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# Energy efficient usage of industrial robots for machining processes

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**Abstract**

Robot guided machining has a great potential to substitute or supplement machining with expensive machine tools as well as the inaccurate manual processing in industrial production systems. Beside the costs and quality, energy efficiency is one of the most relevant factors for the implementation of innovative and sustainable technologies. The Fraunhofer Institute for Production Systems and Design Technology IPK investigated the total energy performance of a milling robot system. As a result of this investigation, an energy balance of the system was created. In addition, application-specific cutting parameters, path strategies for an energy-optimized usage of the system were identified. These information allow energy-optimized path planning in CAM systems and can be implemented in energy management systems. The results can help to qualify the robot guided machining for new industrial fields.


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*Keywords:* Energy and Resource Efficiency and Effectivness, Robot guided machining

## 1. Introduction

In the last decade the robot guided machining has evolved from a fundamental research topic to a production technology ready for the industrial usage. Main reason is the technological progress and the ongoing research that led to an improvment of the accuracy and enabled robot machining systems to carry out the tasks of machine tools and humans. In this context Abele et al. [1] investigated the system behaviour during the milling process in 2007 and Pan et al. [2] analysed the vibration/chatter characterisitic with special attention to the systems stiffness. Chen and Dong [3] categorized the development on the field of robot machining into researches on robot machining system development [4], robot machining path planning [5], vibration/chatter analysis including path tracking and compensation, dynamic or stiffness modelling [6]. In addition to the technological feasibility, the economic aspects of using robots in industrial series production get more important for reasons of sustainability. This article focuses on the energy efficiency of robot milling systems and shows up potentials for a robot based resource efficient machining. Since there is no common method to analyse the power consumption of robot milling systems, this article is oriented at earlier investigations on six-axis industrial robots [7] and machine tools [8].

## 2. Robot guided machining

The robot guided machining is an innovative production technology that combines the advantages of a machine tool with the flexibility of an six-axis industrial robot. Therefore, an industrial robot is equipped with a milling tool and can be used for machining operations such as milling, grinding or drilling. Due to the low investment costs, milling robots are alternatives to conventional machine tools. Moreover, the continuous progress of improving stiffness and accuracy of industrial robots will lead to more industrial applications [9]. Another advantage beside the costs of robots is the working apace which allows the processing of workpieces with large dimensions. At the moment milling robot systems in industrial


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series production are mainly used for tasks with relative low accuracy requirements, such as deburring or the cleaning of castings [10]. The main reason for this is the lack of stiffness, which is caused by the kinematic structure of industrial robots. Combined with the process forces, this leads to a deviation from the actual position of the Tool Center Point (TCP) to the set point. Additionally, the lack of stiffness affects the dynamic behavior of the robot milling system which results in a decrease of the surface quality in comparison to conventional machining tool [10]. Nevertheless, industrial robots offer an enormous potential for robot guided machining in industrial series production due to the advancing improvement in accuracy and stiffness [11].

Beside investment costs and process quality, operating costs are one relevant factor for implementing innovative sustainable technology. The energy-efficiency has a direct impact on this value. It is a challenge to identify the relevant energy consumers within the system, by investigating the total energy consumption of the system, and to set up an energy balance. Due to the high individualization of machine tools there is no consistent method for evaluating the energy consumption. Thus, there is no method that could be easily transferred to evaluate the energy consumption of robot milling systems.

Rather, a method must be derived which analyzes all production-relevant subsystems depending on various application scenarios. Additionally, a comparison to the energy balance of conventional machine tools should be possible. To determine the energy consumption and the performance of the milling robot, a suitable and accurate measurement setup is needed. This includes a measurement strategy which fully reflects the power consumption of the individual components of the milling robot system under various application scenarios.

