ENERGY CONSUMPTION MODELLING AND OPTIMIZATION FOR THE UR5E

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Abstract: *For sustainable manufacturing activities, industries that use 6-DOF industrial robots (IR) should consider the energy efficiency of their IR. For example, it has been estimated that on average 8% of the total energy consumption in the vehicles' lifecycle production is consumed by the robots (electrical energy). Nevertheless, IR are used for different tasks such as material handling, assembly, painting, welding, etc., and plays a fundamental role in industries nowadays. In this paper, an energy consumption model is implemented to optimize the energy consumption of a 6-DOF IR. In this paper, the UR5e has been used. For energy optimization, an iterative approach has been proposed, whereby the programmer optimizes the trajectory by rechecking the energy consumption produced by certain joint configurations. The results show different power consumptions for different configurations from which the programmer can use an adequate configuration that allows the execution of the task. The iterative approach is applicable to a serial kinematic robot arm with n-DOF. (free space)*
(14 pt)
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1. Introduction

In the last decades energy prices have been increasing due to several reasons such as higher demand for electricity, fuel costs, government regulations, and market forces (Maggio et al., 2019). For sustainable manufacturing activities, it is meaningful to consider the energy efficiency of an industrial robot.

In the manufacturing industry, industrial robots are used in different tasks such as material handling, assembly, painting, welding, etc. (Chiacchio et al., 2018). Nevertheless, industrial robots consume a significant amount of energy (Stupans et al., 2022). For example, it has been estimated that on average 8% of the total energy consumption in the vehicles' lifecycle is consumed by the robots (electrical energy) (Meike and Ribickis, 2011).

As in (Carabin et al., 2017) illustrated there are two main approaches for the optimization of energy consumption namely the software-based and the hardware-based approach. The aim of this paper is to optimize the energy consumption of the serial 6-DOF industrial Robot (IR) UR5e (Fig. 1).

Fig. 1. UR5e.

For this aim a model for the energy consumption of the IR as well as an energy optimization strategy (based on the energy consumption model) are needed. To identify the inertial as well as the frictional parameters of the links of the IR, thus to model the energy consumption the inverse dynamics approach or the power data approach can be used as shown in (Gautier and Briot, 1998). To reduce the energy consumption a trajectory optimization method will be used. The energy consumption is measured for specific joint configurations and their energy consumption compared with each other.

This paper is structured in six sections. In section 2 a brief introduction about the inverse dynamics model will be introduced on which existing methods rely to model and optimize the energy consumption of an IR.

In section 3 the implementation for the modelling and optimization of energy consumption are explained. In section 4 the conducted experiments will be illustrated. In section 5 the results of the experiments are shown. In which direction future works can be developed based on this paper will be shown in section 6.

2. State of the Art

To model the energy consumption model of an industrial robot the inertial parameters (masses, center of mass, and moments of inertia) of each link as well as the friction parameters of the industrial robot are needed (Liu et al., 2018). However, these parameters are confidential and therefore unavailable to the users (Paes et al., 2014). This is due to the fact that industrial robot companies could affect their competitive market potential by giving such information (Rassõlkin et al., 2011). The inverse dynamic model of an n-DOF serial manipulator is given by the Lagrangian formulation (see (1)) (Grotjahn et al., 2001).

$$\tau_{dyn,i} = \frac{d}{dt}\frac{\partial \mathcal{L}(q_i(t),\dot{q}_i(t))}{\partial \dot{q}_i(t)} - \frac{\partial \mathcal{L}(q_i(t),\dot{q}_i(t))}{\partial q_i(t)} \tag{1}$$

Where $\tau_{dyn,i}$ is the i-th torque at joint i, $\mathcal{L}(q_i(t),\dot{q}_i(t))$ the Lagrangian and $q_i(t),\dot{q}_i(t)$ are the angular position and joint velocity respectively (Grotjahn et al., 2001). The Lagrangian formulation is equivalent to

$$t_{dyn,i} = M(q_i)\ddot{q}_i + C(q_i,\dot{q}_i)\dot{q}_i + G(q_i) \tag{2}$$

Also called Newton-Euler formulation (see Khalil et al., 2003). Where $M(q_i) \in \mathbb{R}^{nxn}$ is the inertial matrix, $C(q_i,\dot{q}_i) \in \mathbb{R}^{nxn}$ is the Coriolis and centrifugal force matrix and $G(q_i)$ is the gravity vector (Liu et al., 2018). Both and are dependent from the inertial parameters such as $XX_i, YY_i, ZZ_i, XY_i, XZ_i, YZ_i$ which are the components of the inertial tensor, mX_i, mY_i, mZ_i which represent the first moment of inertia and m_i the mass of each link.

