DEGREE PROJECT FOR MASTER OF SCIENCE WITH SPECIALIZATION IN ROBOTICS
DEPARTMENT OF ENGINEERING SCIENCE
UNIVERSITY WEST

Model for Energy Consumption of 2D Belt Robot

- Master's Thesis Work

Prithwick Parthasarathy

UNIVERSITY WEST

A THESIS SUBMITTED TO THE DEPARTMENT OF ENGINEERING SCIENCE

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE WITH SPECIALIZATION IN ROBOTICS

AT UNIVERSITY WEST

2016

Date:	June 01, 2016
Author:	Prithwick Parthasarathy
Examiner:	Bo Svensson
Advisor:	Emile Glorieux
Programme:	Master Programme in Robotics
Main field of study:	Automation with a specialization in industrial robotics
Credits:	60 Higher Education credits (see the course syllabus)
Keywords:	Automation, Industrial Robot, Energy Model, Energy Consumption, Energy Minimization
Template:	University West, IV-Master 2.7
Publisher:	University West, Department of Engineering Science S-461 86 Trollhättan, SWEDEN Phone: + 46 520 22 30 00 Fax: + 46 520 22 32 99 Web: www.hv.se

Summary

A production industry with many robots working 24 hours a day, 7 days a week consumes a lot of energy. Industries aim to reduce the energy consumed per machine so as to support their financial budgets and also to be a more sustainable, energy efficient entity. Energy models can be used to predict the energy consumed by robot(s) for optimising the input parameters which determine robot motion and task execution. This work presents an energy model to predict the energy consumption of 2D belt robots used for press line tending. Based on the components' specifications and the trajectory, an estimation of the energy consumption is computed. As part of this work, the proposed energy model is formulated, implemented in MATLAB and experimentally validated. The energy model is further used to investigate the effect of tool weight on energy consumption which includes predicting potential energy reductions achieved by reducing the weight of the gripper tools. Further, investigation of potential energy savings which can be achieved when mechanical brakes are used when the robot is idle is also presented. This illustrates the purpose and usefulness of the proposed energy model.

Preface

First, I'd like to thank my supervisor Emile Glorieux, for all his guidance and time during the course of this thesis work. Next, I would like to extend my regards to my professor Fredrik Danielsson for his comments and suggestions throughout the duration of this course; they have helped me become a better writer and a presenter. Thank you! I would like to express my sincere gratitude to Bo Svensson for his insights and well-reasoned opinions on my work. To my professors from the other courses, our interactions have been special and I would like to take this opportunity to thank you all for your guidance and knowledge filled conversations during the course of my Master's studies.

I would like to thank my fellow students for their valid and well-reasoned opinions on my work and the journey I have travelled with them the last one year. It has been a lot of fun, thanks guys! My friends here in Sweden, you guys have been fantastic! It has been a pleasure to get to know you all on a personal level and our relationship is one which I will cherish forever. *Tack så mycket!*

To my brother, who has been a constant source of inspiration when the chips were down, "*Thanks machan!!*" To my mother and father, thank you for the countless sacrifices you both have made for shaping me into the individual I am today. I hope I have made you both proud in whatever little I have achieved till date. Finally, I'd like to extend my deepest regards to my family and friends back home and to those spread around the world achieving great things!

Affirmation

This master degree report, *Model for Energy Consumption of 2D Belt Robot*, was written as part of the master degree work needed to obtain a Master of Science with specialization in Robotics degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

June 01, 2016

Signature by the author — Date

Prithwick Parthasarathy

Contents

Preface

Main Chapters

Appendices

1 Introduction

1.1 Project Background

Energy conservation is a key aspect towards sustainability and is pursued by both, research and industry [1]. New techniques are continuously being formulated to keep up with the ever increasing demand of the world population. Considering the automotive industry, mass production defines the industry itself. To be able to produce in large volumes involves efficient and error-free methodologies. Simulation models were used in previous research work to ensure optimal production rate and collision-free operation [2] . While production rate and wear are parameters being optimized already using existing models, and with an increasing impetus on energy in today's industrial world, there exists a need to predict and optimize energy consumption of robots in a production line.

1.2 Problem Description

A Production line consists of many production stations. Each station consists of a robot and other material handling devices. While simulation models are used to optimize specific engineering characteristics of a production station(s), there exists a need to predict, understand and minimize the energy consumption of the robots working in the line. To be able to formulate an energy model, there needs to be an understanding as to what parameters, including losses, if any, affect energy consumption of an industrial robots and other material handling devices. The literature review intends to highlight 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. Further, the literature study aims to determine which aspects from the existing model(s) will be best suited for 2D belt robots. The thesis work aims to formulate and verify an energy model of a specific type of Industrial Robot, a 2D belt robot used for press line tending. An illustration of a 2D belt robot is shown in Figure 1 and is explained further in Section 3.

1.3 Aim

- To formulate and validate experimentally an energy model to predict the energy consumed by a 2D belt robot.
  - To investigate the need for which parameters are required for the formulation of the energy model.
  - To implement the model in MATLAB.
- To Verify and validate the proposed energy model on an available 2D belt robot at University West's Production Technology West research centre.

1.4 Limitations

- The proposed energy model is specific, to a 2D belt robot.
- The implementation of the energy model is done only in MATLAB.
- The time span of ten weeks has been used to formulate and validate the energy model suited for a 2D belt robot. Future work would involve investigation of how the proposed energy model can be used for other industrial robots.
- The physical model in the laboratory at University West's Production Technology West research centre used for experimental validation is a scaled down model of the 2D belt robot used in industry.

1.5 Report Overview

This report gives an insight into the methodology followed to formulate, implement and validate the proposed energy model. Section 2 reflects on existing energy models being used for Industrial Robots in general. The various aspects of each model is summarized and subdivided into different categories. Aspects necessary for a 2D belt robot have been taken into consideration to aid in the formulation of the proposed energy model. Section 3 introduces the considered sheet metal press line. Section 4 discusses the methodology employed to formulate the proposed energy model while Section 5 describes the experimental setup and the validation process. The report reflects on the results and discussions in Section 6 and conclusions are included in Section 7.