## 3. Experimental setup

The investigation was carried out on a six-axis jointed-arm robot KR60 HA from KUKA Roboter GmbH, Augsburg. The robot is equipped with the application module Milling 8 kW. The system is located at the Production Technology Centre (PTZ) in Berlin and is used by the Fraunhofer Institute for Production Systems and Design Technology IPK. The milling robot system is divided into the robot controller unit that is connected to the industrial robot and the technology unit, which includes peripherals for control and cooling of the electric spindle. The two subsystems are connected via separate power supplies to the three-phase mains.

For the measurement, a digital oscilloscope WT1800 from Yokogawa, Musashino, Japan, is used. The oscilloscope has six elements for the current and voltage tap of 1 A to 50 A and 1.5 V to 1000 V. The active power accuracy of the meter is ± 0.1 % and allows a sample rate of 50 milliseconds. To ensure reliable power and voltage tap-off, two measurement adapters have been developed within the study. For the electrical wiring, the Three-Phase, Four-Wire System (3P4W) principle was used.

## 4. Experimental procedure and results

Initially, all subcomponents have been analyzed separately, in order to investigate the influence of the system components on the total energy performance of the milling robot system. Based on these results, the path control and slot milling were examined. Finally a test workpiece was machined to simulate the energy consumption during a practical application and to establish the comparability to a machine tool. During each test the electrical power of the technology unit and the robot control unit were recorded separately at a sampling rate of 50 milliseconds. Afterwards, the energy consumption is stated in the unit watt-hour. Contrary to the standard the unit watt-hour is used in order to avoid unnecessary small numbers that would occur by using the unit kilowatt-hour.

### *4.1. Component power*

The recording of the subcomponents power consumption was based on Behrendt et al. [12], who has studied the energy consumption of machine tools in his work from 2012. The measurement included the starting phase and the following phase until a stationary state was reached for each component. The power consumption while all components are activated is about 1385 W and is divided as shown in Fig. 1.

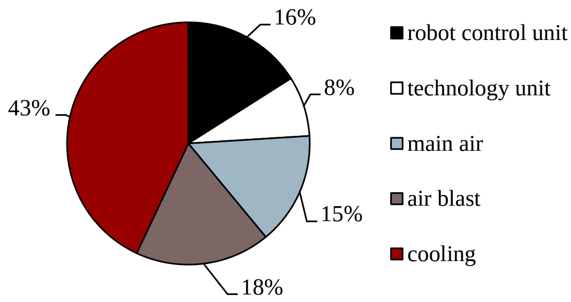


Fig. 1. Standby power consumption of the components

The cooling has the largest share of power consumption, i.e. approximately 600 W (43 %). This is comparable to the behavior of the 9 machining tools which were investigated by Behrendt et al. [12]. The study included four 3-axis vertical milling machines (Mori Seiki (MS) NVD1500 (24,000 and 40,000 rpm), MS Dura Vertical (DV) 5060 and Haas VF-0), a 4-axis horizontal milling center (MS NH8000), two 5-axis vertical milling machines (MS NMV1500 and MS NMV5000), a mill-turn center (MS NT1000) and a CNC lathe (MS NL200SY). The average power consumption in standby mode was in the range of 319 W to 4040 W. The increase of the power consumption is directly linked to the machine complexity. The robot milling system with its power consumption in standby mode is comparable to the lower third of the investigated machine tools. Only two of the investigated machine tools with less complexity (Haas VF-0 and MS NVD1500) undercut the power consumption of the milling robot. However, both machines compose with 4.2 dm³ and

104.9 dm³ have a smaller working space than the examined milling robot system with 270.2 dm³.

