"

The sharing of DC-bus among the several robots is a promising alternative when coupling many robots. Here the same braking/acceleration energy exchange principle in the robot controller is being set into larger scale. The DC bus of the *energy team* can also be supplied by a single, more powerful rectifier instead of several separate ones. The estimated energy savings is approximate to the amount dissipated in balancing resistors. However, the risk of simultaneous acceleration of many robots such creating a power peaks exists.

The use of capacitor *buffers* for industrial robotics is another alternative, which can save a large part of braking energy. At maximal load and speed the amount of energy to be saved for ranges from 1–5kJ. As the DC-bus voltage fluctuation at the upper edge is about 150V the pure capacitance should be at least 80mF. Using the whole available DC voltage 650V range and discharging the capacitors to at least 50V level, already 4-5mF capacitance would be applicable. Taking into account the pauses during the operational hours, the savings with appropriate capacitors would be around 6%. The KR200 tests with 18mF additional capacitance for voltage fluctuations using only the 150V the upper edge for some programs with high amount of short process pauses delivered as much as 19% of energy savings.

4 Movement profile optimization

There are many literatures [5-6] describing the complex path planning algorithms, unfortunately, due to complexity, many of them are hard to implement. In this chapter only the path optimization possibilities are analysed, that are available by OEM's provided robot controllers.

In the vehicle's body shop majority of welding or pick and place tasks are implemented by point-to-point (PTP) commands. At PTP command all axes starts moving in the same time and also stops simultaneously after a time frame that is necessary by the axis that requires the most time to reach the target angle. Since most pick and place tasks prerequisite a specific trajectory only in a matter that any collisions are avoided, there is an open space for trajectory implementation.

4.1 Speed and acceleration variation

The very first notion of movement profile modification is to evaluate it in correlation between tasks cycle time and the potential energy savings. The measurements show a logical trend – running the robot at lower speed, the total consumption decreases, running a robot at constant speed and decreasing the acceleration, the consumption decreases as well. Here, evaluated was the relation of the energy savings and cycle time loss. The overall gain is expressed as a trade-off curve in the Fig. 6 – to the reference of maximal speed and maximal acceleration at which the minimal cycle time is required. It is plotted there a proportional energy consumption against a proportional cycle time extension.

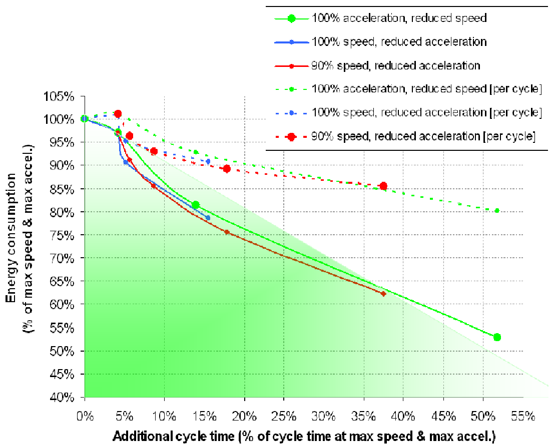

Fig. 6. Trade-off curve, energy savings per extended cycle time

The cost-effective presumption would be, if decreasing robot's speed or acceleration the energy consumption reduces faster than the cycle time increases, it is worth to implement such changes. In the Fig. 6 the line being in the marked triangle means it is cost-effective, being outside, means the cycle time at these points has increased higher than savings benefit. Since running the robot faster, more cycles may be done, each cycle costs less, which is a reason, why the consumption savings per increased cycle time (dotted line) is lower than measuring over a certain time.

From this illustration may derive conclusion that if there is a spare time to do the task slower, it is worth to do so. For example, if it takes 10 seconds to do the pick the component and place somewhere else, and just after that the robot is waiting another 5 seconds for some external signal, there is actually 50% extra time to complete this movement, and by moving slower it may be saved 20% of energy per this cycle time.

Praxis shows, that there are many cases, when robots after a rapid movement at their dynamical edges reach their target positions and then are in standstill. The method is promising, but the complexity begins by trying to implement a predictive controlling – the waiting times must be known in advance.

