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Energy Model for Motion Planning of 2D-Belt Press Line Tending Robots

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Abstract: A current trend in production is to reduce energy consumption where possible not only to lower the cost but also to be a more energy efficient entity. This paper presents an energy model to estimate the electrical energy consumption of 2D-belt robots used for material handling in multi-stage sheet metal press lines. An estimation of the energy consumption is computed by the proposed energy model based on the robot components' specifications, the robot path and trajectory. The proposed model can predict the energy consumption offline by simulation, and thus, before installation, avoiding the need for physical experiments. It is demonstrated that it can be used for predicting potential energy reductions achieved by optimising the motion planning. Additionally, it is also shown how to investigate the energy saving achieved by using mechanical brakes when the robot is idle. This effectively illustrates the usefulness of the proposed energy model.

Keywords: Robotics, Motion Planning, Material Handling, Energy Modelling, Optimisation

1 Introduction

Energy conservation is a key aspect towards sustainability and is conducted both in research and industry [1]. New techniques are continuously being formulated to keep up with ever increasing demands. Considering press lines in the automotive industry, mass production defines the industry itself. To be able to produce in large volumes efficient and error-free methodologies are necessary. A simulation based method were used in previous research work to ensure optimal production rate and collision-free operation [2]. The main optimisation objectives were production rate and wear. However, with an increasing impetus on energy in today's industry there also exists a need to predict and optimise energy consumption. While simulation models are used to optimise specific engineering characteristics of a press station(s), there exists a need to predict, understand and minimise the energy consumption of the robots.

The contribution of this paper is the proposed energy model for 2D-belt robots that are used for multi-robot material handling in multi-stage sheet metal press lines. The presented experimental validation shows that the proposed model's energy consumption estimations are reliable. The usefulness of the proposed model is demonstrated in three different ways. Firstly, it can be used for optimising the motion planning of multi-robot systems in order to find energy optimal motions for tasks with predefined cycle-time. Secondly, when considering the estimated energy consumption by the proposed model as a second objective next to the press line's cycle-time, the set of optimal trade-off solutions for these two objectives can be found by Pareto-based multi-objective optimisation of the press line's motion planning. This is demonstrated for the press line tending case study. Thirdly, it can be used during simulation studies to quantitatively evaluate and analyse specific changes or upgrades for the robots or system. This is demonstrated in this work for upgrading the 2D-belt robots with a mechanical brake to lock the robots' pose when idle.

2 Background

This section highlights existing energy models for industrial robots and other material handling devices such as conveyors, and how these models can be combined effectively with a simulation model to predict the energy consumption of 2D-belt robots working in tandem.

2.1 Physical Models

To optimise the operating efficiency of belt conveyers' models for energy calculation is a necessity [3]. Zhang and Xia [3] investigate two existing energy calculation models; one based on resistance calculation methodology and the other based on energy conversion methodology.

2.1.1 Resistance calculation methodology

Consider a belt conveyer. The energy consumed by the belt conveyer is determined mainly by the motion resistance in the loaded section of the belt and the return belt. In this method, belt resistances are divided into primary and secondary resistances. Primary resistance is the sum of all the friction related resistances, excluding special resistances. Secondary resistances include friction or inertia resistances which could occur only at certain parts of the belt. The total power is obtained as a function of the total resistance which is the sum of the primary resistance, secondary resistance and all other special resistances being considered.

2.1.2 Energy conversion methodology

Zhang and Xia [3] consider power of the belt conveyor under stationary condition as a sum of the following elements along with accessories obtained through special resistances: the power to run the empty conveyer, the power to move material horizontally over a certain distance, and the power to lift material a certain height.

2.1.3 Zhang and Xia's modified Energy Calculation Model

While the resistance calculation model is more accurate when compared to the energy conversion model, since the former considers all problems contributing to total energy consumption, the energy conversion model simplify energy calculation by introducing empirical compensation length constants into its model. This could however not compensate for some energy calculation errors which occur since one or few compensation length constants are used to satisfy all cases. Zhang and Xia's [3] modified Energy Calculation Model follows the basic structure of the two methodologies mentioned above but are characterised by two compensation length variables, one compensation length variable for the power to run the empty conveyer, and the other for the power to lift material a certain height. This makes sure all energy calculation errors, if any, are considered when calculating the power of the belt conveyer under stationary condition.

2.2 Energy Team

A 95% share of work in the body shop in the automobile industry is carried out by robotic-related applications. A slight improvement in the efficiency of these systems could yield in significant CO_2 and energy reduction in the whole production [4]. Meike and Ribickis [4] evaluate the option of a capacitive energy buffer on the robot's DC-bus and propose an approach, the robot *EnergyTeam* to support the need to reduce energy consumption. Several robot programs mocking typical welding and handling applications were run. The recuperated energy was to effectively reuse to cope up with the constant charging and discharging due to numerous acceleration and deceleration phases during welding. The handling applications which had long movements between process points consumed the most energy but also showed the largest savings. Meike and Ribickis [4] inferred that the robot in a body shop usually spent less time in movement, thus the capacitive bank of a single robot being used only $1/3^{rd}$ of the available time. It was proposed to share a capacitive energy buffer among several robots. The energy flow is directed to and from the robots. There exist two implementation options. The first one being for a single centralised rectifier and multiple robots, and the second implementation is for several decentralised rectifiers and several robots. The first option would require in-depth production planning so as to estimate the power required for the entire DC network. The second approach aims to use the robot individually or connect them to the *EnergyTeam* to exchange the excess energy. In this way, there is an energy exchange only when the system requires it.