### *4.2. Axis drives*

To analyze the power consumption of the axes drives, each axis was moved with a defined speed. The results show that axis 2 has the highest power consumption. This is mainly caused by the fact that axis 2 has to perform vertical movements against the gravity. Axis 1 and axis 3 have lower power consumptions because they mainly perform horizontal movements. This is also reflected by the nominal electrical power of the axis drives. Axis 2 has with a nominal electrical power of 5.9 kW a much high influence on the energy consumption then Axes 1 and 3 with a nominal electrical power of 3.2 kW. Axes 4 to 6 with a nominal electrical power of 0.5 kW have less influence on the energy consumption of the system. Table 1 shows the maximum power consumption of 11.79 kW while moving all axes. In comparison to the mentioned standby power consumption of 1.38 kW, it shows the major influence of the axis drives on the energy consumption.

For robot-guided milling processes linear path-controlled motions LIN are mainly used for removing material. For the positioning of the tool the point-to-point movement PTP is mainly used. The power consumption of both movements, the linear path-controlled motion LIN and the point-to-point movement PTP, were examined. First tests, with two points at a range of 1.5 m, show that the point-to-point motion PTP uses approximately twice as much power at its climax as the linear path-controlled motion LIN (Table 1). Nevertheless, the linear path-controlled motion LIN requires more time for the process as the point-to-point motion PTP and therefore consumes more energy which is also shown in Table 1.

Table 1. Power consumption first test

| **speed** | **maximum power consumption** | | | |
|---|---|---|---|---|
| | PTP | duration | LIN | duration |
| 30 % | 1.61 kW | 3.90 s | 1.26 kW | 6.85 s |
| 75 % | 6.69 kW | 2.25 s | 3.62 kW | 3.15 s |
| 100 % | 11.79 kW | 1.95 s | 5.58 kW | 2.50 s |

In order to verify the results of the first test, the tool center point TCP was moved along several ISO standard cubes with different speed levels. The edge lengths 100 mm, 200 mm and 400 mm were selected in accordance with Behrendt et al. [12]. The used point sequence was a-b-c-d-a-e-h-d-f-h-a-g-b-a (Fig. 2).

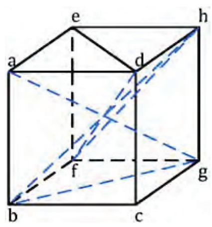


Fig. 2. ISO standard cube with point sequence

In Fig. 3 the power consumption of the movement along a 100 mm cube, with maximal speed is shown. The point-to-point motion PTP leads to a much higher power consumption at the climax than the linear path controlled motion LIN. The point-to-point motion PTP needs 5.4 s. This is a considerably shorter time than the linear path-controlled motion LIN with 9.1 s. The consumed energy of the point-to-point motion PTP is 1.68 Wh. This is lower than the value of the linear path-controlled motion LIN with 1.84 Wh. However, the movements along the cubes with 200 mm and 400 mm show that a point-to-point motion PTP does not consume less energy in any case. As expected, the point-to-point motion PTP is in all tests faster than the linear path-controlled motion LIN. Based on this fact the robot consumes less energy at low speeds significantly. For high speeds the power consumption is similar or partially undercut by the consumption of a linear path-controlled motion LIN. This can be seen in Table 2-4.

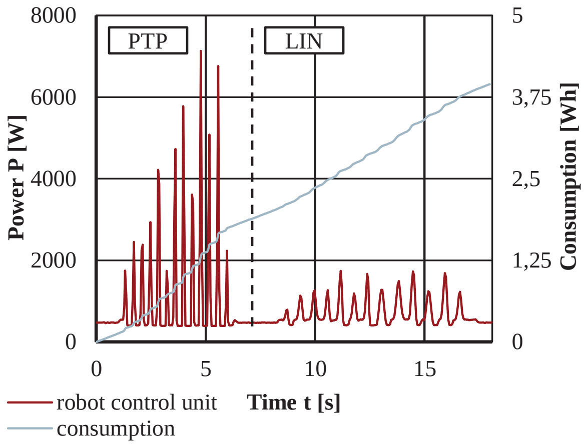


Fig.3. ISO standard cube 100 mm PTP vs. LIN

Table 2. Consumption and time ISO standard cube 100 mm

| **speed** | **consumption** | | **duration** | |
|---|---|---|---|---|
| | PTP | LIN | PTP | LIN |
| 30 % | 2.09 Wh | 3.81 Wh | 10.7 s | 23.0 s |
| 75 % | 1.70 Wh | 2.13 Wh | 6.9 s | 11.4 s |
| 100 % | 1.68 Wh | 1.84 Wh | 5.4 s | 9.1 s |