As mentioned in (Atkeson and Hollerbach, 1986) in the case of interconnected bodies for example serial industrial robots not all inertial parameters are required. This is because some of the inertial parameters appear as a linear combination of other parameters (Mayeda et al., 1990). The minimum set of inertial parameters can be obtained by Gautier and Khalil (Gautier and Khalil, 1988) or by numerical QR decomposition of the observation matrix (Gautier, 1990).

For parameter identification several approaches have been developed which rely on the inverse dynamics model.In (Swevers et al., 2007) an experimental approach for the parameter identification is based on a periodic excitation (finite Fourier Series) of each joint.

The parameter identification is obtained with the help of the maximum likelihood estimation which is simplified to a weighted linear least squares estimation (Verdonck et al., 2001).

The periodic excitation parameters are optimized by solving a nonlinear optimization problem with constraints imposed on the robot's motion (Verdonck et al., 2001). Appropriate values for the trajectory parameters can also be selected by trial and error. An optimization criterion used by the authors in (Swevers et al., 2007) is given by the logarithm of the determinant of the covariance matrix known as the d-optimality criterion (Ljung, 1998).

Other approaches like higher-order polynomials (Fung and Cheng, 2011) as well as finite sequences of joint acceleration (Armstrong, 1989) can be used for joint excitation. The choice of the excitation trajectory compromises the validity of the estimated parameters.

Experiments in (Atkeson and Hollerbach, 1986) show that intuitively chosen trajectories result in degradation of the parameter estimation. The work in (Swevers et al., 2007), (Verdonck et al., 2001) shows that excitation trajectories such as higher-order polynomials or finite sequences of joint acceleration do not take the uncertainties of the measurements into account. The usage of periodic excitation trajectories allows data averaging and estimation of measurement noise.

In (Paes et al., 2014) with the help of the feedback motor current, the parameter identification has been configured. By measuring with the help of a sensor the reaction forces and torques at the base of a serial robotic manipulator a parameter identification model was developed in (Christoforou, 2006). The approach developed in (Christoforou, 2006) consists of the online extraction of the inertial parameters from the sensor to improve the modelled trajectory tracking controllers. A drawback of this method is that the friction parameters of the joints are neglected or to be more precise the friction torque in the equation is not considered. In (Radkhah et al., 2007) an approach has been proposed that mainly relies on the following two steps. Firstly the parameters of the periodic excitation trajectory are optimized through the d-optimality criterion like in (Swevers et al., 2007). Secondly, the standard least-squares procedure is used for the link parameters estimation. Similar to (Christoforou, 2006) the friction parameters are not considered in (Radkhah et al., 2007).

In contrast with the presented works which rely on the inverse dynamics model, in (Liu et al., 2018) a step-by-step parameter identification model is developed by gaining the power data of each motor separately through the software Robotstudio which is used as a power sensor. The excitation of the joints is based on the work of (Swevers et al., 2007).

As proposed in literature *** the identification models assume that the joint friction can be expressed in a linear form. The friction can be divided into a static and dynamic region. The static and dynamic regions are separated by a certain threshold velocity for each joint. The assumed linearity of the friction joints results in significant errors on the identified parameters when a certain threshold velocity of a joint is not exceeded or in other words when the linear friction model is used in the dynamic region as stated in ***. In ***based on the previous work of (Vuong et al., 2009) the threshold velocity is determined.

Similar to the approach in *** the study in (Hao et al., 2021) focuses on the frictional torque, particularly on the modeling of the frictional torque. As in (Hao et al., 2021) the frictional torque combines the joint velocity as well as the temperature of the gearbox in one equation. The thermal model is given by a double exponential law as shown in (Hao et al., 2021).

For Energy optimization Hardware- and Software-based approaches have been proposed. The hardware approaches focus on three aspects, namely on the design or the choice of the system as well as the substitution or addition of hardware components which increases the energy efficiency of the system (Carabin et al., 2017).