2.2.1 Based on a combination of multiple robots

Meike et al. [5] propose a model to increase the energy efficiency of multi-robot production lines in the automotive industry. The model proposed involves a methodology which is a hybrid of the methodologies proposed in [4] and [6]. Meike et al. [5] propose an energy consumption optimisation method for production systems with multiple robots. The proposed method involves time delays of the release of mechanical brakes and time scaling of the robots' motion from the last process point to the home position(s), of which the time scaling approach is similar to the one followed by Pellicciari et al. [6]. In simpler terms, the model aims to capture the dependency of energy consumption on the release time of mechanical brakes and the task execution time. Energy simulation, based on these results, suggests that execution time for a robot task is usually not synchronised with the other robots in the cell. Moreover, there are different energy consumption rates when the robot is in standstill in its home position with unreleased brakes and when it is in its home position with released brakes. These idle times are used to significantly reduce the energy consumption keeping intact the robot dynamics limitations, cycle times and production constraints.

2.3 Robot Trajectory Optimisation

Hansen et al. [7] propose an energy trajectory optimisation method for multi-axis manipulators which employs an electrical exchange through a shared inverter DC link. The approach presented by Hansen et al. is transferable to any kind of multi-axis system which consists of a DC link energy supply. The resulting system consists of a rotational axis and a linear belt drive which moves a variable load and also comprised of a coupled DC link in the servo-inverters. Identical servo-drive components (namely synchronous motors and power inverters) were attached to both axes. The trajectory optimisation approach involved formulating the optimisation problem, defining a path planning method and all associated optimisation parameters and finally defining a scalar cost function for minimisation when the optimisation approach is being applied.

The cost function is said to comprise of a bidirectional energy flow model taking into account all the energy losses as well as the possibility of electrical energy storage and exchange via internal DC link of servo-inverters. The trajectory optimisation approach is validated by comparing measurements and simulation results. Three trajectory scenarios are chosen to investigate the minimum energy optimisation approach. The tests suggest that the total energy losses were reduced for all examined trajectories. Thus, a reduction in cost function always leads to reduced energy supply. Furthermore, the exchange of electrical energy was amplified in most cases. Thus, energy surpluses were reduced. The cost reduction was highest when both axes exhibit distinct motor and generator phases during movement.

Riazi et al. [8] also propose an optimisation algorithm to reduce energy consumption of an industrial multi-robot system. Contrary to Paryanto et al. [9] who identified production planning, commissioning process and process optimisation as the categories on which increasing the energy efficiency of robot systems are based on, Riazi et al. [8] figured out that these would involve changing the configuration of an existing plant. The method proposed in [8] allows for energy optimisation of existing plants without much/any change in their configuration which would affect the production rate. Path of a trajectory is defined by a sequence of poses which a trajectory follows, without including the time instance when a pose is reached [8]. Riazi et al. [8] aimed to find new trajectories with the same path which could schedule the robot motions and also minimise the energy consumption of motions. The proposed optimisation model uses a simple minimisation criterion using a function of squared joints' acceleration. The model uses the original robot trajectory from an actual robotic system as its input and the cost function is minimised by a non-linear programming solver. The essential requirement of the proposed solution is the need to preserve the path. Thus, to satisfy this need, the solution must make sure that the sequence of poses is followed. Therefore, the sequence is the fixed input and the time taken to move between poses is the degree of freedom. The results show potential energy savings up to 45%. Glorieux et al. [10] have adopted this for both cycle-time and energy-optimisation for the press line tending robot trajectories in multi-stage sheet metal press lines. However, this does not exploit the opportunity to re-plan the robot paths in order to achieve further energy savings.

2.3.1 Measure power with good repeatability

Chemnitz et al. [1] consider two similar industrial robots and propose a method to prove that power is measurable with good repeatability by varying the velocity and acceleration of the robot based on a selected motion pattern. The industrial robots considered vary in their age, the Kuka built in 2000 and the Comau built in 2007. The experiment is executed with differing acceleration and velocity. From the experiments it was inferred that the slow motions consumed more energy than the fast the ones, the main reason being the execution time for the slow motion is 10 times more than the time of the fast ones. Quadratic polynomial approximation is used since it fit well when compared to a linear approximation. If the motion lasted longer than the reference motion the power consumed is unchanged. Idling does not have any influence in the calculation regardless of the velocity of motion or the manufacturer of the robot. Very slow or very fast motions consumed the most energy. The tests also confirmed that the Comau robot could save energy if it moved slowly, using all the available time while the Kuka saved more energy if it moved fast and waited. The results could also conclude that even though the robots had similar specifications, the difference in the power consumptions was at least a factor of two. One valid reason for this was the difference in their ages. The payload was not taken into account to highlight the difference in power consumed.

2.3.2 Minimal Touch Approach

Pellicciari et al. [6] focus on energy loss minimisation for pick and place manipulators by means of a *minimal touch* approach. An engineering method was proposed to optimise energy consumption of robotic systems, applicable to both series and parallel manipulators whose dynamic models are known. Most energy minimisation methods described in literature rely on considerable modifications to existing plant or equipment selection or path planning. This can be adopted only in an entirely new plant design process. Pellicciari et al. [6] aim to vary only the task execution time, assuming all other electromechanical system characteristics are given (i.e. no additional costs are expected).