Table 3. Consumption and time ISO standard cube 200 mm

| **speed** | **consumption** | | **duration** | |
|---|---|---|---|---|
| | PTP | LIN | PTP | LIN |
| 30 % | 3.18 Wh | 5.77 Wh | 14.7 s | 33.5 s |
| 75 % | 3.05 Wh | 3.22 Wh | 7.8 s | 15.3 s |
| 100 % | 3.66 Wh | 2.87 Wh | 7.0 s | 12.3 s |

Table 4. Consumption and time ISO standard cube 400 mm

| **speed** | **consumption** | | **duration** | |
|---|---|---|---|---|
| | PTP | LIN | PTP | LIN |
| 30 % | 6.38 Wh | 7.64 Wh | 30.9 s | 39.4 s |
| 75 % | 4.38 Wh | 4.41 Wh | 14.1 s | 16.1 s |
| 100 % | 4.52 Wh | 4.20 Wh | 11.7 s | 12.3 s |

The reason for the differences in power consumption is the fact that for a point-to-point motion PTP the exact trajectory of the tool tip is not relevant since the individual axis drives are brought either synchronously or asynchronously in their final position. In the linear path-controlled motion LIN the tool tip is moved along a predefined path with a definied orientation in space. For this, all axes drives must be synchronized with each other which is why additional acceleration and braking processes are necessary. This mainly has a negative impact on the energy consumption of the linear path controlled motion LIN at low speeds.

In summary it can be said that using the point-to-point motion PTP can help to reduce the total energy consumption. But for the most milling processes it is necessary to use the linear path-controlled motion LIN, so there is only potential to realize energy savings during tool positioning moves.

*4.3. Impact of the cutting parameters*

To determine a set of energy-efficient cutting parameters, milling tests were performed. Therefore a three-edged solid carbid end mill Garant 20 2240, Hoffmann GmbH Quality Tools, Munich, with a diameter of 6 mm was used. The used material was an aluminium-magnesium alloy AlMg3. For the evaluation of the tests, the consumed energy and the material removal rate Q was determined (Table 5).

Table 5. Cutting parameters of the milling tests

| $v_f$ mm/min | n rpm | $a_p$ mm | P wh | Q cc/min | Y wh/cc |
|---|---|---|---|---|---|
| 450 | 10000 | 2.0 | 5.246 | 5.40 | 4.602 |
| 450 | 10000 | 1.0 | 5.139 | 2.70 | 9.016 |
| 450 | 10000 | 0.5 | 4.971 | 1.35 | 17.441 |
| 450 | 7500 | 2.0 | 5.073 | 5.40 | 4.450 |
| 450 | 7500 | 1.0 | 4.855 | 2.70 | 8.518 |
| 450 | 7500 | 0.5 | 4.852 | 1.35 | 17.024 |
| 450 | 5000 | 1.0 | 4.741 | 2.70 | 8.317 |
| 450 | 5000 | 0.5 | 4.710 | 1.35 | 16.252 |
| 675 | 10000 | 2.0 | 3.066 | 8.10 | 2.690 |
| 675 | 10000 | 1.0 | 3.531 | 4.05 | 6.195 |
| 675 | 10000 | 0.5 | 3.357 | 2.03 | 11.779 |
| 675 | 7500 | 2.0 | 3.545 | 8.10 | 3.110 |
| 675 | 7500 | 1.0 | 3.344 | 4.05 | 5.867 |
| 675 | 7500 | 0.5 | 3.259 | 2.03 | 11.434 |
| 675 | 5000 | 1.0 | 3.310 | 4.05 | 5.807 |
| 675 | 5000 | 0.5 | 3.161 | 2.03 | 11.091 |
| 900 | 10000 | 2.0 | 2.820 | 10.80 | 2.474 |
| 900 | 10000 | 1.0 | 2.672 | 5.40 | 4.688 |
| 900 | 10000 | 0.5 | 2.524 | 2.70 | 8.856 |
| 900 | 7500 | 2.0 | 2.805 | 10.80 | 2.460 |
| 900 | 7500 | 1.0 | 2.571 | 5.40 | 4.510 |
| 900 | 7500 | 0.5 | 2.427 | 2.70 | 8.514 |
| 900 | 5000 | 1.0 | 2.576 | 5.40 | 4.520 |
| 900 | 5000 | 0.5 | 2.373 | 2.70 | 8.326 |