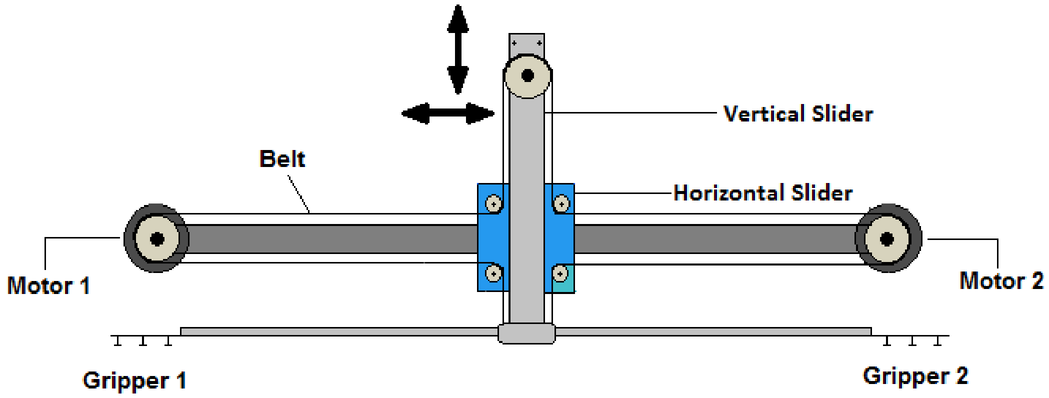

Figure 1 Illustration of a 2D belt robot

2 Literature Review

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. Further, the literature study aimed to determine which aspects from the existing model(s) will be best suited for 2D belt robots. The various aspects of each model is summarized and subdivided into different categories.

2.1 Physical Models

To optimize 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 components along with accessories obtained through special resistances.

- Power to run the empty conveyer.
- Power to move material horizontally over a certain distance.
- 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 may 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 characterized 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 (Using multiple robots as energy buffers)

95% of work in the body shop in the automobile industry is carried out by robotic-related applications [4]. 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.

2.2.1 Evaluating the capacitive energy buffer on the robot's DC-bus

Meike and Ribickis [4] used a test assembly of four electrolytic capacitors. This is the additional capacitor bank. The voltage requirements were achieved by using a series-parallel connection. Several robot programs were run mocking the typical welding and handling applications. The power consumption was measured for the entire system including all static loads. The weld motion involves short movements between process points, thus having numerous acceleration and deceleration phases. This leads to many charging and discharging cycles. The additional capacitor bank aided in large energy savings during the test run due to its fast energy absorption capabilities during the numerous acceleration and deceleration phases. This recuperated energy was effectively reused. The handling application, which involves long movement distances between process points has the highest energy consumption but also the largest savings.

2.2.2 The EnergyTeam Principle

Meike and Ribickis [4] infer that the robot in a body shop usually spends less time in movement. Thus, the capacitive bank of a single robot is being used only $1/3^{rd}$ of the available time. Thus it accumulates less acceleration and decelerating phases as it could physically be possible. To reduce the costs per robot the authors propose that such a capacitive energy buffer could be shared among several robots.

The energy flow is directed to and from the robots. There exist two implementation options:

- A single, centralized rectifier and several robots,
- Several decentralized 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. By this way, there is an energy exchange only when the system requires it.

2.2.3 Based on a combination of multiple robots and time scaling

Meike et al. [5] propose a model to increase the energy efficiency of multi-robot production lines in the automotive industry. The model proposed by the authors involves a methodology which is a hybrid of the methodologies proposed in [4] and [6]. Meike et al. [5] propose an energy consumption optimization 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. The authors run experiments on a real automobile production cell. Energy simulation results based on these results suggest that execution time for a robot task is usually not synchronized 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 Optimization

Hansen et al. [7] propose an energy trajectory optimization 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 optimization approach involved:

- Formulating the optimization problem.
- Defining a path planning method and all associated optimization parameters.
- Defining a scalar cost function for minimization when the optimization 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 authors also validate their trajectory optimization approach by presenting measurement and simulation results. Three trajectory scenarios are chosen to investigate the minimum energy optimization approach. The tests suggest the following:

- Total energy losses were reduced for all examined trajectories. Thus, a reduction in cost function always leads to reduced energy supply.
- The exchange of electrical energy was amplified in most cases. Thus, energy surpluses were reduced.
- Cost reduction was highest when both axes exhibit distinct motor and generator phases during movement.

Riazi et al. [8] also propose an optimization 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 optimization 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 optimization 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 minimize the energy consumption of motions.

The proposed optimization model uses a simple minimization 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 minimized by a non-linear programming (NLP) 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. Experiments were carried out with two industrial robots, both being a KUKA KRC30. Three test scenarios were formulated to validate the approach; an initial trajectory involving both linear and point-to-point motions at various speeds, a shorter path in which one robot begins its downward movement first and the other robot starts moving up when the first robot reaches its destination. The third scenario is similar to the second one except the second robot starts first. The results showed that the optimization algorithm proposed by the authors had the potential to save up to 45% of the total energy consumption. The algorithm saves energy by:

- Employing a weighted sum of squared joints' acceleration of trajectories.
- Permitting the robots to move slower rather than wait for zone access.
- Changing the sequence of operations.

2.3.1 A method to measure power with good repeatability

Chemnitz et al. [1] consider two 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 authors consider robots of similar specifications (for example the payload at the wrist, supplementary payload and reach of the robot are similar in both robots). 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 ones, the main reason being the execution time for the slow motion is 10 times more than the time of the fast ones. The authors use a quadratic polynomial approximation 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 authors do not take into account the payload to highlight the difference in power consumed.

2.3.2 *Minimal Touch* Approach

Pellicciari et al. [6] focus on energy loss minimization for pick and place manipulators by means of a *minimal touch* approach. The authors propose an engineering method to optimize energy consumption of robotic systems, applicable to both series and parallel manipulators whose dynamic models are known. Most energy minimization 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). The authors state that in some scheduling optimization methods [10], [11] it is assumed that the robot operates at its maximum speed when permitted by the scheduling constraints and idles otherwise (stands still). This leads to accelerations which require high power and that the excess energy is wasted in counteracting gravitational loads. The authors determine an energy optimal trajectory by means of time-scaling. This is done by slowing down the operation and also reducing the manipulator idle times. The authors formulate an energy loss ratio of energy loss related to scaled and time-optimal trajectory. The approach is tested on an industrial robot, carrying out cyclic pick and place operation. The results thus obtained, permit the authors to parametrize and adjust manipulator operation so as to minimize energy consumption, provided the scheduling or manufacturing constraints permit these changes.

2.3.3 Power flow assessment in servo-actuated automated machinery

Oliva et al. [12] consider a system in which a permanent magnet synchronous motor coupled with a standard power converter, both of which are directly connected to a slider crank mechanism. The authors aim to predict accurately the major sources of power loss within the system. The identification procedure consists of design of experiments, data acquisition, signal processing, parameter estimation and model validation. The authors aim to identify the parameters required to define a predictive formulation for the power demand and thus to test the accuracy of their prediction. The authors devise two models as part of their estimation phase; a dynamic model which aims at identifying the dynamic parameters, and a power flow model to identify the power flow parameters. The formulation thus uses the identified dynamic parameters and power flow parameters as its inputs to yield the power demand prediction. In both these models the design of experiments involves a selection of parameterization for the trajectory, selection of a suitable cost function and deriving the optimal existing trajectory using optimization techniques. The data acquisition and signal processing phase involves the identification of variables in specific such as motor angular position, motor and inverter currents and DC-link voltage. A suitable low pass filter (in this case the Butterworth filter) is used in both the forward and backward direction to remove noise without adding phase shift to the signal. Velocity and acceleration are thus obtained by applying the first and second order central differences respectively to the filtered positions. The mechanical and inverter power is subsequently calculated. The estimation stage involves estimating the dynamic and power flow parameters and the torque constants. Once these are obtained, their accuracy is tested. The authors conclude that the system parameters could be successfully identified via non-invasive experimental methods. The proposed formulation shows accurate predictive capabilities as long as the power prediction error is comparable to the noise of the power measure itself.