In some scheduling optimisation methods, it is assumed that robots operate at maximum speed when permitted by the scheduling constraints and otherwise are idle [11,12]. This leads to accelerations which require high power and that the excess energy is wasted in counteracting gravitational loads. An energy optimal trajectory was determined by means of time-scaling. This is done by slowing down the operation and also reducing the manipulator idle times. An energy loss ratio of energy loss related to scaled and time-optimal trajectory was formulated. The approach is tested on an industrial robot, carrying out cyclic pick and place operation. The results thus obtained, permit to parametrise and adjust manipulator operation so as to minimise energy consumption, provided the scheduling or manufacturing constraints permit these changes.

3 Problem Statement

The presented work in this paper is concerned with how to model the energy consumption of 2D-belt robots in order to consider the trade-off between energy consumption and cycle-time during the motion planning optimisation for multi-robot material handling systems. The motivation for this is enabling to take into account the energy consumption offline during simulation-based motion planning. This provides 'right-first-time' capabilities for energy minimal motion planning of 2D-belt robots. This is done in this work in the specific context of 2D-belt robots using in the multi-robot system for material handling in multi-stage tandem press-line for stamping sheet metal parts. The energy consumption of 2D-belt robots is determined by the following aspects:

1. Design of the robot links
2. Design of the drivetrain
3. Design of the end-effector
4. Motion planning: path and trajectory

The focus in this work is on the fourth aspect in the above list, i.e. the relationship of how the robot path and trajectory to complete its assigned task influences its energy consumption. For clarity, the term *path* is used to refer to the route the robot follows through the workspace and the term *trajectory* refers to the velocities and accelerations of the robot when moving along the path. The robot path and trajectory are determined by the motion planning parameters, such as the start and goal positions as well as the velocity scaling factors.

In the earlier work by Glorieux et al. [16], it was shown that the multi-robot motion planning for material handling in multi-stage press lines is one of the main aspects that determines the cycle-time as well as the wear of the robots' components, and thereby thus, the press line's productivity. This indicates that there typically will be specific constraints concerning cycle-time and robot wear, and these will restrict the degree-of-freedom for adjusting the motion planning to reduce the robots' energy consumption. Furthermore, it can thus be concluded that the energy consumption model needs to be designed such that it can be integrated within the existing cycle-time and robot wear models. These existing models include the relationship to obtain the robot path/trajectory based on the motion planning parameters that can be tuned [2]. This has been re-used in this work in order to guarantee compatibility for integrating the proposed energy model. The resulting problem that is addressed in this paper is how to model the energy consumption based on the robot path/trajectory i.e. path, velocity and acceleration.

4 Case Study – Sheet Metal Press Lines

A sheet metal press line typically includes several press stations, as shown in *Figure 1*. Each press station consists of a press and a downstream robot (which loads plates onto the press). Each station has its own control system taking care of that part of the press line. These individual control systems communicate with each other and thereby handle the interaction between the press stations. The control parameters per station are specific for each product. The robot motions are divided into different segments, each segment being dedicated to a specific operation such as loading plates, unloading plates, moving between presses etc. To start the motion of a specific segment, a robot would receive a specific start-signal form another press or robot in the press line. This holds true for the press stroke operation as well. These start-signals, and thus the synchronisation is position-based.

To achieve collision-free time/energy minimal operation of the press line, optimally synchronised robot trajectories and position-based synchronisations are necessary. Robot velocities, robot paths, the start-signals for robot operations and press stroke constitute the control parameters. These must be tuned specifically to suit each station since the shape of the dies, grippers and plates vary. This also aids in avoiding collisions, which is absolutely necessary. The production rate of the line is affected by these parameters to a large extent. Badly tuned parameters will lead to a lower production rate and excessive wear of equipment. Optimising these parameters would give the industry monetary benefits.

Figure 1 illustrates the considered (tandem) press line. Products move through the line from left to right. A specialised 2D-belt robot is used in the considered press line as shown in *Figure 2*. The robot is placed between two presses and is responsible for unloading the downstream press and loading the upstream press. The plates are placed on the intermediate table prior to loading them on to the upstream press in the next cycle. If necessary, the fixtures on these tables can reorient the products. The tool mounted on the 2D-belt robot has two grippers, one on each side of the stream of the press line, as shown in *Figure 2*. In this way, it can pick up or place two products at the same time. The tool, thus, can pick up the pressed product from the downstream press and the product from the intermediate table. This allows the robot to unload the downstream press and load the upstream press in one motion. This leads to the presence of strong interactions between the different press stations which make the synchronizations of the operations absolutely essential so as to avoid collisions and have a high production rate.

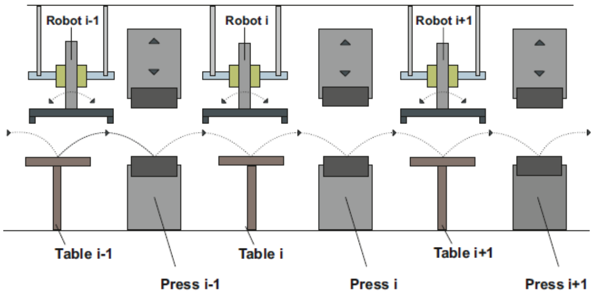

Figure 1: Illustration of tandem sheet metal press line

The energy consumption of the press line tending robots, and thereby any energy savings, could be considered insignificantly small relative to the energy consumption of the stamping presses. However, in absolute terms, the robots' energy consumption rapidly becomes significant for the press line tending robot case study considering there are up to six robots in a press line, for multiple press line in a press shop, and there is nearly no down-time (i.e. in operation three shift per day, seven days of the week). Regardless, working towards accomplishing savings in the robots' energy consumption is relevant, particularly when there is no compromise in terms of productivity (i.e. cycle-time and robot component wear) because in this case the saved energy consumption of the robots is a reduction of non-value adding costs.