In (Li and Bone, 2001) the energy consumption of a three-DOF parallel manipulator has been compared with a serial manipulator with the same DOF, workspace, and payload. It is shown that the parallel manipulator is more energy efficient in the XY-Plane and less energy efficient in the Z-direction.

In (Hirzinger et al., 2002), (Yin et al., 2016) the focus relied on a lighter design of a serial-link robot. The aim in (Hirzinger et al., 2002), (Yin et al., 2016) is to reduce the moving masses which results in the reduction of the torque due to the lighter weight and inertia of the masses and thus in the reduction of the energy consumption. In (Hirzinger et al., 2002) a serial seven DOF redundant robot made of ultralight carbon-fiber-reinforced polymer is studied. In (Yin et al., 2016) an optimization design that focuses on the mechanical dimensioning of each link, joint and lightning holes of the links is proposed to get a robotic arm with lower mass, more compact structure, and lower power consumption. In (Gale et al., 2015) a flywheel has been added to a 6 DOF serial-link robotic manipulator as an energy storage device which has been integrated into the robot without the modification of the electrical subsystem of the robot. By storing the excess of power and converting it to mechanical energy the flywheel can provide the stored energy in cases of joint acceleration where more energy is needed. This enables the reduction in power consumption.

Software-based approaches focus either on trajectory optimization or Operation scheduling (Carabin et al., 2017). In (Hansen et al., 2012) a dynamic model of a multi-axial robot has been developed which considers the electrical drives and inverter losses. With the help of the model an appropriate cost function (time integral of the DC-bus power). In (Hansen et al., 2012) PTP (Point-to-Point) trajectories are considered which are defined by B-Spline functions. The Optimization of the parameters is given by gradient-based methods.

In (Meike et al., 2014) the energy optimization is based on the implementation of energy-reducing trajectories given by means of time scaling and on reducing the release time of the actuator brakes. In (Luo et al., 2015) for energy minimization of a serial industrial robot, the joint trajectory functions are optimized by using the Lagrange interpolation method and considering the position as well as the stability constraints of the robot. By using the Chebysev nodes Runge’s phenomenon is avoided in the Lagrange interpolation method.

In (Fung and Cheng, 2014) the PTP trajectory of serial robotic manipulator is given by a high-degree order polynomial whose optimal parameters are determined by using genetic algorithms. Constraints such as joint angular position, velocity, and acceleration are considered as well.

3. Information

For the implementation of the dynamic model and trajectory optimization of the UR5e the simulation software Matlab, Simulink, SolidWorks, ROS moveit, and Gazebo will be used.

