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ORIGINAL ARTICLE

Reducing the energy consumption of industrial robots in manufacturing systems

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Abstract Reducing the energy consumption of industrial robots (IR) that are used in manufacturing systems has become a main focus in the development of green production systems. This is due to the reality that almost all automated manufacturing processes are using IR as the main component. Thus, reducing the energy consumption of IR will automatically reduce operating costs and CO_2 emissions. Therefore, a method for reducing the energy consumption of IR in manufacturing systems is desired. Firstly, this paper presents a literature survey of the research in energy consumption analysis of IR that is used in manufacturing processes. The survey found that current research in this field is focused on the development of simulation models of IR that are able to be used to predict its energy consumption. Secondly, a modular model to analyze power consumption and dynamic behavior of IR is developed. Afterward, an experimental investigation is carried out to validate and estimate the accuracy of the model developed. The investigation shows that the developed modular model can be conveniently used to optimize the industrial robot's operating parameters, which are commonly needed for production planning and at the process optimization stage. In addition, the investigation shows that the process constraints, environment layout, productivity requirement, as well as the robot payload and operating speed are the key factors that must be considered for optimizing the productivity and efficiency of IR.

Keywords Energy efficiency · Industrial robots · Power consumption · Manufacturing systems · Production planning · Operating parameters

1 Introduction

Mechatronic industries often use IR as the main component in their automated manufacturing systems, especially for handling and material processing. The robot's repeatability, accuracy, speed, and efficiency are the main reasons for that decision [1]. By utilizing IR in manufacturing systems, an industry is able to reduce operating costs and to increase the productivity. However, due to the current strict policy guideline concerning CO_2 emissions and due to rising energy costs, reducing the energy consumption of IR is desired [2–4]. This is because the energy consumption of IR is approximately 8 % of the total electrical energy consumed in production processes [5]. Therefore, a reduction in the energy consumption of IR is very important in order to improve manufacturing systems' efficiency. Furthermore, research on energy consumption analyses of IR can help manufacturers define a strategy for facing new challenges in production systems, e.g., energy flexibility in energy supply, which is caused by the extended use of renewable energy [6].

Energy consumption reductions for IR can be achieved at different stages of a manufacturing systems' development: during production planning, commissioning processes, or

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at optimization stages (see Table 1). At the production planning stage, when decisions concerning manufacturing processes are addressed, planning engineers are more flexible with optimizing the process and defining a strategy for reducing energy consumption with several methods. Within the context of IR, at this stage, efficiency can be improved, for example, by optimizing the IR operating schedule and choosing IR that have low energy consumption rates [7] or by optimizing IR operating parameters and their operating conditions. Meanwhile, at the commissioning stage, reducing energy consumption can be conducted by eliminating waiting time and reducing the idle time of IR. At this stage, reducing the energy consumption of IR is not as flexible as in the production planning stage; many constraints such as manufacturing productivity must be considered. Methods for reducing the energy consumption of IR in the process optimization phase have stricter constraints; at this stage, the engineer cannot change the hardware apparatus of the IR or the production rate of the manufacturing systems. For instance, the energy reduction method can be initiated by releasing the actuator brake earlier and implementing optimal trajectories using time-scaling methods [8].

The aim of our research is to develop a modular model for IR that is able to be used for analyzing power consumption and its dynamic behavior. Thus, it can be used in the development of an automated manufacturing system, especially at the process planning and process optimization stage. This is because only limited energy data are available at the early development stage, and at the process optimization stage, the optimization method using experimental investigation on the existing manufacturing system requires great effort and time. Furthermore, this paper also has the aim to summarize existing methods from the past 20 years of research that have the purpose of reducing the energy consumption of IR used in manufacturing systems. The remainder of this paper is structured as follows: Section 2 reviews the current methods that have been developed by researchers and industry for reducing the energy consumption of IR. Moreover, a discussion of these methods and the research potential in the field of IR energy consumption will also be presented. Section 3 describes modeling methods for developing a modular model of IR. In this respect, an application of the developed model is presented with a case study for an electronic production line. In addition, experimental validation is also provided in this section. Section 4 presents the results of both the simulation and the experimental investigation and their discussions. Finally, Section 5 discusses conclusions and future work.

Table 1 Methods for reducing the energy consumption of IR at different development stages

Development stages	Example methods	Flexibility
Production planning	Defining IR operating schedules; choosing a low-energy-consumption IR	High
Commissioning process	Eliminating waiting time and reducing idle time	Medium
Process optimizations	Optimizing IR trajectory; adjusting IR braking time	Low

2 Existing methods for reducing the energy consumption of IR

Several methods that were proposed by researchers for reducing the energy consumption of IR as part of manufacturing systems are presented in this section. These include energy reduction methods based on theoretical, experimental, or modeling and simulation approaches. In addition, energy reduction methods that are provided by industry and which are available commercially will also be presented. Currently, there are three major methods used to reduce the energy consumption of IR that have been developed by researchers: developing an energy-efficient motion planning algorithm, optimizing IR operating parameters, and optimizing IR operation schedules (see Fig. 1).

Detailed discussions of these methods are presented in the following sub-section.

2.1 Developing energy-efficient motion planning

Research on the development of energy-efficient motion planning is the oldest method for reducing the energy

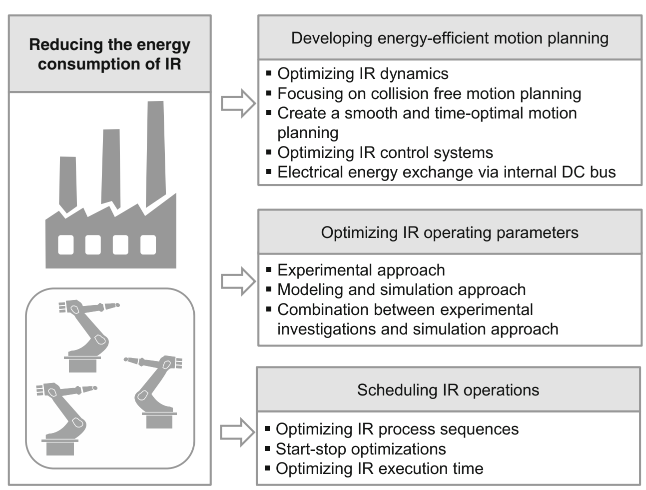

Fig. 1 Existing methods for reducing the energy consumption of IR

consumption of IR. In the late 1960s, an optimal energy consumption trajectories problem was formulated by Stepanenko [9]. Afterwards, this method became one of the common methods for reducing energy consumption of IR. Classical investigations into this method were performed by analytical formulations while considering IR system dynamics, as proposed in [1, 10]. But after the 2000s, an experimental investigation became more commonly used [11–13]. Furthermore, due to simulation capabilities, many recent researchers use a simulation and modeling approach, e.g., [14–16]. In addition, researchers using the simulation approach commonly validate their simulation results by comparing them with an experimental investigation.