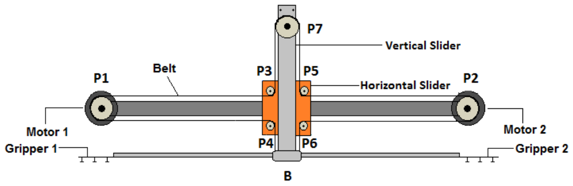

Figure 2: Illustration of considered 2D-belt robot

5 Energy Model Formulation

Consider the 2D-belt robot from *Figure 2*. The robot has a vertical slider, a horizontal slider and two motors (i.e. Motor 1 and Motor 2). A time synchronous belt rolls over pulleys P1, P2, P3, P4, P5 and P6. The vertical slider moves upwards and downwards while the horizontal slider moves left and right. For the considered 2D-belt robot, the two motors are identical permanent magnet synchronous AC motors. To be able to optimise the energy a robot model must be formulated. The input to the model is the robot's trajectory.

The model is based on the torque load for each motor to estimate the power, as in the work by Berselli et al. [14], according to the following formula

$$P_t = \sum_{m=1}^{2} \frac{R \cdot \tau_m^2}{K_t^2} + \frac{\omega_m \cdot K_r \cdot \tau_m}{K_t} \qquad (1)$$

where P_t is the total electrical power of the motor, τ_m is the torque load on motor m, R is the electrical resistance, K_r is the back-emf constant, and K_t is the torque constant and ω_m is the angular velocity of motor m. To calculate the torque of motor, the torque was considered as the sum of the torque from vertical slider's movements(τ_1), torque from the horizontal slider's movements (τ_2), torque from the motor/gear/pulleys inertia (τ_3), and the torque resulting from friction during the horizontal slider's movements (τ_4):

$$\tau_m = \tau_1 + \tau_2 + \tau_3 + \tau_4 \qquad (2)$$

The torque of the vertical slider's movements is calculated as following

$$\tau_1 = \frac{\frac{m_{vsp}}{2} \cdot \left(a_y^{tcp} + g\right) \cdot r_{p1}}{i} \qquad (3)$$

where m_{vsp} is the mass of the vertical slider, a_y^{tcp} is the vertical acceleration of the robot's TCP, g is the gravitational acceleration, r_{p1} is the radius of Pulley 1, and i is the gear factor. The torque of the horizontal slider's movements is calculated as follows

$$\tau_2 = \frac{(m_{vsp} + m_{hsp}) \cdot a_x^{tcp} \cdot r_{p1}}{i} \qquad (4)$$

where m_{hsp} is the mass of the horizontal slider, and a_x^{tcp} is the horizontal acceleration of the robot's TCP.

The torque resulting of the motor's and gear's inertia is calculated as follows

$$\tau_3 = \dot{\omega}_m \cdot \left(J_{motor} + J_{gear} + \frac{J_{pulleys}}{i}\right) \qquad (5)$$

where $\dot{\omega}_m$ is the angular acceleration of the motor, and J_{motor}, J_{gear} and $J_{pulleys}$ are the inertia of the motor, gear and the pulleys, respectively.

The torque of the friction of the horizontal sliders movements is calculated as follows

$$\tau_4 = \frac{\mu \cdot (m_{hsp} + m_{vsp}) \cdot (g + a_y^{tcp}) \cdot r_{p1}}{i} \qquad (6)$$

where μ is the friction factor.

6 Experimental Validation Energy Model

For the first assessment, an experimental validation of the proposed energy model was performed to evaluate its accuracy for estimating the energy consumption of the 2D-belt robot.

6.1 Experimental Set-up

The experimental setup consisted of a computer with necessary hardware and software, a *Chauvin Arnoux C.A 8335* wattmeter, used to measure the energy consumed, two *SEW Eurodrive* servo-drives and a 2D-belt robot. The 2D-belt robot is a *Binar UniFeeder* robot [14] for press lines; in this work a smaller model was used. The wattmeter was connected to the input cables to the servo-drive. Two tests were carried out to validate the proposed energy model, constant velocity test and variable velocity test. The pick and place operation of the robot was divided into 4 segments:

1. Home to Pick,
2. Pick to Wait,
3. Wait to Leave ,
4. Leave to Home,

as shown in *Figure 3*. The velocity of the robot motion was then varied for each segment specifically depending on the test being performed. The input trajectories to the energy model calculations for these specific tests are generated with the simulation model of the 2D-belt robot's controller proposed by Glorieux et al. [2, 13]. The tests were not repeated because it was found that the variation over several repetitions is insignificant for the performed comparison. This work does not consider the energy losses in the servo-drive (rectifier and invertor) and the servo-motor.