2.4 Summary of Literature Review

Based on the literature study thus far, energy models have been classified based on different criteria, see Table 1. The criteria are as follows:

1. Based on Design.
2. Based on Path Planning.
3. Based on number of robots.

The author has classified the literature reviewed in accordance with the following guidelines to the criteria. The design criterion highlights the dependency of the design of the robot (which includes its components like the servo-drives or the belt) on the energy model and/or how an energy model can be adapted to suit an existing design of the robot. Trajectory optimization and its approaches, which aim to optimize the trajectory of the robot, fall under the Path planning criterion. The literature which describes how multiple robots collaborate to save energy together, fall under the number of robots criterion. Few literatures are a combination of more than one criterion. This has been marked in Table 1 clearly.

Table 1 Classification of Energy Models based on various criteria

Author(s)	Design	Path Planning	Number of robots
Zhang and Xia [3]	x		
Meike and Ribickis [4]			x
Hansen et al. [7]		x	
M.Chemnitz et al. [1]		x	
S.Riazi et al. [8]		x	x
M.Pellicciari et al. [6]	x	x	
D.Meike et al. [5]		x	x

3 Sheet Metal Press Lines

A typical sheet metal press line consists of four to six press stations in line, placed next to one another, as shown in Figure 2. The sheet metals move through every press station from left to right, where each station performs a specific operation on the sheet metal. 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 from another press or robot in the press line. This holds true for the opening and closing of the press as well. Synchronising the operations and interactions between stations require that these start signals are communicated. 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, opening and closing of presses and the start signals for segments of robot motions 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, excessive wear of equipment, and a higher energy consumption by the robots. Optimising these parameters would give the industry monetary benefits. Figure 2 illustrates the considered (tandem) press line. Products, say sheet metals, move through the line from left to right. A specialised 2D-belt robot is used in the considered press line as shown in Figure 1. The robot is

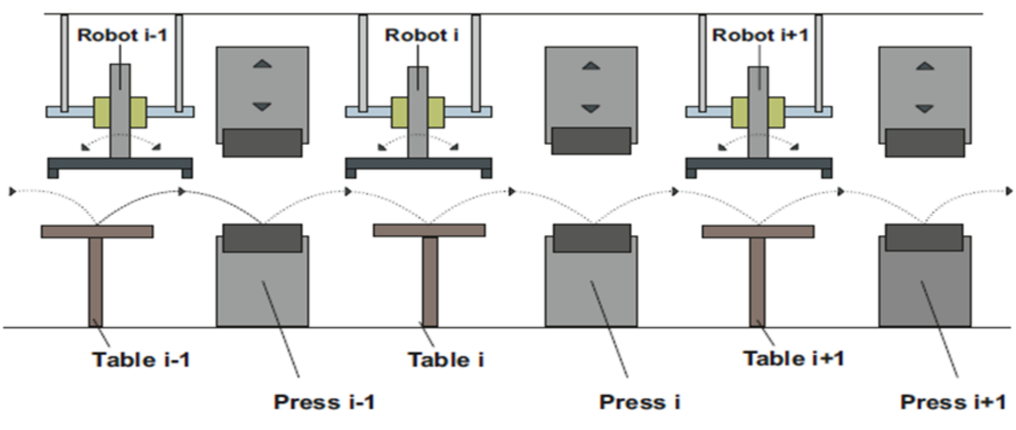

Figure 2 Illustration of tandem sheet metal press line

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 1. In this way, it can pick up or place two products at the same time. The tools, 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 synchronization of operations absolutely essential so as to avoid collisions and have a high production rate.

4 Method

The method which was followed to carry out this thesis work in a structured and efficient manner is described as follows:

- **Literature Review:** The literature review phase was used to select related literature, read, review and reflect on them. The results from the literature review formed the basis for the thesis work. Parameters related to 2D belt robots were taken into consideration and the proposed energy model was formulated based on knowledge gained form the literature review and the author's knowledge as well.
- **Energy model formulation:** The formulation of the proposed energy model will be conducted with knowledge gained from the literature reviewed, reviewing more related literature as well as from the current knowledge of the author.
- **Implementation of Energy model:** To implement the energy model, the author has to familiarise the simulation tool so as to narrow down to possibilities of effective implementation.
- **Validation of Energy model:** Verification and validation of the proposed energy model is to be carried using experimental methods. The experimental results will be compared to the simulation results from the energy model so as to analyse how accurate the energy model would be.

5 Energy Model Formulation

Consider the 2D-belt robot from Figure 3. The robot has a vertical slider, a horizontal slider, motors termed Motor 1 and Motor 2. A long thin time-synchronous belt rolls over pulleys P1, P2 (attached in front of motors 1 and 2 respectively), P3, P4, P5, P6 and P7. The vertical slider moves upwards and downwards while the horizontal slider moves left and right. Table 2 describes the rotational direction of the pulleys and the corresponding directional movement of the robot's TCP and the sliders.

Table 2 Directional information of robot TCP (and pulleys)

P1	P2	TCP
↻	↺	↑
↺	↻	↓
↺	↺	→
↻	↻	←

To calculate the torque generated, the author considers the following:

1. Mass of P1-P6 to calculate the moments of inertia.
2. Mass of the vertical slider and horizontal sliders.
3. Moments of inertia of the motor and the gear (from specifications).