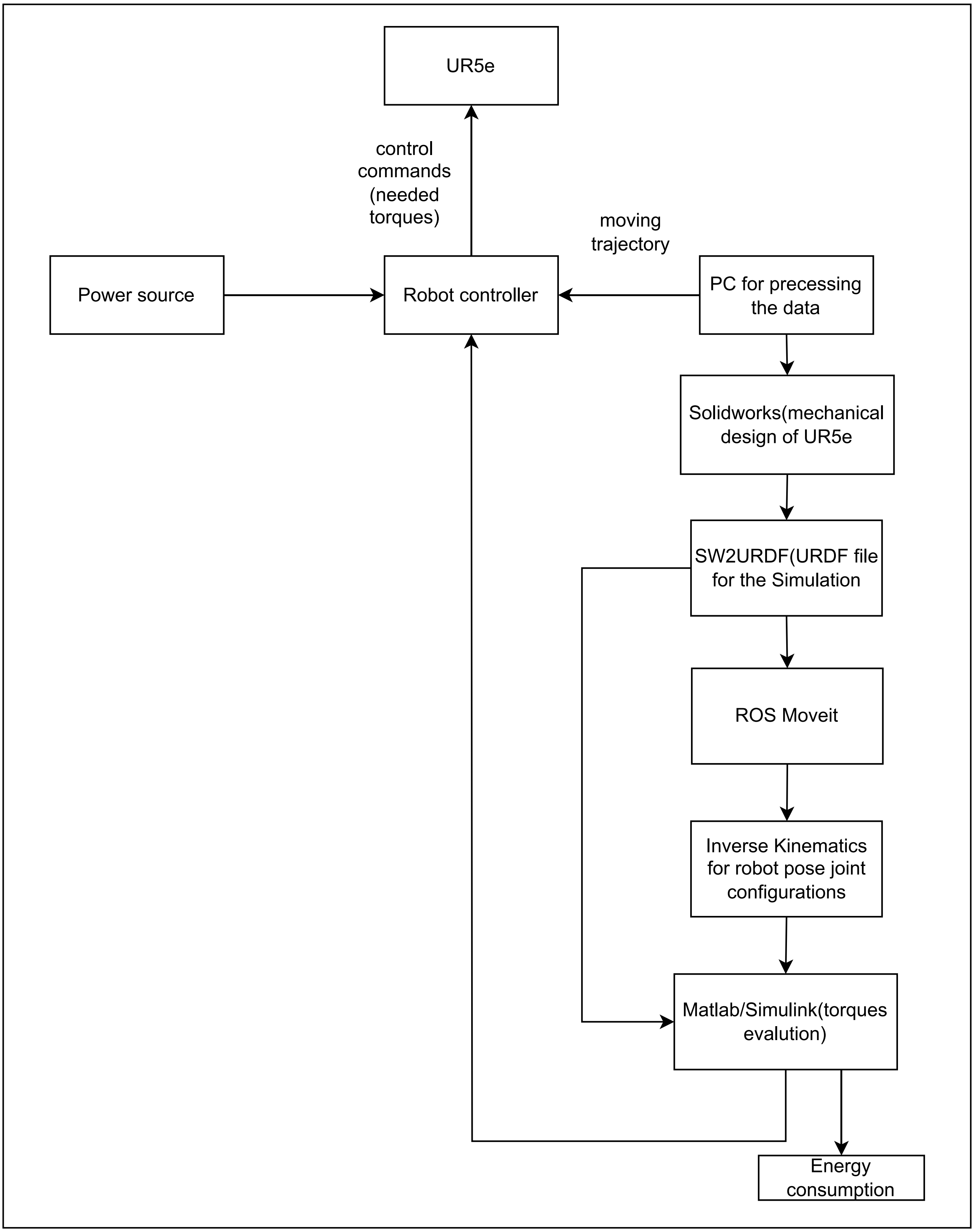

Fig. 2. System Design.

In Fig. 2. the system design illustrates the different software interfaces. The main hardware of the system is the robot controller and the UR5e which are simulated in the gazebo world simulation software as well as in Simulink. The kinematics of the robot are defined using the DH-Parameters. The main aim of the system is the parameter identification for the computation of the needed torques as well as the energy optimization.

For the parameter identification, a urdf file of the robot is generated and used to generate a rigid body tree model of the robot. A Simulink model of the robot is created, and the inverse dynamics block in Simulink is used for the parameter identification for the evaluation of the joint torques. Where the inputs are the joint configuration, velocities and accelerations and the output of the inverse dynamics block is a $Nx1$ vector of the required joint torques, where N is the number of non-rigid joints.

A Simulink model for the inverse kinematics configuration has also been created the only difference to the forward kinematics model is that the inputs of the model are the x, y and z positions of a desired pose. The orientation is not considered to increase the computational efficiency of the Levenberg-Marquardt inverse kinematics solver in Simulink. For the Levenberg-Marquardt inverse kinematics solver, the home joint configuration $\vec{q} = [0°, 0°, 0°, 0°, 0°, 0°]$ has been taken as the initial guess.

After implementing the dynamic model, the energy consumption must be minimized. For energy optimization, a cost function needs to be defined. In this paper, the aim will be to minimize the total mechanical power of the robot given by the following equation (see 3)

$$P_{robot} = \sum_{i=1}^{n} |\tau_i(t) * \dot{q}_i(t)| \qquad (3)$$

Where $\tau_i(t)$ defines the needed torque and $\dot{q}_i(t)$ the angular velocity of the i-th joint. T is the integration time. In this case n is equal to six, because the UR5e possess six axes. In this paper, PTP trajectory optimization will be considered. To optimize the energy consumption an iterative approach is used, whereby the programmer optimizes the trajectory by rechecking the energy consumption produced by the proposed implementation. This approach ensures awareness about energy consumption over several iterations as shown in Fig. 3.

The Threshold is a value that must be decided by the programmer and depends on different factors such as energy prices, companies' economic strategies, etc. Due to the orientation restriction in the inverse kinematics Simulink model, multiple joint configurations are not possible in the inverse kinematics Simulink model. To overcome the mentioned restrictions a ROS Moveit package of the UR5e has been created. Different joint configurations (multiple inverse kinematics solutions) have been determined for different robot positions with the help of the KDL (Kinematics and Dynamic Library) inverse kinematics solver.