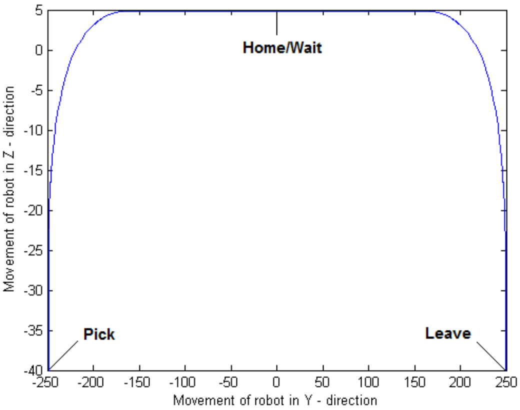

Figure 3: Illustration of the robot trajectory and the 4 robot segments

6.2 Results and Discussion

Tests with constant velocities were conducted. The velocities chosen for these tests were 12%, 20%, 35%, 50%, 80% and 100% of the maximum velocity of the robot. The velocities were chosen in such a way that the test could investigate the variation in energy consumed for very slow, very fast and intermediate velocities.

Comparing the results for calculated energy consumption with the measured energy consumption in *Figure 5*, it can be concluded that the modelled curve and the experimental curve have similar profiles. The deviation between the modelled and experimental results is reasonable considering the losses of the servo-drive and the servo-motor, and also bearing friction are not taken into account. This thus confirms that the energy model holds true and can be used to predict the energy consumption of a 2D-belt robot working at various velocities, though there is a constant underestimation of the absolute energy consumption value that was measured. However, since the main purpose is to minimise energy consumption the absolute value is of less importance.

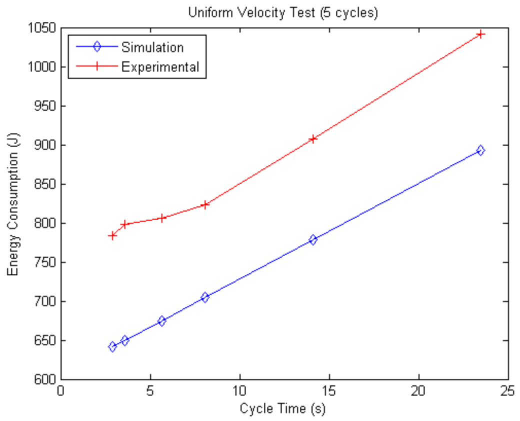

Figure 4: Plot illustrating the simulated and experimental energy consumption results for six different robot velocities, i.e. 12%, 20%, 35%, 50%, 80% and 100% of the maximum velocity.

7 Optimisation Model for Multi-Robot Material Handling in Multi-Stage Press Line

The next investigations are based around simulation studies using the proposed energy model during the motion planning optimisation of the multi-robot systems for the material handling in the multi-stage press line in the considered case study. This section describes the used model for the trajectory generation of the robots and the multi-robot coordination for those robots that operate simultaneously in a shared workspace. In total, the considered press line includes five presses and six material handling 2D-belt robots.

The input for the optimisation model are the optimisation variables for generating the robot path and trajectories according to the robot control system. The model then outputs the cycle-time for the entire press line, and also the generated paths and trajectories for the robots. The latter can then be used by the proposed energy model to estimate the energy consumption of the robots in the considered system.

It includes three different submodules that are stepwise executed. The first submodule generates the robot paths according to the provided optimisation variables, and the second submodule creates the speeds and accelerations for the trajectory to follow the previously created path. The third and final submodule calculates the timings for the multi-robot coordination between the material handling press tending robots and the presses, in order to avoid collisions. Based on the multi-robot coordination, the cycle-time of the entire press line is then also calculated for the function evaluation value of the optimisation.

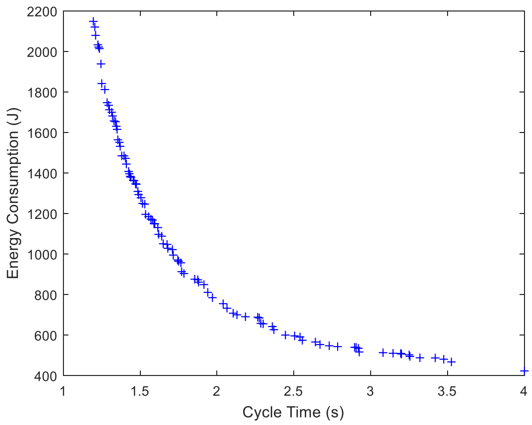

Figure 5: Pareto-front showing the trade-off between cycle-time and robots' energy-consumption, obtained by multi-objective optimisation of robot trajectories and multi-robot coordination, using the proposed energy model

The implementation of the optimisation model is based directly on the control code for the Programmable Logic Controllers used for a real-world press line in the automotive industry. It has been verified against measured motions of the robots and presses in the real-world press line. A detailed description of the optimisation model is presented in earlier work by Glorieux et al. [2].

From previous work on energy optimisation and multi-robot motion planning [8], it has been shown that the available cycle-time for the robot motion is a determining factor for the minimal energy consumption. In multi-robot systems, the available cycle-time for each of the robot motions is determined by the timings for the multi-robot coordination. It therefore was found relevant to investigate multi-disciplinary optimisation of robot trajectories while taking into account both the multi-robot coordination and the robots' energy consumption.