The input of the model is the robot's trajectory. The two motors employed for the 2D belt robot considered in this work are identical permanent magnet synchronous AC motors. The model calculates the torque load for each motor to estimate the power according to the formula [16]

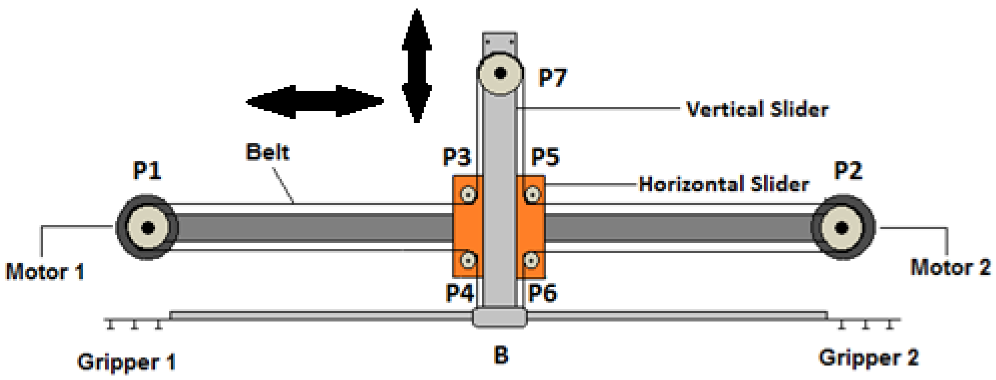

Figure 3 Illustration of considered 2D belt robot

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

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, K_t is the torque constant and ω_m is the angular velocity of motor m.

To calculate the torque of motor, the author considers the torque 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):

$$\tau_m = \tau_1 + \tau_2 + \tau_3 + \tau_4.$$

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

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

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

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

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

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

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 are calculated as follows

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

where μ is the friction factor.

It is important to note that the individual torques sans the torque of the motor and gear are divided by a factor of i which is the gear ratio so as to compensate for the difference in the rotational speeds of the driver and the driven gears. The proposed energy model as described above is implemented using MATLAB.

6 Experimental Validation

6.1 Experimental Set up

The experimental setup consisted of a computer with necessary hardware and software, a Chauvin Arnoux C.A 8335 Watt meter, used to measure the energy consumed, two SEW Eurodrive servo-drive and a 2D belt robot. The 2D belt robot is a Binar UniFeeder robot [15] for press lines, in this work a smaller model was used. The Watt meter was connected to the input cables to the servo-drive. Two tests were carried out to validate the proposed energy model, uniform velocity tests and variable velocity tests. The pick and place operation of the robot was divided into 4 segments as shown in Figure 4:

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

The velocity of the robot motion was then varied for each segment specifically depending on the test being performed. The input trajectories for the energy model calculations for these tests are generated with the simulation model of the 2D-belt robot's controller proposed by Glorieux et al. [2], [14].

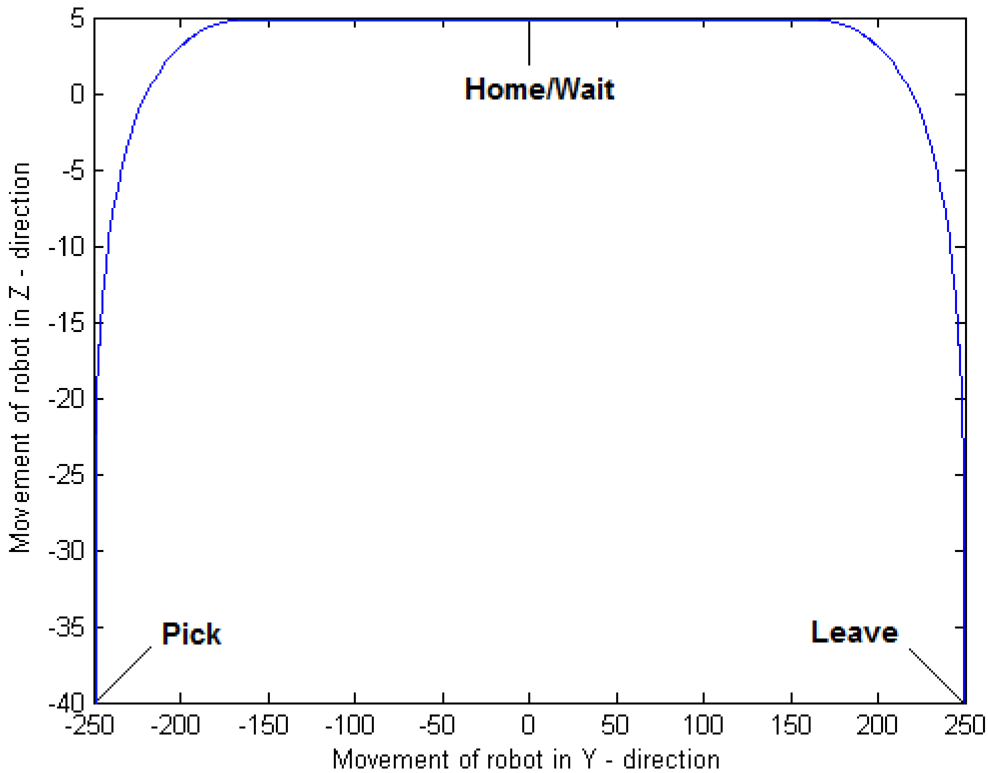

Figure 4 Illustration of the robot trajectory and the 4 robot segments

6.2 The Validation Process

Experimental validation was performed to investigate whether the proposed energy model accurately estimates the energy consumption of the 2D-belt robot. The author proposed the following tests to validate the energy model using practical means:

1. Uniform Velocity Tests
2. Variable Velocity Tests

6.2.1 Uniform Velocity Tests

In this test, all robot segments were set to a specific velocity, making the robot motion to proceed with a uniform velocity. A robot segment refers to the motion of the robot between particular segments, say two specific points. For a pick and place operation there are 4 robot segments; Home to Pick, Pick to Wait, Wait to Leave and Leave to Home. This defines the trajectory of the robot motion as shown in Figure 4. The velocities chosen for this test were 12%, 20%, 35%, 50%, 80% and 100%. 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.

The first stage of this test was to simulate the energy model to obtain cycle times and energy consumption values for the velocities mentioned above. Once the results were obtained, the energy model was to be validated using a real 2D-belt robot. Tests at the different velocities mentioned above were carried out and their results were compared with the ones from the simulation. The results from the Uniform Velocity Tests can be found in Table 3 from Appendix A and Table 4 from Appendix B.

Figure 5 illustrates the comparison of the simulation and experimental results from the uniform velocity tests for 1 individual cycle and 5 individual cycles of robot motion. A cycle is when the robot has picked up an object from the pick position and leaves the object in the leave position. The x-axis refers to the cycle time in seconds [s] and the y-axis refers to the energy consumed in Joule [J]. The simulation model uses the formulated energy equation to compute the energy consumption of the 2D belt robot at a specific velocity. This result is then compared to the energy consumption value obtained from real time tests which was conducted on an available 2D-belt robot setup. Both the simulation and the experimental curves have a similar profile. This 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. This is due to the fact that the energy consumption of the servo drive and other losses are not incorporated in the proposed energy model's calculation.