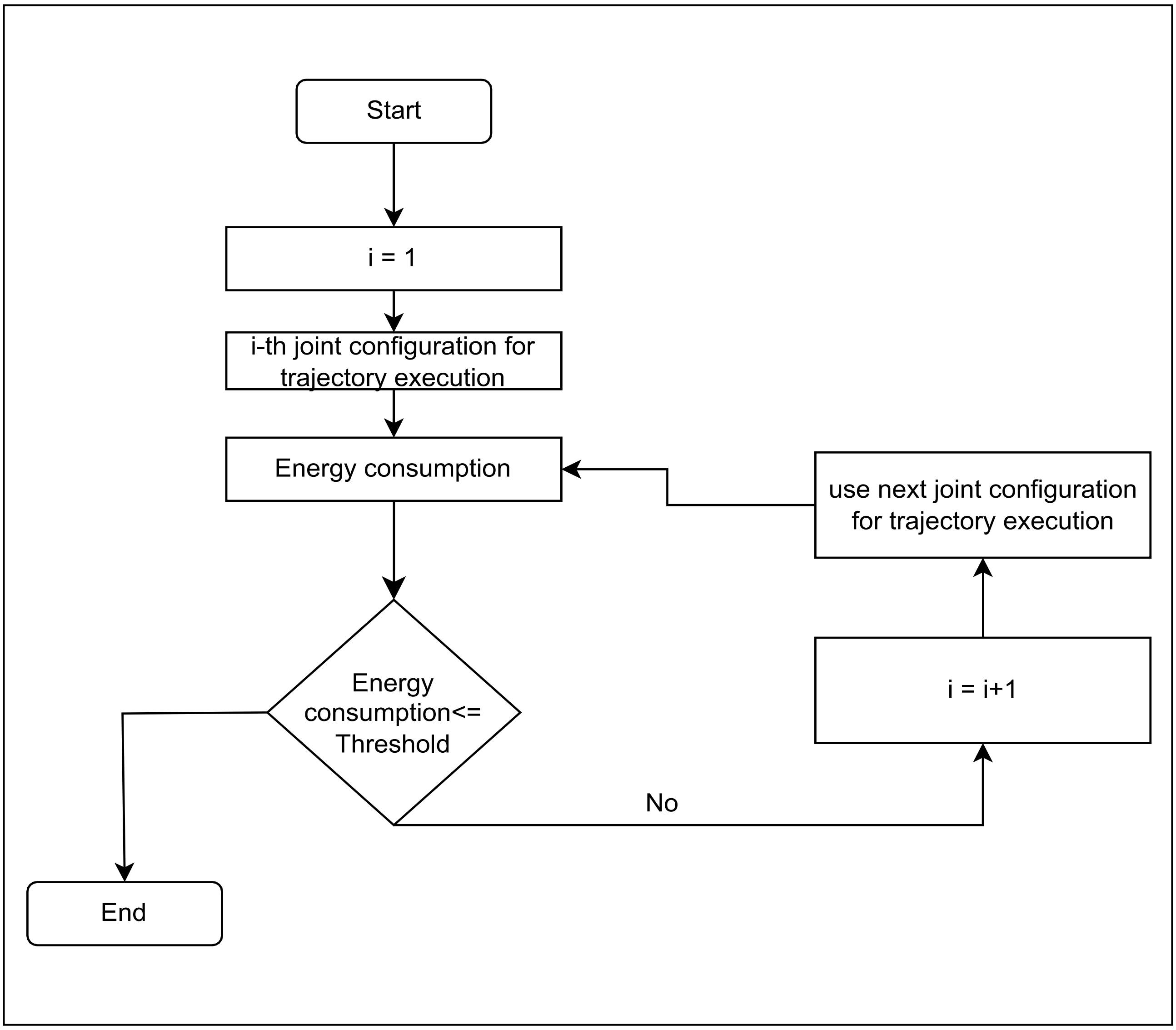

Fig. 3. Energy consumption approach.

The joint configurations are saved in a csv file and then can be used in the forward kinematics Simulink model to compute the mechanical power of the system using Simulink. The joint configuration file will be generated only if the robot position is in the robot workspace and not a singularity. The different joint configurations can be obtained by changing the orientation of the end effector. The csv file can then be used in the forward kinematics model and the energy consumption computed.