In several of the performed investigations, the motions of the material handling robots in the multi-stage tandem press line from the case study are optimised while considering the coordination between the robots and the presses, and also the energy consumption of these material handling robots. In order to guarantee a certain productivity for the press line, a penalty constraint is introduced in the optimisation model that ensures that the cycle-time for the press line is within a certain desired range, i.e. ± 0.1 seconds in this study. When the cycle-time is outside of the allowed range, the constraint assigns a large penalty value to the objective value in order to indicate that the solution is infeasible. This type of constraint is something called $\varepsilon -$*constraint scalarisation* for multiple objective optimisation [15]. The objective for the optimisation is minimising the energy consumption of the material handling robots. For other investigation, the press line's cycle-time and the robots' energy consumption are considered separately as objectives.

8 Simulation Studies

This section presents the two simulation studies that have been performed to evaluate the proposed energy model and demonstrate its potential usages. The first study demonstrates how the proposed energy model can be used for optimising the motion planning and coordination in multi-robot systems, such as the multi-stage sheet metal press lines. For this, the proposed energy model needs to be integrated in the motion planning optimisation model, and be considered in constraints or the objective function. This consequently allows the optimisation to consider the robots' energy consumption, e.g. as an objective and/or in constraint functions. When two objectives (i.e. cycle-time and energy) are taken into account during Pareto-based multi-objective optimisation, the optimal robot motion parameters for the possible trade-offs between these objectives can be discovered. The presented simulation study demonstrates this for the considered sheet metal press line.

The second simulation study evaluates the use of a mechanical brake to lock the robot's pose when it is idle in order to reduce the energy consumption. This demonstrates the type of quantitative investigations and analyses that can be done in advance by using the proposed energy model in order to evaluate specific changes or upgrades for the 2D-belt robots. The mechanical brake investigation is extended to the entire multi-robot material handling in the considered press line. By integrating the proposed energy model in the optimisation model as discussed earlier, the robots' energy consumption can be considered when optimising the motion planning together with the multi-robot coordination.

8.1 Multi-Objective Optimisation

The first simulation concerns the optimisation of the robot trajectories and the multi-robot coordination. The focus is on analysing the optimal solutions for the different trade-offs between cycle-time of the system and the energy consumption of the robots. The algorithm used for the multi-objective optimisation is the $^{mo}C^3DE$ proposed by Glorieux et al. [16], since it has been shown to be very effective for optimising large-scale non-fully separable optimisation problems, such as trajectory and coordination optimisation for multi-robot systems. The termination criterion for the optimisation was 50,000 function evaluations, where each function evaluation refers to one execution of the motion planning model to evaluate the provided set of optimisation variables by the optimiser.

The result of a multi-objective optimisation with the $^{mo}C^3$ algorithm is a Pareto-front, showing the optimal solutions for the different trade-offs between the considered objectives. Such a Pareto-front obtained from multi-objective optimisation of the trajectories and multi-robot coordination of the tandem press line considered in the case study is shown in the *Figure 5*. The minimum cycle-time for the press line is 1.195 seconds, which corresponds to the duration of the press stamping stroke. In other words, for the solution that gives the shortest cycle-time for the press line, the presses start the next stamping stroke directly after completing the previous one. The press line tending robots unload the stamped plate and load a new plate while the press is opening and closing. This can be seen clearly in the time-schedule for this solution, which is shown in *Figure 6*. The coloured bars in the time-schedule diagram indicate in time when a robot is idle (i.e. white) and when moves (blue for unloading and yellow for loading). The time-schedule diagram also shows whether a press is idle (i.e. white) or performing its stamping motion (i.e. blue). In *Figure 6*, the time-schedule for two cycles of the press line are shown.

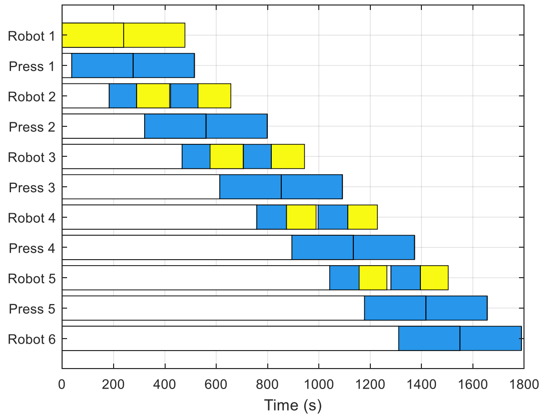

Figure 6: Time schedule for material handling robots and presses in multi-stage tandem press line with fastest cycle-time (1.195 s)

The solutions on the other side of the Pareto-front show the energy optimal solution for material handling robots in the multi-stage press line of the considered case study. The cycle-time for this solution is 4.0 seconds. For this solution, the presses are idle for a certain amount of time between the strokes in order to provide enough time for the energy-optimal robot motions to unload and load the plates from the press. These idle times for the press can be seen in the time-schedule for this solution that is shown in *Figure 7*.

This demonstrates that including an energy model in the multi-robot motion planning optimisation model enables to co-adapt the multi-robot coordination to facilitate the energy-optimal motions for the robots for collision-free operation of the system.

8.2 Mechanical Brake – Single Robot

Further, with the proposed energy model, it was possible to predict the potential energy saving that can be achieved by using mechanical brakes when the robot is idle. This would avoid the energy consumption to hold the vertical slider and the tools. The energy consumption for this scenario was calculated with the proposed energy model. From these calculations, it was calculated that approximately 32 J/s can be saved when the mechanical brakes are used during idle-times for the used 2D-belt robot.