4.2 Point approximation

Most robot controllers allow to *fly-by* the programmed process points of TCP within the predefined range and without stopping there. This effect is called *point approximation*, which creates the movement smoother, often shorter and therefore quicker. An example of approximation between two TCP linear movements (LIN) is shown in Fig. 7.

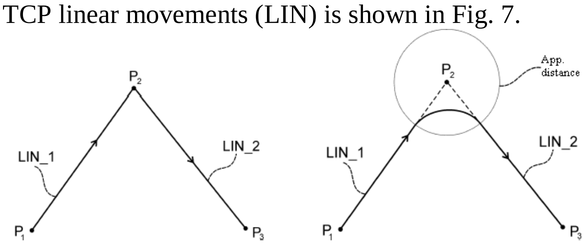

Fig. 7. Principle of approximation (LIN) [5]

Results of the measurement on KUKA Quantec Series robot with KRC4 controller of approximation distance impact on energy consumption in Fig. 8 shows a positive trend towards lower consumption at higher PTP approximation. The reason for this is a logical premise that the consumption is lower, when the TCP trajectory is shorter and there are less acceleration/deceleration phases in the path and these phases around process points are smoother. The trend remains similar at different override.

An example program of 300mm approximation distance results in 15% energy consumption in reference to same program not using the *fly-by* points.

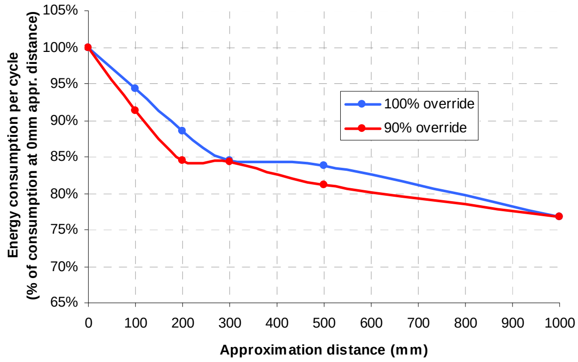

Fig. 8. PTP approximation distance impact on energy consumption

The actual optimization possibilities are dependent on initial robot's program. The disadvantage at large approximation distance is the deviation from the original path. However, 1000mm approximation does not mean that the TCP will always be going to fly-by the programmed point in the 1000mm distance [5]; as far as the deviation does not lead to any collisions it is a practical approach to save up 20% of movement costs.

5 Intelligent brake management

Articulated robots require motors with accurate response characteristics and dynamic behaviour – fast starts, stops and reversals. To fit these requirements, the permanent magnet (PM) synchronous machines today is *de-facto* industry standard for robotics applications. They are usually normally equipped with mechanical normal-close brakes. According to measurement, the 6 axis medium and heavy duty industrial robot's motor brakes require 100-130W to keep them opened during the movement. What kind of options are here is discussed further.

5.1 Release time

The 6 axes articulated robot by reaching its target position is being kept in a still state by it motors' stator currents. If there is no movement command continuing after a certain amount of time (differs from one manufacturer to another) the motor drives are turned off and mechanical brakes are released – the robot is in a type of stand-by mode.

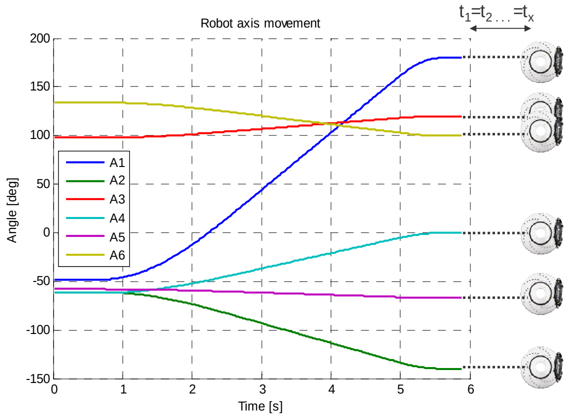

Fig. 9. Brake management, current state

For standard KUKA controllers this time delay is t=20s.According to measurements on KUKA series Quantec KRC4, the standby states are accordingly 510W, when drives are active, and 210W when they are off and brakes are released, which is a difference of 300W. Evaluating a range of statistical values, if the time delay were decreased to t=2s, according to data from real body-shop robot programs, it would result in extra ~3.5 hours/day spent in stand-by mode with released brakes and consuming 300W less during this time or ~289kWh per robot per year. However, this would result in additional 9.5 million switching cycles in 15 years instead of otherwise only 1.7 million. Releasing the brakes after 4 seconds it would result in saved 207kWh per year per robot with total switching cycles below 5 million. Since the movement profiles of the robots strongly differ, the actual limit is to be adjusted individually.