The results show that the feed rate $v_f$ has the biggest impact on the energy consumption. By increasing the feed rate $v_f$ from 450 mm/min to 900 mm/min at a spindle speed of 5000 rpm and a depth of 0.5 mm, the energy consumption decreases from 4.710 wh to 2.373 wh. This invert relation between feed rate $v_f$ and energy consumption is caused by the direct influence of the feed rate $v_f$ on the processing time. In addition, the power consumption during the machining process is regardless of spindle speed, depth of cut or feed per tooth approximately on the same level. This is due to the high constant basal power in the standby state that is mainly associated to the auxiliary systems.

To compare the energy efficiency of the milling robot system with a vertical machining center, the assessment criteria for energy-efficiency was calculated. This value was defined by Mori et al. [8]. This criterion sets the consumed energy P in ratio with the cutting volume MR. The determined values provide an initial indication of the energy-efficiency of the system. At this point it should be mentioned that the used criterion refers to the energy efficiency alone, disregarding important factors like roughness values and geometrical accuracy of machined parts. Nevertheless, the criteria for energy-efficiency defined by Mori et al. [8] provides an important indicator for the evaluation of the energy efficiency. The energy efficiency values for the investigated parameter combinations are in the range of 2.460 Wh/cc to 17.441 Wh/cc. The average is 7.842 Wh/cc. The milling center analyzed by Mori et al. [8] achieved energy efficiency values below 2.0 Wh/cc, especially during roughing operations. However, only a small comparability of the two systems is given. For the test at the IPK and Mori's tests different materials were used. Nevertheless, the energy-efficiency values suggest that conventional machine tools have a much higher energy-efficiency than current milling robot systems. This is due to the fact that machine tools can use more efficient parameter settings than robot milling systems. This is also caused by the lack of stiffness.

*4.4. Determination of the cutting performance by performing an aircut*

To determine the cutting performance, a test with six consecutive cutting lanes has been carried out. For each lane the programmed depth of cut was 1 mm. For the test, the end circumferential milling, defined according to DIN 8589 3, was performed. Afterwards the power consumption of an aircut was recorded (Fig. 4).