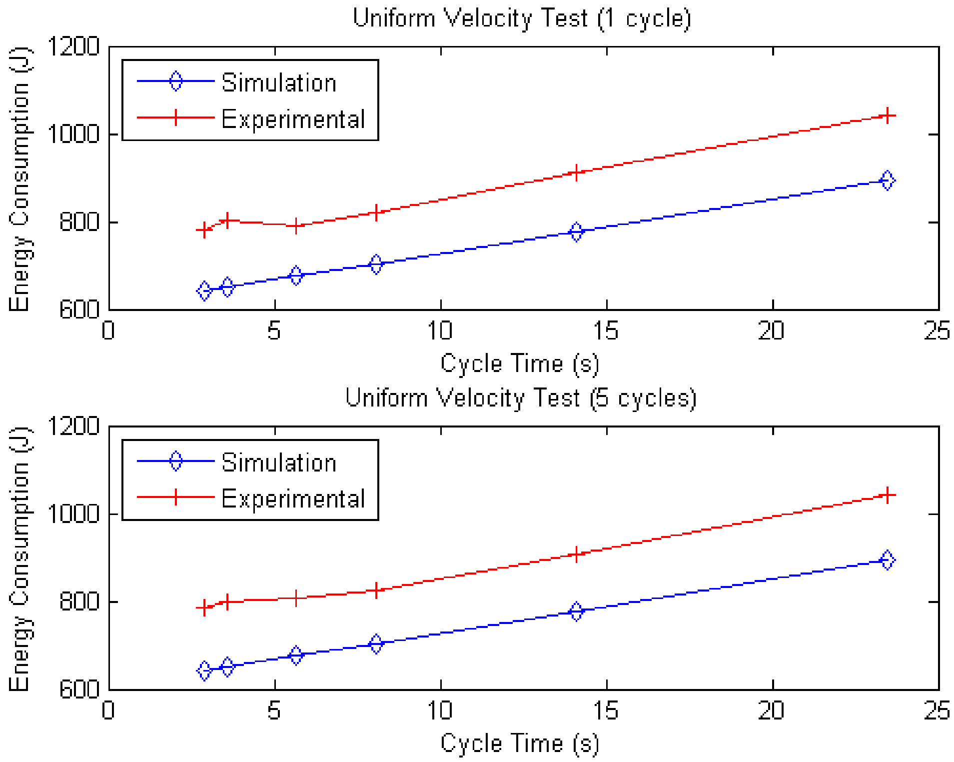

Figure 5 Plots comparing the simulation and experimental energy consumption curves from the uniform velocity tests for 1 cycle (top) and 5 cycles (bottom)

6.2.2 Variable Velocity Tests

In this test, each robot segment was set to a specific velocity, in such a way that each segment had a different velocity. This was to ensure the robot motion proceeded with different velocities so as to investigate the role of variable velocities on the energy consumption. The velocities were chosen between the ranges of 12% to 100% with different combinations. Tests at the different variable velocities were carried out and their results were compared with the ones from the simulation. The simulated and experimental values are then plotted using MATLAB and compared if both curves followed a similar profile. Figure 6 illustrates the simulated and experimental energy consumption curves from the variable velocity test for 1 cycle and 5 cycles of robot motion. The x-axis refers to the cycle time in seconds [s] and the y-axis refers to energy consumption in Joule [J]. As Figure 6 suggests, the similar profiles of the simulated and experimental curves meant that the proposed energy model is valid and can be used to predict the energy consumption for a 2D-belt robot working at various velocities though there is a constant underestimation of the absolute energy consumption value that was measured. The results from the variable velocity test are part of Table 5 from Appendix C and Table 6 Appendix D.

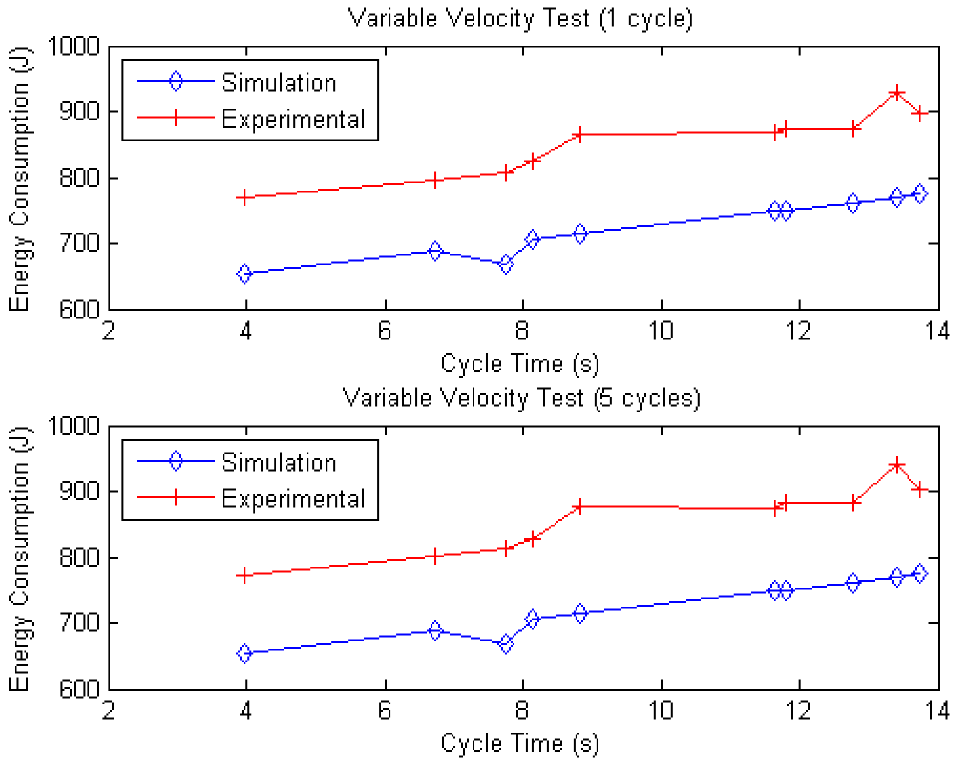

Figure 6 Plot illustrating the simulated and experimental energy consumption curves from the variable velocity tests for 1 individual cycle (top) and 5 individual cycles (bottom)

6.2.3 Uniform Velocity Test with arbitrary weight

Tool weight could have a drastic effect on the energy consumed during robot motion. Heavier tools could lead to higher energy consumption rates for a robot to perform a pick and place operation within its cycle time. The author, thus, wanted to evaluate the effect of tool weight on energy consumption. For this purpose, a weight of 3.36 kg was bolted on to the tool holder to mock the gripper. The weight of 3.36 kg was arbitrary. This test was to only check and thereby confirm any differences in energy consumed. The test was carried out for uniform velocities between v = 12% and v = 100%, 5 repetitions for each velocity. This test was also used as a medium to further experimentally validate the proposed energy model. The results from this test can be found as Table 7 in Appendix E. Figure 7 shows the plot illustrating the simulation and experimental curves of energy consumption with and without tool weight. The effect of tool weight on energy consumption was further investigated and is explained in the next section.