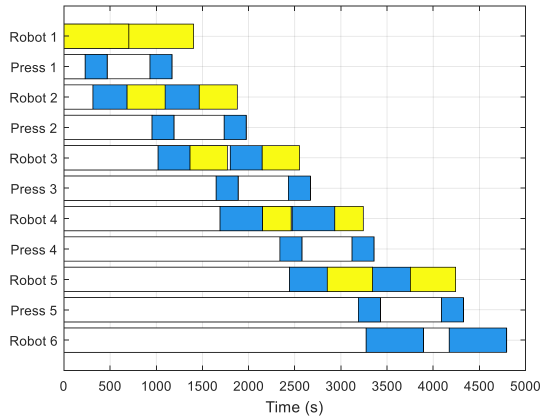

Figure 7: Time schedule for material handling robots and presses in multi-stage tandem press line with energy-optimal cycle-time (4.0 s)

This means, when the robot is moved at higher velocities, a large amount of energy is consumed to slow down the robot and hold it for a long time in a standstill position. The right balance can be obtained between idling and high velocity motions during a production process to increase energy savings. The role of mechanical brakes while standing still could further enhance the use of the proposed energy model. In some cases, during a continuous production process, if a robot moves quickly to complete its operation and spends much of the cycle time idling, a lot of energy can be consumed. The energy model can then be used to modify the planned trajectory to minimise the robot's energy consumption. Energy minimisation could be achieved in multiple ways; (1) if a robot moves slowly using up much of its idle time or (2) the robot moves quickly and prefers to stay idle [1]. Such scenarios can be evaluated using the simulation energy model.

8.3 Mechanical Brake – Multi-Robot Systems

This section presents how the proposed model can be used to investigate the potential saving by using a mechanical brake for the 2D-belt robots, and how it affects the motion planning and coordination of multi-robot systems. As a case study, the multi-robot material handling for a multi-stage sheet metal press line will be considered.

For this investigation, the motion planning is optimised using a single-objective function to minimise the robots' energy consumption. Furthermore, the aforementioned penalty constraint for the *$\varepsilon -$constraint scalarisation* to ensure a predefined cycle-time for the press line is used in the optimisation model. The motion planning optimisation is done for 12 different predefined cycle-times, i.e. 1.195, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 3.00, 3.50, 4.00, 4.50, 5.00 seconds. This set of motion planning optimisations are performed twice, once considering robots without a mechanical brake and once for robots with a mechanical brake. The results will provide data for comparing robots with mechanical brakes against robots without mechanical brakes. Note that some of these results were obtained from the resulting Pareto-front by multi-objective optimisation with the ${}^{mo}C^{3}$ algorithm (for cycle-time of 3.5 s and below), others (for cycle-time above 3.5 s) that are not on the Pareto-front by single objective optimisation with the $C^{3i}DE$ algorithm proposed by Glorieux et al. [17,18]. It is also important to note that, since these optimisation algorithms are stochastic, each motion planning optimisation was repeated 10 times in order to get statistically reliable results.

The mean and standard deviation (i.e. error bars) values for the robots' minimal energy consumption for the range of predefined cycle-times are presented in *Table 1*. The results are also plotted against each other in *Figure 8*, to compare the different trends with and without mechanical brakes.

Table 1: Results motion planning optimisation

cycle-time	*energy without brake*		*energy with brake*		*Diff*
seconds	*Mean*	*std*	*mean*	*std*	*%*
1.195	2220	77	2252	79	+1.4
1.25	1970	55	1986	78	+0.8
1.50	1381	34	1345	37	-2.6
1.75	1088	56	1017	37	-6.6
2.00	886	101	809	30	-8.63
2.25	720	40	716	30	-0.5
2.50	639	30	644	28	+0.9
3.00	591	13	559	24	-5.4
3.50	585	22	510	24	-12.8
4.00	588	27	423	0.3	-28.0
4.50	635	24	423	0.3	-33.3
5.00	980	47	423	0.3	-56.4

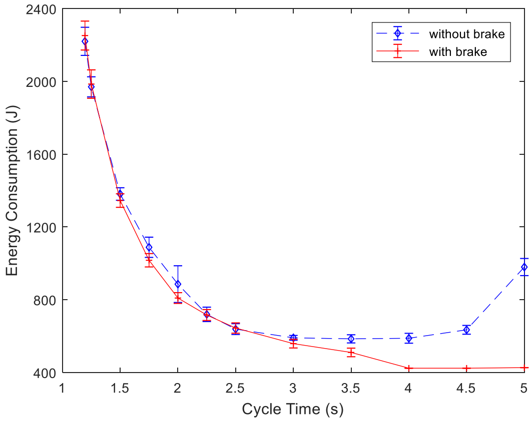

Figure 8: Results minimum energy consumption for different predefined cycle-times

From the presented results, it can be seen that for the short cycle-times (i.e. 1.195 to 2.5 s), there mostly is no significant difference in energy-consumption when using mechanical brakes compared to using no brakes. As discussed earlier, for solutions with a short cycle-time for the press line, the robots (and presses) are almost never idle. The time-schedule in *Figure 6* clearly shows this phenomenon. It can thus be concluded that this is the reason why using robots with a mechanical brake for short cycle-time solutions does not give a reduction in energy-consumption.