In order to determine an optimal motion planning, there are many constraints that must be considered. From the literature, the most widely acknowledged optimization constraints are environment constraints (e.g., collision), dynamic behavior (e.g., vibration, torque, speed, and acceleration), energy consumed, and execution time. For instance, the detailed approaches for optimizing the energy consumption of IR based on collision constraints can be found in [17–19], while those based on optimal time trajectory can be found in [20].

The generation of a standard procedure for efficient motion planning begins with defining a starting point, a final point, and reference points for the gripper path [21]. Björkenstam et al. [19] suggested that when developing energy-efficient motion planning, at least three steps should be executed:

(i) develop free-collision motion planning,
(ii) formulate the optimal control problem to follow a defined path, and
(iii) solve and optimize a improved motion planning.

Meanwhile, more complex optimization criteria are presented in [20], which not only focuses on collision constraints but also on the minimum execution time and the minimum jerk that is related to IR productivity and quality.

Another research that uses energy-efficient motion planning method can be found in [22, 23]. In their research, they discovered a solution for reducing the energy consumption of IR by optimizing their motion planning without changing system configurations. The proposed method is conducted with time-scaling concerning a robot's motions from the last processing point to the robot' home positions and by reducing the time release of the robot's brake. Both modeling and experimental investigations are used in their method. Robot motor drives as the main component of IR are modeled in detail with mechanical and electrical losses [8]. Although these methods were successfully tested and able to reduce the energy consumption of IR significantly, the approaches developed are only valid for a specific IR robot model.

A simulation environment for analyzing the effect of IR motion planning with respect to the energy consumption of IR has been developed by Roßmann et al. [24, 25]. The developed simulation environment is based on calculating the energy consumption of every motor of the robot axis. Another method that focuses on motion planning optimizations can be found in [26]. This method is performed by an amplification of energy exchange via the internal DC bus among IR motor drives and optimizing the common point-to-point (PTP) trajectory. In general, for the past 20 years, the main objective for using motion planning optimizations has been to reduce the energy consumption of IR by developing efficient path planning and collision-free motions [27, 28].

2.2 Optimizing operating parameters of IR

Optimizing IR energy consumption by optimizing their operating parameters was proposed by several researchers. For instance, experimental investigations can be found in [29–32], in which a specific IR is used in their investigations. In previous authors' works [33, 34], both simulation and experimental investigations are conducted. Here, a robot model was developed in order to overcome the drawback of an experimental investigation that is only valid for a specific robot model. Afterwards, an actual measure is utilized to validate the IR model.

Reducing the energy consumption of IR using this method is very powerful when used at the production planning stage since after manufacturing systems were established, changing the operating parameters of IR alters the production rate such that, in most cases, this method cannot be implemented. However, by combining the simulation method and experimental validation, this method can be used not only at the production planning stage but also at the optimization process stage, when changing the manufacturing systems' processes is needed due to new process sequences. From the system engineer's point of view, this method is very powerful since it is not necessary to change the software or hardware of the IR systems.

2.3 Scheduling IR operations

Scheduling IR operations is another method that is also widely used to reduce the energy consumption of manufacturing systems. This method is initiated by optimizing the work schedule of IR by reducing their operating time, idle time, and optimizing the robot sequence of IR subtasks [35–37]. An example for the implementation of this method is the automatic start-up and shutdown of the IR during production-free time on weekends. Based on [7], the estimated yearly saving potentials of IR energy consumption in the automotive industry is around 31 % (see Fig. 2).

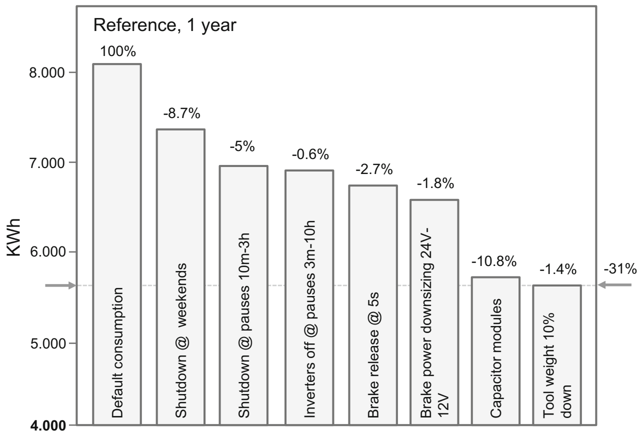

Fig. 2 Energy-saving potential per activity in an automotive industry [7]

The objective in using this method is to reduce operating time and minimize idle time by optimizing the IR schedule. This method is also very convenient for operating engineers, and is the most effective solution when other methods are impossible to implement. Using the new standard communication protocol of the automation system, *PROFIenergy* is one example implementation of this method [38].

2.4 Commercial and industrial solutions

Commercial solutions that are already available are mostly based on modeling and simulation approaches and developed by IR manufacturers, such as *RobotStudio*, which was developed by ABB. In *RobotStudio*, there is a signal analyzer toolbox that can be used to predict the energy consumption of an ABB robot [39]. Using this tool, the energy consumption of IR at several operating parameters can be predicted. Furthermore, researchers from the Institute MMI, RWTH Aachen [40] have also developed a software tool for analyzing the energy consumption of robots that can be used in several applications, such as for aerospace and industrial automation, and has a greater focus on motion planning analysis. Another commercial software tool, *Tecnomatix*, from Siemens in the next few years will offer a solution that utilizes an energy consumption model of IR in their manufacturing systems package; currently, the software is still in the testing phase [41].

In addition to the aforementioned methods that are mostly used in research approaches, there are several methods that are also used in industry. Based on [7, 42] common methods that are used by industries for reducing the energy consumption of IR are listed below:

- Choosing IR with low energy consumption for a certain manufacturing process
- Reducing the weight of IR components
- Optimizing IR trajectory
- Optimizing IR operating time
- Implementing an intelligent mechanical brake system

From an industrial perspective, these methods are more relevant and easily to be implemented without changing the existing manufacturing systems.