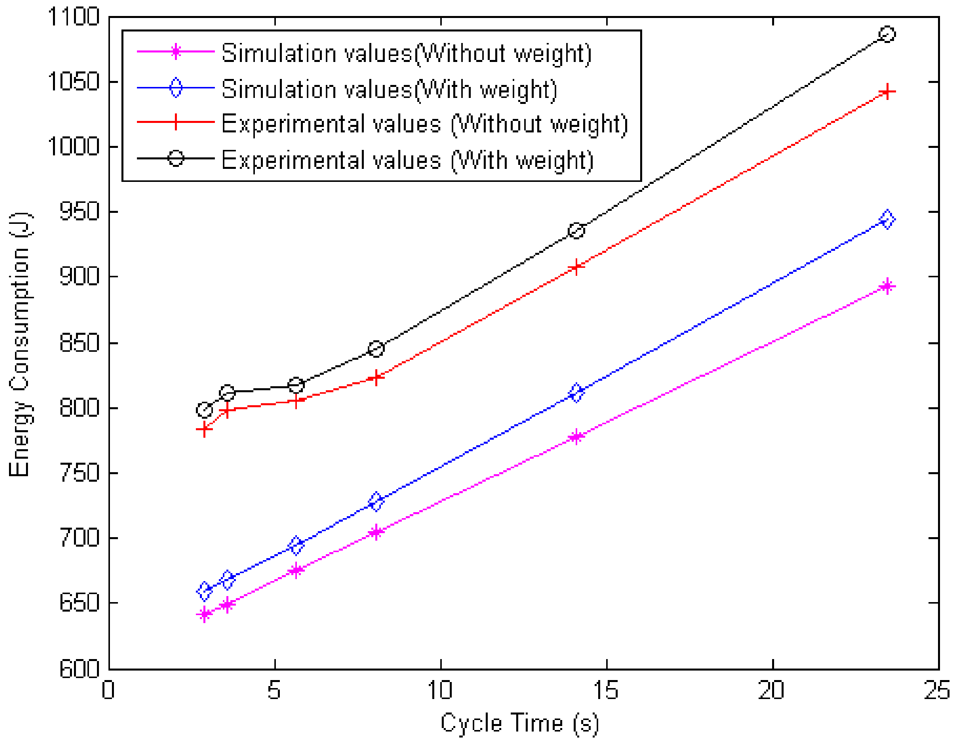

Figure 7 Plot illustrating the simulation and experimental curves of energy consumption comparting tests with and without tool weight

7 Results and discussion

The energy model to predict the energy consumption of a 2D-belt robot was formulated and implemented in MATLAB. To validate the energy model, various tests were carried out.

Uniform velocity tests was carried out in a way that the robot would perform a pick and place operation for 1 cycle and 5 cycles in which each robot segment was set to the same velocity, between 12% and 100%. In the variable velocity tests each robot segment was set to a certain speed but varied from one another. The combinations of velocities were between 12% and 100% and similar velocity parameters used in the Uniform velocity tests were followed. The combinations were chosen such that the robot would be put through very high, very low and intermediate velocities to perform a pick and place operation for 1 and 5 cycles. From both the tests, it was clear that even though the simulation and experimental power consumption curves were found to have similar profiles, there did exist a constant underestimation of the absolute energy consumption value that was measured. This is due to the fact that the energy consumption of the servo drive and other losses are not incorporated in the proposed energy model's calculation.

The energy model is thus, formulated and validated. As part of the work, the validated energy model was used to conduct theoretical tests so as to study the effect of tool weight on energy consumption of the 2D belt robot. The validated energy model also demonstrated the possibility to theoretically predict the potential energy saving that can be achieved by using mechanical brakes when the robot is idle, which will be discussed further in this section.

7.1 Tool Weight Investigation

While the validation of the simulation model was successfully executed by conducting tests and verifying the results from the simulation model experimentally, the author wanted to investigate the rate at which energy consumption increases per kilogram weight added to the gripper. Savings in energy consumed would bring monetary benefits to industries, and the weight of the gripper used as the tool in the 2D belt robot does contribute to the energy consumption while performing pick and place routines.
The following tests were calculated using the proposed energy model. The curves shown in Figure 8 illustrate the effect of tool weight on power consumption for different velocities. Velocities of 25%, 50% and 100% were chosen and the tool weights used were 1kg, 5kg, 10kg, 15kg and 20 kg. The energy model was then employed to obtain the simulated values for the selected velocity and weight parameters. For every 5 kg weight added, the energy consumption value was obtained from the simulation and regression was used to compute the energy consumed per kilogram weight added for each velocity parameter. According to these calculations, following energy saving can be obtained for the different velocities:

- around 8.4 J/kg for 25% velocity,
- around 4.6 J/kg for 50% velocity,
- around 3.6 J/kg for 100% velocity.

This means that for a production industry working 24 hours a day, 7 days a week, a lot of energy can be conserved as well as benefitting them monetarily. Thus, by employing the verified simulation model one could predict the energy consumption and savings in energy consumed per kilogram of weight added for a particular velocity of motion. Results from the tests are attached as Table 8 in Appendix F.