For the inverse kinematics model for the robot position, the signal builder block in Simulink is used to set the values of the x, y and z of the robot position. The values are functions of time. The energy consumption gets as well automatically computed.

4. Experiments

The experiments have been executed as shown from the following flow diagram. Fig. 4 shows the interaction between the two software. The following robot poses have been used for testing's sake.

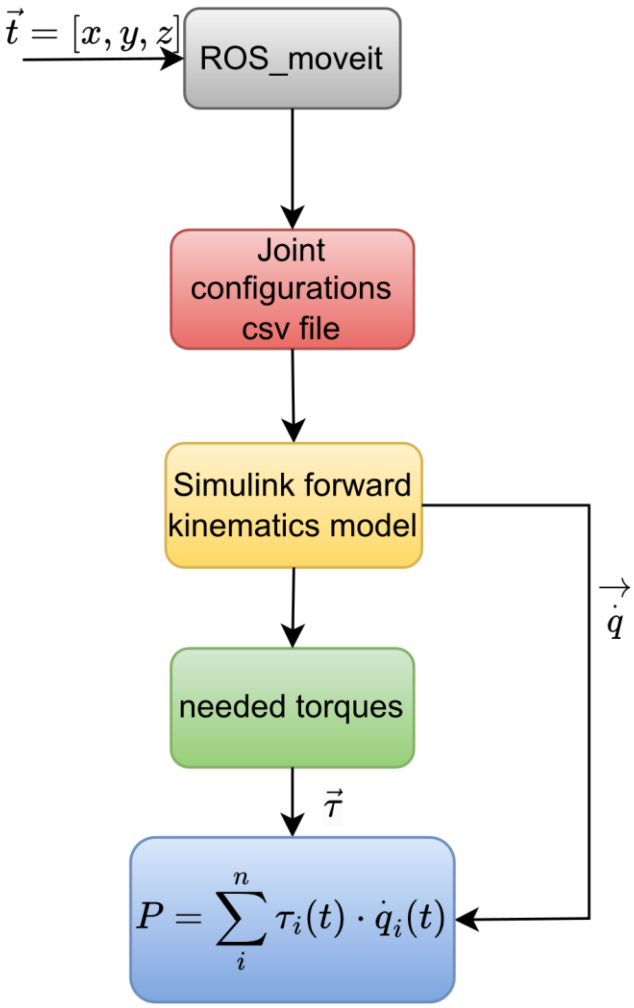

Fig. 4. Flow diagram.

x	*y*	*z*	*roll*	*pith*	*yaw*
-0.7	-0.0124	0.1	-3.14	0.001432	-1.5704
-0.7	-0.0124	0.1	-3.14	0.5158	-1.570
-0.7	-0.0124	0.1	-3.139	0.7908	-1.57
-0.7	-0.0124	0.1	-3.14	-0.5163	-1.57
-0.7	-0.0124	0.1	-3.139	-0.7908	-1.57
-0.7	0.3	0.1	-3.14	0.001432	-1.5704
-0.7	0.3	0.1	-3.14	0.3587	-1.5702
-0.7	0.3	0.1	-3.14	0.515	-1.568
-0.7	0.3	0.1	-3.14	-0.3567	-1.5718
-0.7	0.3	0.1	-3.14	-1.0484	-1.5704
-0.504	-0.2212	0.6	1.5373	1.2967	-2.7858
-0.504	-0.2212	0.6	-3.14	0.5158	-1.5718
-0.504	-0.2212	0.6	-3.14	0.7908	-1.57
-0.504	-0.2212	0.6	-3.14	-0.5163	-1.5718
-0.504	-0.2212	0.6	--3.14	-0.7908	-1.5704

Tab. 1. Test poses.