2.5 Discussion and suggestion

Although many solutions for reducing the energy consumption of IR have been provided, every method continues to have its advantages and drawbacks. Optimizing the motion planning of IR can reduce the energy consumption significantly; however, this method is only interesting from a theoretical point of view, but less interesting for a practical scenario, since changing the existing IR hardware system requires a great deal of effort and costs [8]. Therefore, this method is only effective from an IR manufacturers' point of view, which has a capability to develop an IR control system. The operating engineer has less flexibility with implementing this method.

Optimizing the operating parameters of an IR in order to reduce its energy consumption is a relatively new method after the requirement concerning energy prices and energy policies are increasing. Therefore, there are still few researchers that explore this method. However, this method is only effectively used at the production planning stage, while the productivity rate of a manufacturing system is planned. To overcome this limitation, incorporating a simulation model into this method is very advantageous when optimizing the existing manufacturing process is required.

The current commercial solutions are still limited to analyzing specific IR models and only focus on their environmental conditions, which limits the simulations of IR internal components. An integrated solution for a manufacturing system's process planning does not yet exist. This makes the analysis and optimization processes time-consuming and cost-intensive. Optimizing IR operation-times can also be used to reduce energy consumption in manufacturing systems. The implementation of this method primarily takes place in the production planning stages since this method requires a specific hardware and software configurations. The industrial methods are also useful but are predominantly only appropriate for certain manufacturing process in specific manufacturing systems.

Among these methods, modeling and simulation have received a deep attention from researchers due to their ability to analyze IR systems easily and at reasonable costs [33]. In addition, IR simulation model can be used in several manufacturing systems' development stages, in production planning for predicting the power consumption of an IR or in optimization stages for optimizing the manufacturing process without performing an experimental investigation. The modeling and simulation approach is the best solution for IR energy optimization. Therefore, in this research, a modular model of IR, which was developed based on a multi-domain simulation paradigm, is proposed for analyzing and optimizing the energy consumption and the dynamic behavior of IR.

3 Modeling and simulation approach for reducing the energy consumption of IR

In this section, simulation approaches as a solution for analyzing the energy consumption and the dynamic behavior of IR are presented. Firstly, the section presents a development method of a modular IR model with a detailed model of its mechanical and electrical losses. Afterwards, a validation of the IR model is presented using a comparative study between simulated and measured results.

3.1 Development of a dynamics and energy model for IR

A dynamics model of an industrial robot was developed using the Modelica language with *Catia Systems Engineering* software tools (see Fig. 3) that use to analyze the power consumption and the dynamic behavior of the IR. The presented model is based on the extended model that was developed in [33]. Improvements in mechanical and

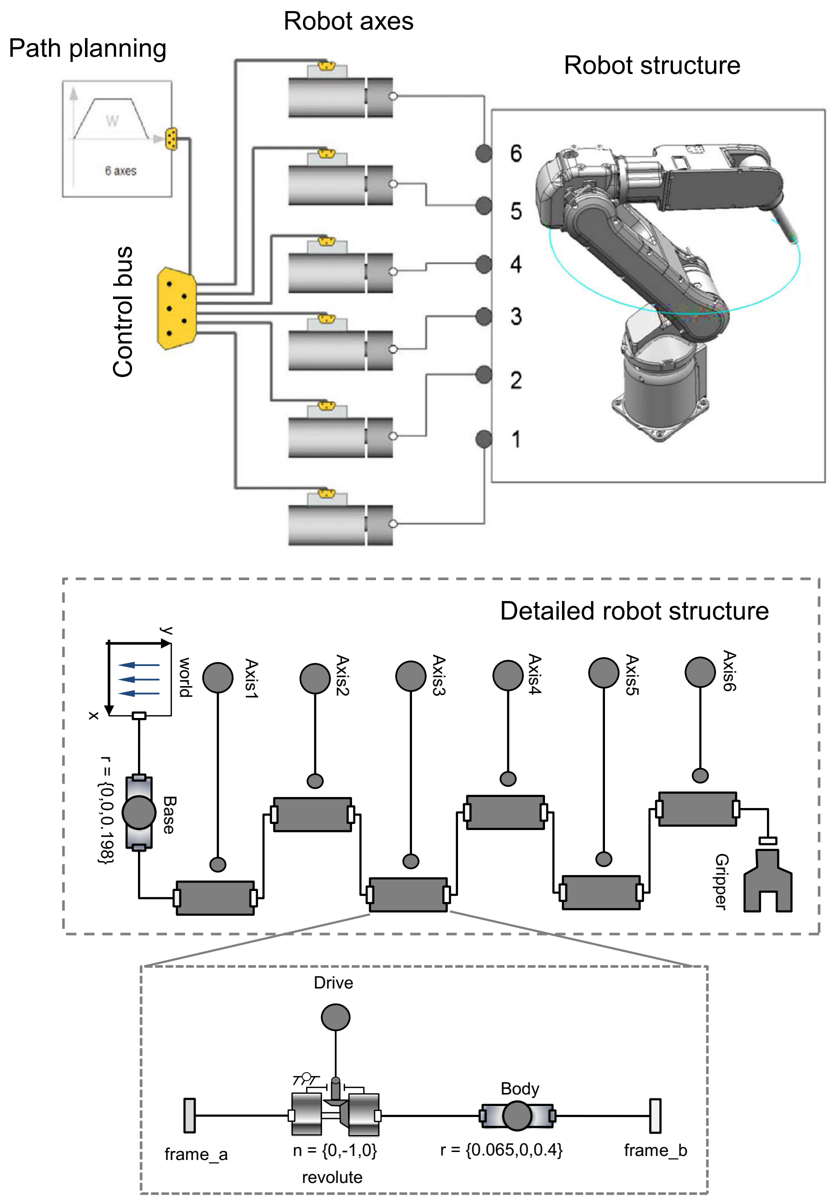

Fig. 3 The dynamic model of a six-axis industrial robot

electrical losses of its motor drive are emphasized in this simulation model.

The components of basic IR models, e.g., the motor drive model, motor controller, body model, or the transmission model, are stored in the Modelica Library. Therefore, it can be used to analyze the dynamics and power consumption of several robot models. In this research, the initial parameters of the model are gained primarily from the actual robot specifications. For example, for case study analysis, the Motoman MH5L model was developed, which used the input parameters from [43] and from actual measurements of a robot platform. For other robot models, aside from using IR specifications, an approximation is performed. For instance, the inertia tensor of several IR models is calculated by using CAD software tools, e.g., *Solid Edge* or/and *Catia*. CAD software for approximating the inertial tensor of IR is commonly used by researchers since it can reduce development time and efforts, as presented in [44]. The detailed approximation method of the inertial tensor of an industrial robot structure can be found in [45]. In order to create movement of the robot, the standard path planning model (PTP and PTP2) from the Modelica Standard Library is used.