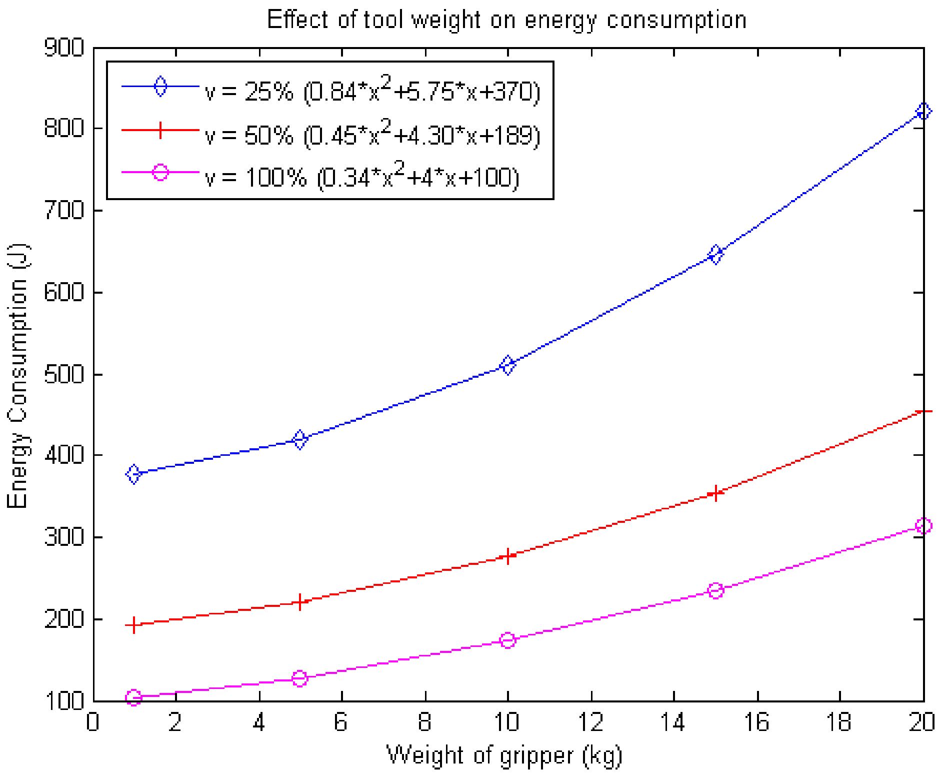

Figure 8 Plot illustrating the effect of tool weight on power consumption

7.2 Mechanical Brake Investigation

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 that approximately 32 J/s can be saved when the mechanical brakes are used during idle-times.

This means, when the robot is made to move at higher velocities, a large amount of energy is consumed to brake and hold the robot 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 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 has to spend much of the cycle time idling, a lot of energy can be consumed. The energy model can be used to schedule processes in a way to minimise energy consumption. Energy minimisation could be achieved in multiple ways; say if a robot moves slowly using up much of its idle time or the robot moves quickly and prefers to stay idle [1]. Such scenarios can be evaluated using the simulation energy model.

8 Conclusions

This work proposes an energy model for 2D belt robots for press line tending. The energy model was formulated and validated by conducting tests on an available 2D belt robot. The proposed energy model is generic for different 2D-belt robots models, as it is entirely based on its components' specifications (e.g. dimensions, masses, inertia) and for any trajectory. The successful validation by conducting various tests on a 2D-belt robot is presented.

The energy consumption estimations by the model are based on calculating the torque of each moving component which contributed to motion in the 2D belt robot during a pick and place operation. The energy consumption is computed from the calculated torque. Experimental tests were carried out to obtain energy measurements to confirm the model's estimations.

The work also shows that the proposed energy model can evaluate potential energy savings resulting by reducing the weight of the gripper tools. Technological advancements in materials can be used to reduce the weight of the gripper as much as possible to produce the expected the results required while also saving energy consumed by the robot while performing its pick and place operation. The work also demonstrates how potential energy saving for using mechanical brakes when the robot is idle is estimated by using the proposed energy model. The successful validation of the proposed energy model demonstrates its effectiveness for use in further work.

8.1 Future work and research

Energy consumption can be minimised by running a robot slowly using up much of its idle time or by moving it quickly and preferring to stay idle [1] . The future work would involve adapting the validated energy model for larger production lines with many stations. Further, incorporation of scheduling parameters as well as how the validated energy model could be made suitable for realistic production scenarios will be investigated. While it is possible to easily adapt the validated energy model for such scenarios, it would involve studying the possibilities of how the related control parameters, signal synchronisations etc. can be taken into account so as to enhance the usability of the energy model for larger production lines.

8.2 Critical Discussion

Right from the start of the literature review phase, the work involved in conceptualising and executing the thesis work has personally aided me in learning how to execute what has been pre-planned in a structured manner. There existed numerous cases, when I had to brush up my knowledge in Physics so as to move on with the project work. Moreover, my knowledge and skills in MATLAB has increased, which was a big question mark when I started off with the project. The ten weeks could have been utilised in a more effective way if I was able to recollect the fundamentals in Physics quicker than I did and also have more knowledge specific to 2D belt robots. The energy model would have been made much better and suitable for more realistic scenarios, given the opportunity to redo the work with the knowledge of today.

8.3 Generalisation of the Results

While simulation models exist in today's industrial world, to optimise parameters such as production rate and wear, and with industries focussing immensely on energy conservation, the need for a model to predict energy consumption of robot(s) during the pre-planning phase has been satisfied. The validated energy model would be the foundation to build on for an energy model to suit larger production lines and realistic production scenarios. There does not exist a model to predict energy consumption of robot(s) prior to installation, which makes this study very unique. Further investigation and effort into updating the validated energy model would make it readily usable by industries.

9 References

[1] M. Chemnitz, G. Schreck, and J. Kruger, "Analyzing energy consumption of industrial robots," in *ETFA2011*, 2011, pp. 1–4.

[2] E. Glorieux, B. Svensson, F. Danielsson, and B. Lennartson, "Simulation-based Time and Jerk Optimisation for Robotic Press Tending." ESM, pp. 377–384, 2015.

[3] Shirong Zhang and Xiaohua Xia, "A new energy calculation model of belt conveyor," in *AFRICON 2009*, 2009, pp. 1–6.

[4] D. Meike and L. Ribickis, "Recuperated energy savings potential and approaches in industrial robotics," in *2011 IEEE International Conference on Automation Science and Engineering*, 2011, pp. 299–303.

[5] D. Meike, M. Pellicciari, G. Berselli, A. Vergnano, and L. Ribickis, "Increasing the energy efficiency of multi-robot production lines in the automotive industry," in *2012 IEEE International Conference on Automation Science and Engineering (CASE)*, 2012, pp. 700–705.

[6] M. Pellicciari, G. Berselli, F. Leali, and A. Vergnano, "A minimal touch approach for optimizing energy efficiency in pick-and-place manipulators," in *2011 15th International Conference on Advanced Robotics (ICAR)*, 2011, pp. 100–105.

[7] C. Hansen, J. Kotlarski, and T. Ortmaier, "Experimental validation of advanced minimum energy robot trajectory optimization," in *2013 16th International Conference on Advanced Robotics (ICAR)*, 2013, pp. 1–8.

[8] S. Riazi, K. Bengtsson, O. Wigstrom, E. Vidarsson, and B. Lennartson, "Energy optimization of multi-robot systems," in *2015 IEEE International Conference on Automation Science and Engineering (CASE)*, 2015, pp. 1345–1350.

[9] Paryanto, M. Brossog, M. Bornschlegl, and J. Franke, "Reducing the energy consumption of industrial robots in manufacturing systems," *Int. J. Adv. Manuf. Technol.*, vol. 78, no. 5, pp. 1315–1328, 2015.

[10] S. Panek, O. Stursberg, and S. Engell, "Optimization of Timed Automata Models Using Mixed-Integer Programming," 2004, pp. 73–87.

[11] A. Kobetski and M. Fabian, "Time-Optimal Coordination of Flexible Manufacturing Systems Using Deterministic Finite Automata and Mixed Integer Linear Programming," *Discret. Event Dyn. Syst.*, vol. 19, no. 3, pp. 287–315, Sep. 2009.