The x, y and z values are in meters and the roll, pitch, yaw values are in radians (see Table 1.). The 15 robot poses are three different robot positions with five different orientations. This is done to generate different joint configurations. To prevent motion plan errors the robot after each position gets in its home pose with the joint configuration $\vec{q} = [0°, 0°, 0°, 0°, 0°, 0°]$. The robot also starts from the home pose.

q_1	q_2	q_3	q_4	q_5	q_6
-7.12°	34.77°	-2.62°	37.26°	-90°	7.17°
-3.59°	36.33°	-2.64°	40.99°	-60°	4.18°
-2.01°	37.71°	-2.65°	42.19°	-45°	2.71°
-10.56°	34.82°	-2.46°	31.38°	240°	12.03°
-12.04°	35.23°	-1.92°	25.14°	225°	17.02°
-30.63°	41.71°	9.64°	32.01°	-90°	30.69°
-28.69°	42.59°	6.58°	45.85°	-70°	30.36°
-27.81°	43.54°	6.09°	52.23°	-60	31.31°
-32.56°	42.17°	13.19°	17.59°	250°	34.20°
-35.34°	47.68°	26.51°	-23.98°	225°	54.92°
22.38°	2.88°	10.85°	4.16°	0.5°	-3.53°
17.60°	9.178°	35.24°	-35.92°	-60°	-26.74°
19.42°	11.66°	38.89°	-45.94°	-50°	-26.74°
8.85°	2.39°	23.32°	-15.99°	240°	-10.17°
6.94°	0.71°	18.91°	-11.33°	225°	-9.77°

Tab. 2. Joint configurations.

Table 2. shows the solutions of the inverse kinematics. For each joint a trajectory function $q_i(t)$ is defined by an affine linear function which connects every two values after another in the corresponding column, whereby the time interval between two values of each column is $\Delta t = 1.5s$. For the inverse kinematics model, the values of x, y and z of the end effector are as well defined as linear functions as shown in Fig. 5., where the minimum value of z is 0.1.

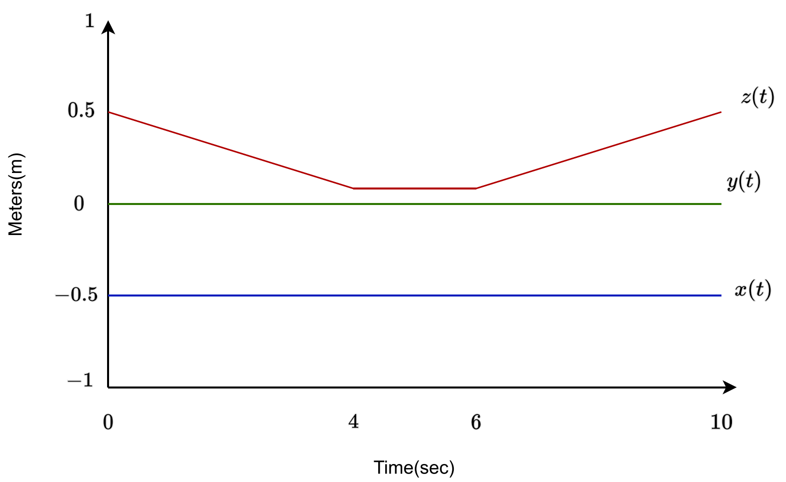

Fig. 5. Flow diagram.

5. Results

The results of the forward kinematics Simulink model are summarized in the following table.

Configuration	Mechanical Power
1	3399.7 W
2	3191.4 W
3	3291.5 W
4	3434.3 W
5	3332.5 W
6	4732.0 W
7	4432.3 W
8	4537.9 W
9	4987.7 W
10	3413.2 W
11	759.3 W
12	1079 W
13	363.25 W
14	1490.6 W
15	1116.5 W

Tab. 3. Joint configuration's power consumption.

Where the i-th configuration refers to the i-th row of Table 2. For the inverse kinematics Simulink model, a total power consumption of 6136.63 W has been calculated.

6. Conclusion and outlook

On the one hand, in this paper the mechanical power consumption of a robot arm has been evaluated, which is generated during the execution of an end effector trajectory. The execution of an end effector trajectory is fundamental for the execution of any industrial task. On the other hand, the evaluation with the considered poses does not consider factors such as printing quality, capability to grasp an object etc. Therefore, the programmer should only consider robot poses which make the task executable and satisfy all engineering quality standards. This is for example the case when an object is 3D-printed several trajectories must be executed. The optimization of the trajectory could lead to a different form which is not desired. The work of this paper gives an awareness of the total energy consumption by the execution of an industrial task.

Future works should consider the integration of this work in flex pendants and existing robot programming software's of companies such as ABB, UR5e, KUKA etc. Other approaches could consider both energy optimization and engineering quality standards of a specific industrial task in order to automize the given approach of this paper.

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