As a case study, the universal contacting module (UCM) cell that contains several assembly system components, including an industrial robot, is used. The UCM cell is used as the test platform as part of an electronic component production facility [see Fig. 4].

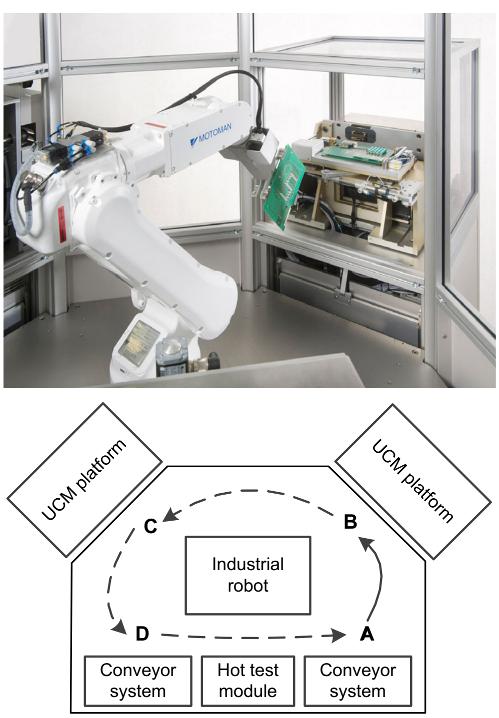

Fig. 4 The configuration of the comprehensive test platform (UCM) and the robot cycles (design by IMAK GmbH)

3.2 Power losses in the IR model

The power losses of IR, both mechanical and electrical, are important to consider in the development of a high-accuracy IR model due to its significant contributions to power consumption simulation results. The power (P) and energy consumption (W) over time $0-t$ of IR can be formulated as shown in Eq. 1 [30, 46]. The equation shows that the robot's torque (T), its angular velocity (ω), and the mechanical and electrical efficiencies (η_m, η_e) of the drives highly influence the robot's power and energy consumption. Therefore, analyzing IR under several payloads and operations speeds and developing an accurate power losses of IR, both mechanical and electrical losses, are expected.

$$P = \sum_{i=1}^{n} T_i \omega_i \frac{1}{\prod_{i=1}^{n} \eta_{m,i} \eta_{e,i}}; \qquad W = \int_0^t P dt \tag{1}$$

The power losses occur in every component of an industrial robot and can be classified in the following terms:

Power losses in the IR body mechanism. The power losses in this component are mainly caused by friction losses due to the mechanical friction of the IR structure, e.g., friction in the gear transmission and gear bearing, and friction in every joint of the IR and due to the lubrication effect. The friction losses in the IR model are modeled based on the Coulomb and viscous friction, which depend on the speed and input torque [47].

Power losses in the IR motor drive. The drive system of IR is used for actuating the robot structure. Most of six-axis IR use a permanent magnet synchronous machine (PMSM) as the main motor drive [8], while some use an induction motor drive. The electrical power losses in this component also occur in common electric machines. In the motor drive, these losses are depicted in Table 2, which in our IR motor drive model was equipped with all of these losses, i.e., core losses (p_c), windage and friction losses (p_f), stator and rotor losses (p_r), as well as stray load losses (p_s). The model of every motor loss (p_{loss}), which is modeled using Modelica is formulated in Eq. 2. All different motor drive losses are formulated based on the equations in Table 2.

$$p_{loss} = p_c + p_f + p_r + p_s \tag{2}$$

The evaluation of the motor drive losses using these equations was performed by Modelica Associations [49],

Table 2 Power loss model of an industrial robot motor drive [48, 49]

IR motor drive losses	Explanation
Core losses	Core losses or iron losses occur due to the magnetization process of the core material (hysteresis) and due to the eddy current effect in that process. Generally, this loss contributes about 20–25 % of the total motor losses. As previously mentioned, the core losses consist of hysteresis and eddy current losses; thus, core losses (p_c) are expressed as follows: $p_{\mathrm{c}} = p_{\mathrm{ref}}\left(r_{\mathrm{H}}\frac{\omega_{\mathrm{ref}}}{\omega} + 1 - r_{\mathrm{H}}\right)\left(\frac{v}{v_{\mathrm{ref}}}\right)^2$ (3) Equation 3 shows that core losses are modeled based on angular remagnetization velocity (w) and actual voltage (v). Thus, p_{c} can be modeled as a frequency-dependent conductor, which is expressed as follows: $G = \frac{p_{\mathrm{ref}}}{v_{\mathrm{ref}}^2}\left(r_{\mathrm{H}}\frac{\omega_{\mathrm{ref}}}{\omega} + 1 - r_{\mathrm{H}}\right)$ (4) To calculate the core losses, the ratio of hysteresis losses (r_{H}) with respect to the total core losses should be defined. However, this is simplified by defining $r_{\mathrm{H}} = 0$ since the velocity of the changes in the magnetic field cannot be easily detected in Modelica, which means that hysteresis loss is not considered.
Windage and friction losses	Stator winding and friction losses are caused by the bearing friction and air resistance of the motor. These losses contribute around 8–12 % of the motor's total losses and do not depend on motor load. These losses depend on speed; therefore, they are modeled based on the following equations: For $\lvert\omega\rvert > \omega_{\mathrm{Linear}}$: $\tau = \mathrm{sign}\,(\omega)\,\frac{p_{\mathrm{ref}}}{\omega_{\mathrm{ref}}}\left\lvert\frac{\omega}{\omega_{\mathrm{ref}}}\right\rvert^{\mathrm{power}_{\omega}^{-1}};$ (5) For $-\omega_{\mathrm{Linear}} \le \omega \le +\omega_{\mathrm{Linear}}$: $\tau = \frac{p_{\mathrm{ref}}}{\omega_{\mathrm{ref}}}\left(\frac{\omega_{\mathrm{Linear}}}{\omega_{\mathrm{ref}}}\right)^{\mathrm{power}_{\omega-1}}\left(\frac{\omega}{\omega_{\mathrm{Linear}}}\right)$ (6) The exponent power_w is approximately 1.5 for axial ventilation and 2.0 for radial ventilation. To stabilize the simulation model, the friction torque is approximated by a linear curve.
Stator and rotor losses	Stator and rotor losses occur as a result from the current (I) that flows through the stator and rotor winding. These losses are also called I^2R losses. As a result from these losses, the rotor and stator of the electric motor is heated. I^2R losses contribute around 55–60 % of the total motor's losses. Different with the core, friction and windage losses, stator and rotor losses depend on the motor load. The models of stator and rotor losses (p_{r}) are expressed in the following equations: $p_{\mathrm{r}} = i^2 R_{\mathrm{Operation}};$ $R_{\mathrm{Operation}} = R_{\mathrm{ref}}\left(1 + \alpha_{\mathrm{ref}}\left(T_{\mathrm{Operation}} - T_{\mathrm{ref}}\right)\right);$ (7) $\alpha_{\mathrm{ref}} = \frac{\alpha_{20^{\circ}\mathrm{C}}}{1 + \alpha_{20^{\circ}\mathrm{C}}\,(T_{\mathrm{ref}} - 293.15)}$ where i is the current, R is the resistance of the motor, α_{ref} is the linear temperature coefficient of the specific material, and T_{ref} is the reference temperature.
Stray load losses	Stray load losses occur when the motor is operating under its specific load as the result of leakage fluxes through the stator winding. This loss also depends on the motor load capacity and normally contributes around