For the longer cycle-times (i.e. 3.0 to 5.0 s), the results show a significant reduction in energy consumption when using robots that have a mechanical brake. In Table 2, it can be seen that the reduction for the robots' energy consumption is between -5.4% for 3.0 s cycle-time and goes up to -56.4% for 5.0 s cycle-time. It is particularly interesting to see that for the cycle-times of 4 s and above, the robots' energy consumption remains the same when using mechanical brakes. This indicates that the robot motions for these three cycle-times are the same, and the only difference is that these solutions include longer idle times for the robots. This was confirmed when the time-schedules were analysed.

The difference between with and without mechanical brake was investigated for the solutions with a cycle-time of 5 s, since 56.4% is a remarkably large difference. The time-schedule for these solutions without and with mechanical brake are shown in *Figure 9* and *10*, respectively. When comparing the two time-schedules, it can be seen that the duration of the robot motions is longer without mechanical brakes (*Figure 9*) compared to with mechanical brakes (*Figure 10*). This indicates that without mechanical brakes slower motions have a lower energy consumption compared to faster motions plus idle time. However, these slower motions do still have a higher energy consumption compared to the energy optimal faster motions excluding the idle time, i.e. the robot motions with mechanical brakes shown in *Figure 10*.

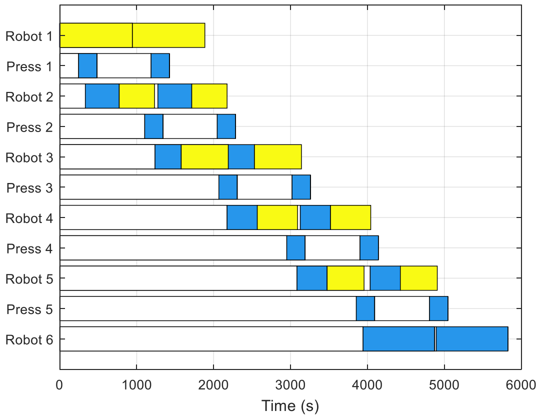

Figure 9: Time-schedule for optimal trajectories and multi-robot coordination for press line tending using robots without brake and cycle-time 5.0 s

These results and conclusions are of course specific for the considered case study for the multi-stage sheet metal press line. However, what is relevant for the work presented in this paper, is that these conclusions demonstrate the usefulness and relevance of using the proposed energy model during the motion planning of similar multi-robot systems as the material handling in the press line. It enables considering the robots' energy consumption during the multi-robot motion planning to quantitatively evaluate the potential energy savings by using robots with mechanical brakes. The proposed energy model for 2D-belt robots can be further extended in order to incorporate the usage of multiple robots together as energy buffers, as proposed in earlier research works [4-6]. It is then possible to evaluate the concepts proposed in these works for the considered press line.

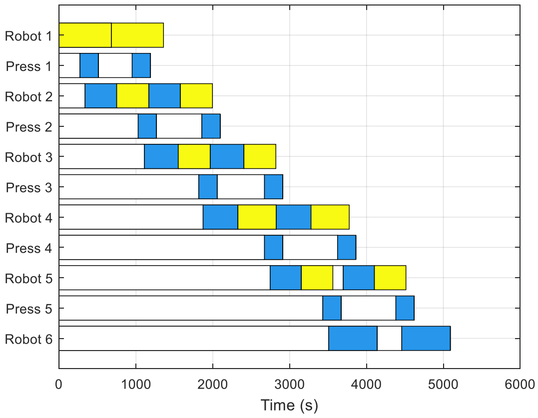

Figure 10: Time-schedule for optimal trajectories and multi-robot coordination for press line tending using robots with brake and cycle-time 5.0 s

Another example of a similar possible investigation that is enabled by the proposed energy model is to evaluate different materials for the gripper of the 2D-belt robot. When the grippers mounted to the 2D-belt robot have a smaller mass, the energy consumption of the robots will be lower. Using the proposed energy model, one can evaluate the lower energy cost against the extra cost for grippers made of lighter materials [19] and could consequently be used to consider energy consumption during multi-disciplinary gripper design optimisation and multi-robot motion planning [20]. It should be noted that making changes to the design of the grippers should be done with caution as it has been shown that the gripper design not only affects the energy consumption but also the multi-robot coordination [21] as well as the dimensional quality of the manufactured sheet metal parts [22] in the multi-stage press line.

9 Conclusions

This paper proposes an energy model for 2D-belt robots. The proposed energy model is generic for 2D-belt robots, as it is entirely based on its components' specifications (e.g. dimensions, masses, inertia) and for any trajectory. It combines concepts from both conveyor belt and industrial robot energy models that have been proposed in literature. The energy consumption estimations by the model are based on calculating the torque of each moving component which contributes to motion. The energy consumption is computed from the calculated torque. A specific case study where 2D-Belt robots are used for material handling in multi-stage sheet metal press lines is considered in this work. The successful validation by conducting various experimental measurements on a real-world 2D-belt robot has been presented.

This paper also demonstrates the capabilities of the proposed model to estimate the energy consumption during offline motion planning and how this can support simulation studies. A main benefit of this is that the motion planning can be done before installation. The manner in which the proposed model can be used for motion planning optimisation, both with single and multi-objectives, has been demonstrated. The model also allows to evaluate and analyse specific system configurations without needing to perform experiments and measurements. It is shown how the potential energy saving for robots with mechanical brakes for when it is idle can be predicted by using the proposed energy model. Additionally, it was demonstrated how the potential energy saving with the mechanical brake can be analysed across different cycle-times for the considered sheet metal press line, and how this affects the motion planning.

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