5.2 Asynchronous Braking

Considering the novice braking methods, a new type of process point commands are necessary. In a regular PTP command the other 5 axes are actually rarely running at maximal speed/acceleration because the speed is adjusted so that all axes reach the target point at the same time period (synchronous PTP), what it takes to move the axis, which the most time. This one axis usually has to do the largest axial movement. This means that in an example in Fig. 9, where one axis is turning of about 120° (Fig. 10 A1), but others of about 10°-20° (A3,A5,A6) the last ones are spinning with less than 10% of their maximal speeds. This effect may have an advantage as described in 0, but if an alternative was a quick turn and a brake release for those motors, whose according axes have reached their target positions as shown in Fig. 10, additional energy savings might be achieved. The energy is saved based on both, the earlier brake release and less energy required overcoming a rotational friction, when spinning the axis faster.

In the example shown in Fig. 10 during the whole movement brakes of 4 axes could be released asynchronously, which would result in a gain of an additional 2 seconds stand-by mode time per shown particular movement.

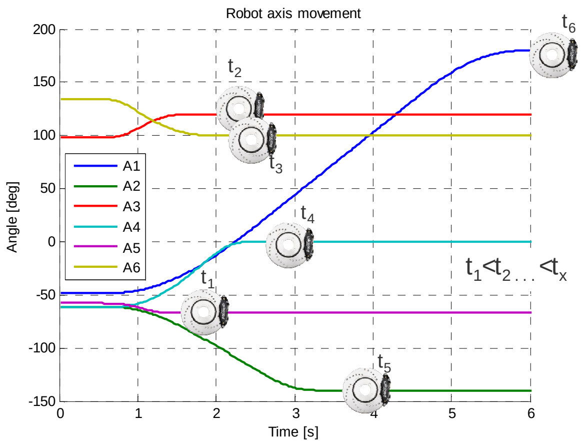

Fig. 10. Asynchronous brake release

According measurements, the return time required activating the brakes and switching on the drives is 50-100ms depending on robot generation, which has to be considered when significantly reducing its release periods. As described before, more active usage of mechanical brakes requires a significantly higher number of open/close cycles that can not exceed manufacturers determined limits. The implementation complexity and potential savings of this method is yet unknown.

5.3 Power adjustment

The power required to open the brakes and to keep them opened significantly differs. Universal timer-based power reducers are available on the market that after the power peak of switching-on decrease the voltage on PWM basis, which are often used for types of valves.

According to measurement, to keep the brakes of motors of KR210 open after they're switched on, it is satisfactory with just 30% of currently used amount. The approach of variable voltage supply and therefore the power of brakes are so far unknown in industrial robotics. This can deliver 60-80 W (or 10-15% of standstill power of KR210) power savings over the whole time, when robot is in the movement. Assuming there are 250 working days a year, the brake power reduce could deliver maximum savings of 270-360 kWh a year.

Conclusion

In the automobile industry more than 95% work in the body shop is done by robotics-related applications. Because of the high degree of automatisation and cyclically reparative behaviour of robots, even little improvements in the efficiency of their systems may result in significant energy and CO_2 emission reduction in whole production.

While analysing a whole robotic system, the energy savings potential is found as in the optimization or advancement of robot's hardware, as also in the strategic use and production planning phases. Combining all the described strategic usage approaches like appropriate robot choice, robot shutdown, stand-by mode active usage, trajectory optimization methods, the technical advancements like asynchronous brake management, brake power adjustment, more reusing the recuperated energy, the total energy savings can exceed 40% according to reference programs without these modifications. The implementation complexity, however, must be taken into consideration. Because of the fact that the actual savings are hardly application dependent and one method may as rise as decrease the influence of others, so only the statistic averages are estimated.

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