Table 2 (continued)

4–5 % of the total losses. The stray load losses are modeled according to the standards EN 60034-2 and IEEE 112, which are formulated in following equations:

$p_s = \tau\omega;$

$$\tau = \frac{p_{\mathrm{ref}}}{\omega_{\mathrm{ref}}}\left(\frac{i}{I_{\mathrm{ref}}}\right)^2\left(\frac{\omega}{\omega_{\mathrm{ref}}}\right)^{\mathrm{power}_{\omega}^{-1}} \quad (8)$$

where w is the actual angular velocity and i is the current of the machine. The exponent power$_w$ represents the dependency of the stray load torque on the angular velocity.

as depicted in Fig. 5, which was conducted with an asynchronous induction machine.

Power losses in IR motor control systems. This loss also includes inverter losses in the electric motor and in its rectifier. Before the electrical power can be used by the motor, the current and voltage flow into the motor control system component, such as the power converter, AC/DC module (rectifier), and DC bus, first. During this process, there are power losses [8].

In addition to all of these losses, IR also need electrical power to operate the supporting components, such as computers, monitors, and the IR controller. The electrical power that is used for these components is relatively constant during the robot operation. In our research, these components are not included in the developed model.

The general power losses that occur in the IR are shown in Fig. 6. Due to the priority task and limitation of the Modelica language, only power losses in the IR body mechanism and power losses in the IR motor drive are modeled in the IR simulation model.

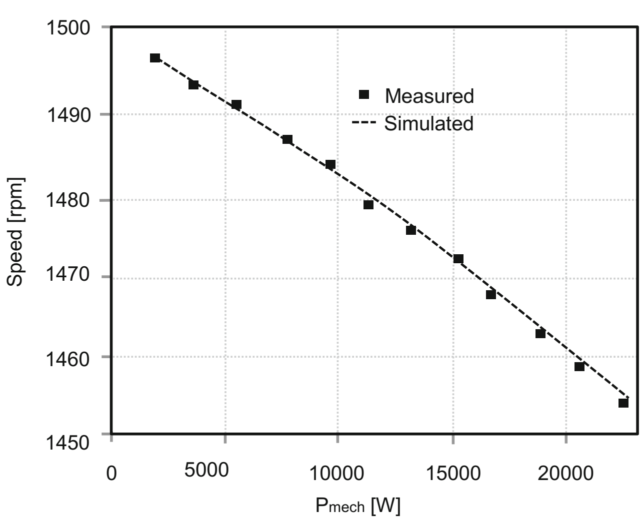

Fig. 5 Speed of the asynchronous induction machine, simulation results compared with actual measurements [49]

3.3 Validation of the IR model

Experimental investigation is the best solution for validating the simulation results as long as it can be performed at acceptable costs and times. When an actual measurement is not possible or too expensive, a sensitivity analysis is performed. In this research, an experimental investigation was conducted using a measurement unit that has the ability to measure the electrical behavior of the IR, such as voltage, current, and power during the robot's operation. The measurement unit collects the electrical data every 0.0001 s, afterwhich these data are stored in the PC of the measurement unit. The experimental setup is shown in Fig. 7.

For a comparative study, the execution time and dynamic characteristic of IR are used as the criteria to choose the simulation task. The power consumption of the IR is analyzed based on the robot movement from position D to A; for the dynamic behavior analysis, the robot movement is simulated