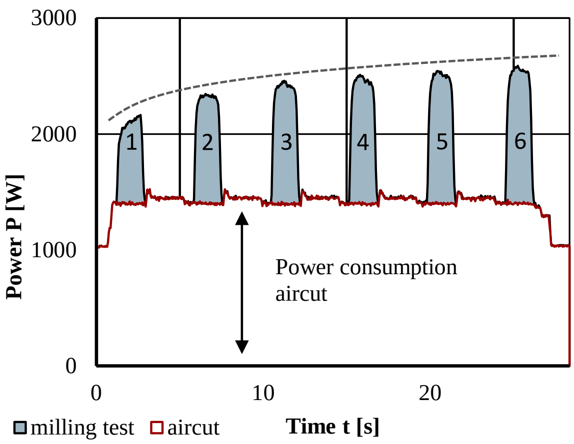


Fig. 4: pure cutting performance lane 1-6

By subtracting the recorded power consumption of the aircut from the power consumption of the real cutting test, the pure cutting performance could be determined as shown in Fig. 4. The test shows that the average proportion of the cutting performance of the total power consumption amounted to 40.53 %. The detected rise of the cutting performance, shown in Fig. 4, can have different reasons. On the one hand the rise of the power consumption between the single cutting lanes can be a result of the growing side flank. This can increase the friction value between cutter and side flank with each milled lane, especially while corner milling, whereby. On the other hand the rise of the power consumption can result from a push away of the tool tip. This deflection of the tool leads to a deviation between programmed and real path and changes the process condition such as depth of cut. Conventional machine tools have efficiency in the range of 20 to 30 % [8, 14]. In comparison the milling robot system has a good relation between supplied and used energy. However, for the most machine tools, a high effort for the supply with cooling lubricants was conducted. If an equivalent cooling system is installed in the investigated milling robot system, the efficiency will decrease significantly. If the robot could achieve comparable removal rates, the robot could be even an economic alternative to machine tools.

*4.5. Machining power*

To simulate the use of the milling robot system in industrial series production, a test workpiece was machined. During this test the power consumption was recorded. Since there is no uniform standard for evaluating the economic efficiency of machining tools, a test workpiece was choosen inspired by a test workpiece from the NCG [15] and a standard test piece that was proposed by the Japanese Standards Association [16]. First is recommended to evaluate the accuracy of five-axis milling machines. Second is used to evaluate the power consumption of machine tools. It includes a multiple number of different geometry elements to verify the shape-, position- and geometric-accuracy. For the production the same three-edged solid carbid end mill and material was used.

The processing time for the workpiece was 11.45 min while a volume of 10.79 cc was removed. The machining of the test workpiece is shown in Fig. 5.

Fig. 5. Machining of the workpiece

For the manufacture of the workpiece, a total of 333.94 Wh electrical energy was consumed. Of this amount, 203.85 Wh (61 %) were consumed by the technology unit with the electric spindle. About 130.09 Wh (39 %) were consumed by the robot control unit with the axis drives. Moreover a power profile was set up with the captured data (Fig. 6) that shows the consumed energy of the components during the milling test. Fig. 6 shows that the cooling has comparable to machine tools a mayor influence on the energy consumption.

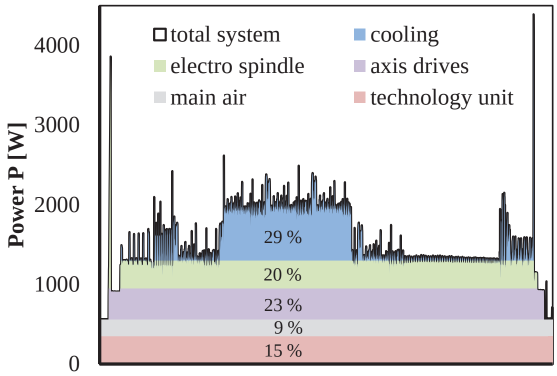


Fig. 6. Power profile milling test

## 5. Conclusion

While implementing a new, innovative and sustainable technology, the energy-efficiency is one relevant factor. This paper shows that the cooling and the movement speed of the robot have the major impact on the energy consumption. With growing interest of science on the robot guided machining, an improvement of the static and dynamic stiffness as well as the machining accuracy will occur. Current investigations focus on the thermal influences on the machining accuracy [9] or try to increase the accuracy by compensating the deflection of the tool tip with improved robot controls [12]. With these improvements more efficient process parameters can be used, which results in an increase in energy efficiency of robot milling systems. The results of this paper can be used for an assessment of planned process automations based on machining industrial robots. Furthermore, the results can be used for energy-optimized path planning in CAM systems. Moreover the results can help to install an energy monitoring-system and can be implemented into an energy management system.

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