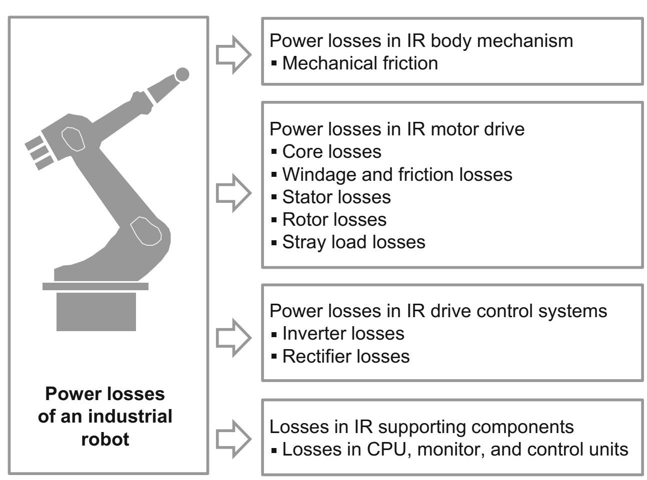

Fig. 6 Power losses in IR

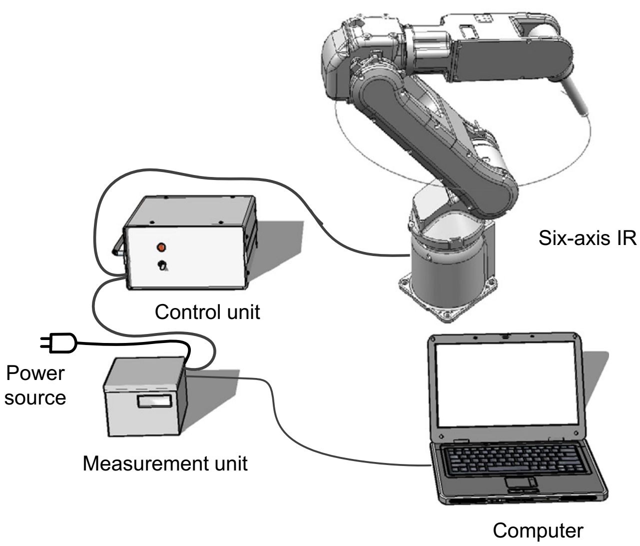

Fig. 7 Experimental setup to measure electrical behavior of IR

from position A to B (see Fig. 4). In both simulation and experimental investigations, the payloads of the robot varied from 2 to 3 kg at two robot speeds: 20 and 40 % of the maximum speed. These operating conditions were also used to analyze the effect of IR operating parameters on the power consumption and the dynamic behavior of IR. For the route D to A, the robot movement only used axis1 and axis2 while the other axes were on standby, using PTP motion instruction. While moving from position A to B, axis5 and axis6 have a grater range of motion than the others. The execution time and dynamic characteristics of the robot are used as the main criteria for defining these movements. During these movements, electric parameters and dynamic responses of the robot were monitored.

4 Results and discussion

In this section, both simulation and experimental results are presented. The section begins with a discussion on the deviations of the simulation and experimental results. Furthermore, a discussion on the effect of robot operating parameters and dynamic behavior on its energy consumption is presented. In addition, strategies that are used to reduce the energy consumption of IR based on our results are provided at the end of this section.

4.1 Deviations from the modeling approach

To determine the accuracy of the developed IR model, a comparison between simulation and experimental results is used. The comparison is performed based on electrical behavior values, such as the motor drive current and the power consumption of the IR. Comparison data were collected from the robot at the following operating conditions: 3 kg payload and 20 % of the maximum speed. A comparison between the measured and simulated motor drive's current and power consumption of the robot is depicted in Fig. 8 and shows that there is an approximatelly 6 % power deviation between simulated and measured result. This is mainly caused by the IR control unit and its components that are not included in the simulation model due to the limitation of the simulation tool. However, the power consumption trend is nearly similar. At the beginning and end of the robot movement path, the power and current are relatively low. This trend occurs due to the motor drives having not been loaded at the beginning, and at the end, their speed and friction is reduced.

As shown in Fig. 8, the developed models are adequately accurate for predicting the electrical behavior of the IR. The resulting deviation is relatively minimal since the losses of the IR model are well modeled.

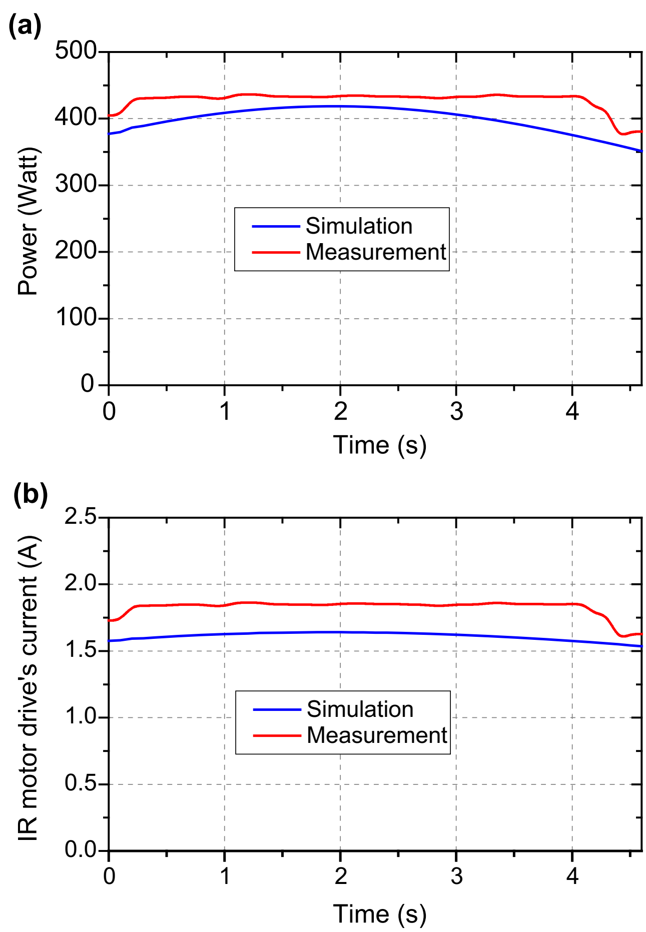

Fig. 8 Deviation of the simulated from the experimental results: **a** power consumption of the robot and **b** motor drive's current

4.2 Effects of IR operating parameters on the power consumption

In order to analyze the effect of the IR operating parameters on the power consumption, both simulated and actual measurement investigations were performed. The focus of this investigation was to analyze the effect of IR payloads and the operating speed. The IR power consumption at different payloads is shown in Fig. 9. This figure shows that the payload of the IR influences its power usage. Both simulation and experimental results showed that higher payloads lead to higher rate of power usages. This is because at higher payloads, the torque of the IR axis is also higher. Thus, the power consumption of IR is linear with respect to the robot's payload. Adding 1 kg payload contributes to an approximately 1.2 % increase in power. Moreover, Fig. 9 also shows that the difference in robot power consumption for the simulation and actual measurements is about 50 W, which is a result of the power consumption of the robot control unit apparatus that is not modeled. In addition, this figure also shows that the power usage increases at the beginning and decreases at the end.

Similar to the payload effect, the operating speed also has a significant effect on the power consumption of the robot. Higher speeds lead to higher power consumption (see Fig. 10). However, higher speeds reduce the robot operation time that means having the potential for reducing the energy consumption of IR. A slower operating speed will lead to longer operating times, and thus, the robot requires more energy consumption since the energy consumption is a function of time. Therefore, it can be said that in order to reduce the energy consumption of IR, the operating speed should be set to the medium range, not too slow and not too high (see Fig. 11), which was also found in [39]. The optimal speed is due to the balance between energy consumption

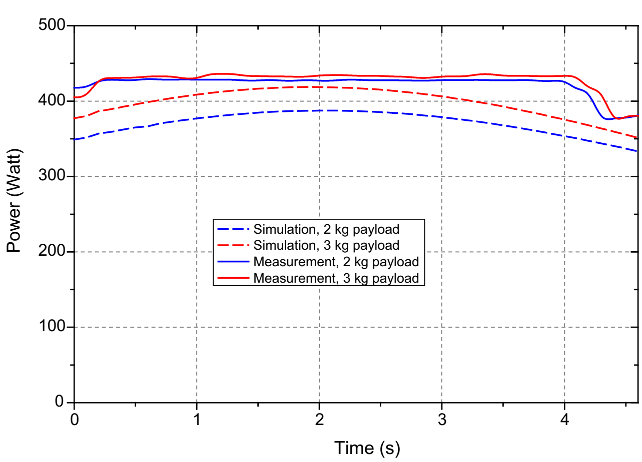

Fig. 9 Power consumption of the robot at different payloads

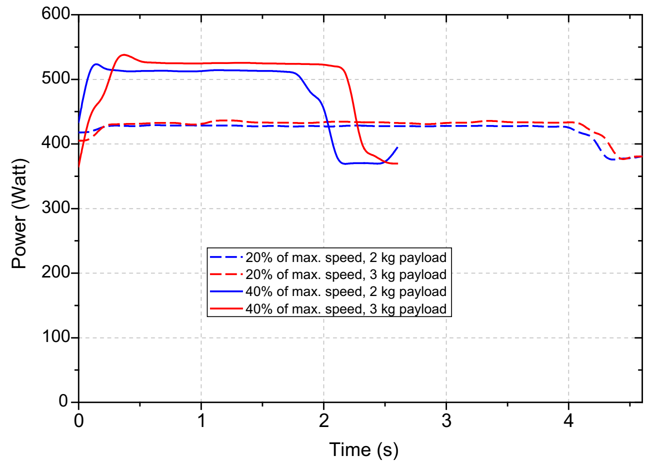

Fig. 10 Power consumption of the robot at different operating speeds

gravimetric and inertial contributions [50]. However, layout constraints and productivity requirements of IR must be considered. Without constraints to the IR path, operating at a higher speed is suggested, but when there are many constraints, slower speeds are preferred.

4.3 Effects of the dynamic behavior on the power consumption

The dynamic behavior plays an important role in improving the performance and efficiency of IR. The robot's mass, payload, speed, center of gravity, and the inertia of every IR axis are important factors that influence IR dynamics [51]. In this sub-section, the effects of the dynamic behavior of IR on the energy consumption is presented. The developed model was used to analyze the dynamic behavior of IR, and the analysis was performed around the sixth axis due to its high vibrations. The input parameter for IR movement was designed using PTP, which generates instructions for moving the robot from an initial position to a final position. The

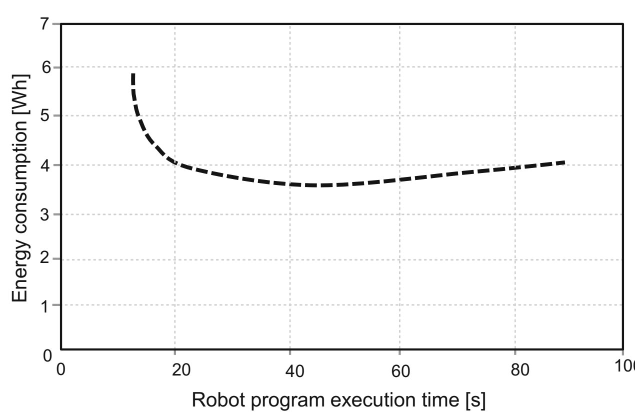

Fig. 11 Energy consumption of IR at several operating speeds [39]

input parameters are positions, robot speed, and the defined maximum acceleration. Based on these data, the PTP model sends the angle, speed, and acceleration reference to every motor drive of the robot. In every motor drive, the rotation is controlled by the PI and PID controller, which are equipped with an angle, speed, and acceleration sensor.

The speed response of the robot under several operating speeds and payloads is shown in Fig. 12. As shown in Fig. 12a, the operating speed of robot has no influence on the robot speed response. The fluctuation of the speed response with starting motion is relatively minimal. This shows that the robot control and the damper model of the robot were able to reduce excessive acceleration.

Moreover, the effect of robot payload is shown in Fig. 12b. This figure illustrates that the payload value has a strong correlation with the speed response. During the beginning of the motion, the speed response is affected by the payload value; a higher payload causes a higher speed response. In general terms, Fig. 12 shows that the operating conditions of IR have significant effects at the beginning of IR motion. This is the reason why, at the beginning of the IR motion, the energy consumption is relatively high (as shown in Fig. 13). During that time, the IR needs more power to actuate the motor drive. Therefore, it can also be concluded that in order to reduce the energy consumption of IR, smoothing the IR motion is suggested (see Fig. 14). This figure shows that smooth motion planning is more energy efficient than rough/extreme motion.

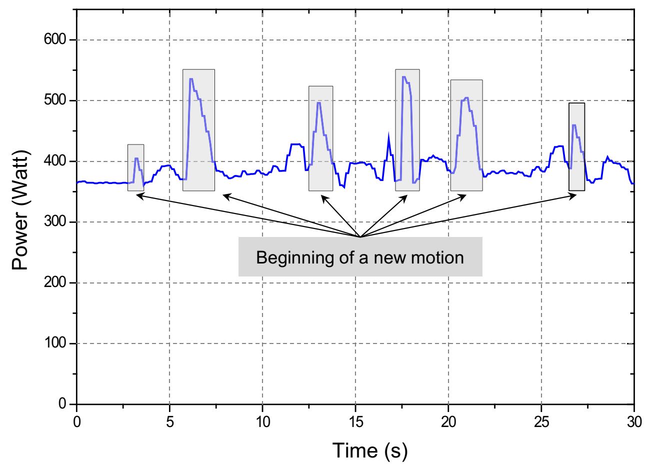

Fig. 13 Power consumption of the robot during its first 30 s

4.4 Strategies for reducing the energy consumption of IR

Using the robot simulation model that was developed in this research, the power consumption and the dynamic behavior of the robot can be predicted. Therefore, it can be used to optimize the operating parameters and its motion. The

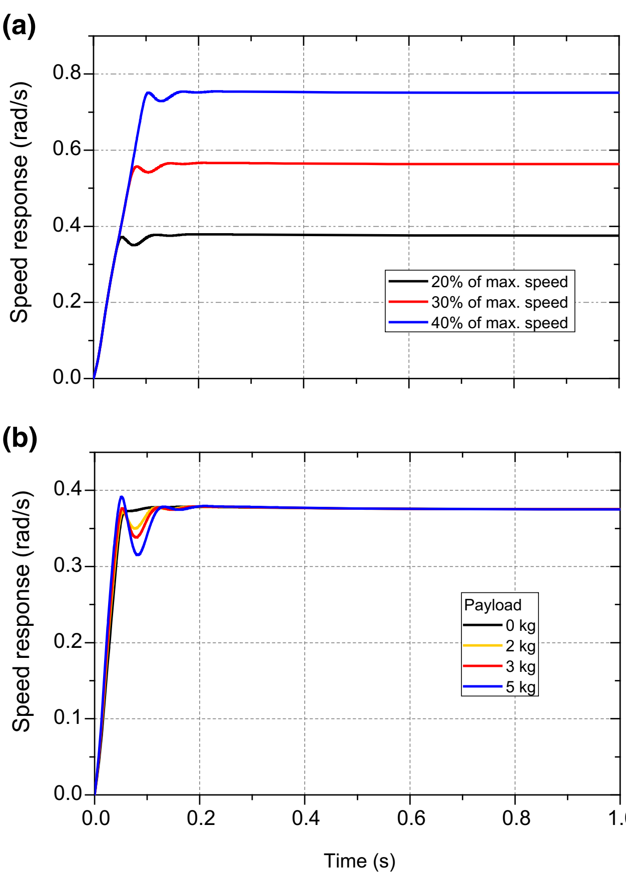

Fig. 12 Dynamics of the IR, **a** at varying speeds and **b** with varying payloads

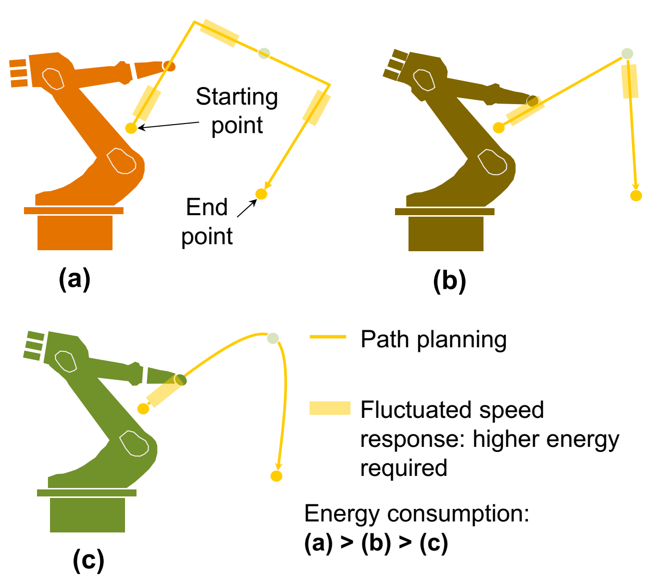

Fig. 14 Smoothing IR motions to avoid excessive energy consumption during beginning of the motion

relation between the IR simulation model, the energy consumption, and the dynamic behavior are shown in Fig. 15. The productivity requirement, e.g., speed, payload, and environmental conditions (layout constraints) are used as the initial input for optimizing the IR operating parameters. These initial data are used as the initial parameter for the IR model that was developed based on the multi-domain modeling paradigm. The simulation results from the developed model will provide the dynamics and electrical behavior of the IR. The IR performance and the power consumption were analyzed in detail using these data. Finally, an iterative simulation was performed for optimizing the operating parameters of IR.

Based on investigation results, which were obtained from actual measurements and modeling methods, it was shown that the following methods can be employed in order to improve the efficiency of IR used in manufacturing systems:

- The payload has a significant impact on the power consumption of the IR since it changes the torque of the IR axis. Therefore, to reduce the energy consumption of IR, reducing the weight tools of systems that are used by IR is suggested. The method can be implemented by using light-weight material for tooling system components.
- Smoothing the IR motion planning will reduce energy consumption. This is because starting robot motions need more power to accelerate the IR motor drive systems.
- Operating speeds have a significant impact on the energy consumption of IR. Thus, operating the IR at medium speeds, not too fast and not too slow, is suggested.

The investigation also shows that in order to reduce the energy consumption of IR, the productivity requirements and environmental conditions of the manufacturing systems must be considered. Combining several reduction methods that adhere to the system requirements is suggested in order to optimize the energy consumption of IR.

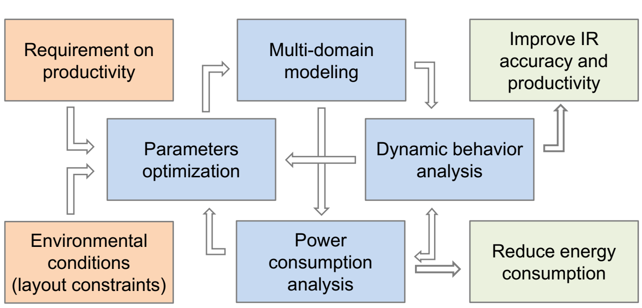

Fig. 15 Multi-domain simulation approach for reducing the energy consumption of IR

5 Conclusion

In this paper, a comprehensive review of the research and practical methods for reducing the energy consumption of IR used in a manufacturing system is presented. Many methods have been developed; however, current methods are commonly difficult to be implemented due to many technical problems, such as changing existing IR control systems. Moreover, existing methods are still lacking in the interaction analysis of IR internal components. In addition, the methods that can be used in the early production planning stage are limited. The simulation approach as a new trend in this field is a promising method due to its use in several manufacturing systems' development stages, from production planning to process optimization stages. Therefore, in this research, a modular model of IR for analyzing their power consumption and dynamic behavior are proposed. An actual measurement on a specific IR is also performed in this paper, which is used to determine deviations from simulation results and to evaluate the IR model accuracy.

Using the developed model, the power consumption of the IR under several operating parameters can be predicted. Therefore, the model proves very useful in the early production planning phase, in which limited data are available. Based on the validation results, the developed models are adequately accurate for predicting the electrical behavior of the IR. Thus, it can be used to analyze the electrical and dynamic behavior of IR. The simulation and measurement results show that the operating parameters, i.e., speed and payload, strongly influence the power consumption and dynamic behavior of IR. A higher operating speed and payload will increase the power consumption of IR. Therefore, reducing the power consumption of IR can be performed by optimizing the IR operating speed, reducing the weight of tooling systems, and smoothing the IR motion. Further work should address the implementation and evaluation of the developed simulation model for more complex manufacturing systems, such as an automotive assembly system.

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