[12] E. Oliva, G. Berselli, M. Pellicciari, and A. O. Andrisano, "An engineering method for the power flow assessment in servo-actuated automated machinery: Mechatronic modeling and experimental evaluation," *Robot. Comput. Integr. Manuf.*, vol. 38, pp. 31–41, 2016.

[13] "SEW Eurodrive," 2016. [Online]. Available: http://www.seweurodrive.com/produkt/movitools-motionstudio.htm.

[14] E.Glorieux, F.Danielsson, B.Svensson, B.Lennartson, "Constructive Cooperative Coevolutionary Optimisation for Interacting Production Stations," *The International Journal of Maufacturing Technology,* pp. 673–688, 2015.

[15] Binar Olofström AB, *'Binar Press Automation - UniFeeder'*, 2004. [Online]. Available: http://www.binarolofstrom.se/Products/he_UniFeeder.asp[Accessed: 2016-06-02]

[16] G.Berselli, F.Balugani, M.Pelliciari, M.Gadaleta, "*Energy-optimal motion for Servo-Systems: A comparison of spline interpolants and performance indexes using a CAD-based approach,* Robotics and Computer-Integrated Manufacturing, pp.55-65, 2016.

A. Uniform velocity test for 1 individual cycle

Table 3 Results from uniform velocity test for 1 individual cycle

Cycle	Position of Robot	Velocity	Cycle Time (s)	Energy Consumed (Simulation Results) (J)	Energy Consumed (Experimental Results) (J)
1	Home to Pick	12%	23.475	893.2616	1041.96
	Pick to Wait	12%			
	Wait to Leave	12%			
	Leave to Home	12%			
2	Home to Pick	20%	14.115	778.1865	908.88
	Pick to Wait	20%			
	Wait to Leave	20%			
	Leave to Home	20%			
3	Home to Pick	35%	8.09	704.2399	819.20
	Pick to Wait	35%			
	Wait to Leave	35%			
	Leave to Home	35%			
4	Home to Pick	50%	5.685	674.8527	789.19
	Pick to Wait	50%			
	Wait to Leave	50%			
	Leave to Home	50%			
5	Home to Pick	80%	3.575	649.6441	803.64
	Pick to Wait	80%			
	Wait to Leave	80%			
	Leave to Home	80%			
6	Home to Pick	100%	2.875	641.4609	778.82
	Pick to Wait	100%			
	Wait to Leave	100%			
	Leave to Home	100%			

B. Uniform velocity test for 5 individual cycles

Table 4 Results from uniform velocity test for 5 individual cycles

Cycle	Position of Robot	Velocity	Cycle Time (s)	Energy Consumed (Simulation Results) (J)	Energy Consumed (Experimental Results) (J)
1	Home to Pick	12%	23.475	893.2616	1041.788
	Pick to Wait	12%			
	Wait to Leave	12%			
	Leave to Home	12%			
2	Home to Pick	20%	14.115	778.1865	907.672
	Pick to Wait	20%			
	Wait to Leave	20%			
	Leave to Home	20%			
3	Home to Pick	35%	8.09	704.2399	823.584
	Pick to Wait	35%			
	Wait to Leave	35%			
	Leave to Home	35%			
4	Home to Pick	50%	5.685	674.8527	805.688
	Pick to Wait	50%			
	Wait to Leave	50%			
	Leave to Home	50%			
5	Home to Pick	80%	3.575	646.6441	797.816
	Pick to Wait	80%			
	Wait to Leave	80%			
	Leave to Home	80%			
6	Home to Pick	100%	2.875	641.4609	783.47
	Pick to Wait	100%			
	Wait to Leave	100%			
	Leave to Home	100%			

C. Variable velocity test for 1 individual cycle

Table 5 Results from variable velocity test for 1 individual cycle

Cycle	Position of Robot	Velocity	Cycle Time (s)	Energy Consumed (Simulation Results) (J)	Energy Consumed (Experimental Results) (J)
1	Home to Pick	12%	11.645	748.4886	868.24
	Pick to Wait	20%			
	Wait to Leave	50%			
	Leave to Home	80%			
2	Home to Pick	80%	11.820	750.3323	873.24
	Pick to Wait	50%			
	Wait to Leave	20%			
	Leave to Home	12%			
3	Home to Pick	12%	13.745	774.3026	896.99
	Pick to Wait	20%			
	Wait to Leave	20%			
	Leave to Home	80%			
4	Home to Pick	80%	13.420	770.6841	928.98
	Pick to Wait	12%			
	Wait to Leave	12%			
	Leave to Home	80%			
5	Home to Pick	35%	7.745	669.2981	808.25
	Pick to Wait	50%			
	Wait to Leave	100%			
	Leave to Home	20%			
6	Home to Pick	100%	8.815	714.1717	866.02
	Pick to Wait	12%			
	Wait to Leave	50%			
	Leave to Home	80%			

Cycle	Position of Robot	Velocity	Cycle Time (s)	Energy Consumed (Simulation Results) (J)	Energy Consumed (Experimental Results) (J)
7	Home to Pick	12%	12.785	762.0418	874.19
	Pick to Wait	20%			
	Wait to Leave	35%			
	Leave to Home	50%			
8	Home to Pick	50%	3.980	654.695	768.27
	Pick to Wait	75%			
	Wait to Leave	80%			
	Leave to Home	100%			
9	Home to Pick	30%	6.720	715.1156	795.18
	Pick to Wait	40%			
	Wait to Leave	50%			
	Leave to Home	60%			
10	Home to Pick	60%	8.140	705.0970	823.92
	Pick to Wait	35%			
	Wait to Leave	20%			
	Leave to Home	50%			

D. Variable velocity test for 5 individual cycles

Table 6 Results from variable velocity test for 5 individual cycles

Cycle	Position of Robot	Velocity	Cycle Time (s)	Energy Consumed (Simulation Results) (J)	Energy Consumed (Experimental Results) (J)
1	Home to Pick	12%	11.645	748.4886	875.306
	Pick to Wait	20%			
	Wait to Leave	50%			
	Leave to Home	80%			
2	Home to Pick	80%	11.820	750.3323	882.204
	Pick to Wait	50%			
	Wait to Leave	20%			
	Leave to Home	12%			
3	Home to Pick	12%	13.745	774.3026	902.386
	Pick to Wait	20%			
	Wait to Leave	20%			
	Leave to Home	80%			
4	Home to Pick	80%	13.420	770.6841	940.170
	Pick to Wait	12%			
	Wait to Leave	12%			
	Leave to Home	80%			
5	Home to Pick	35%	7.755	669.2981	814.112
	Pick to Wait	50%			
	Wait to Leave	100%			
	Leave to Home	20%			
6	Home to Pick	100%	8.815	714.1717	875.802
	Pick to Wait	12%			
	Wait to Leave	50%			
	Leave to Home	80%			

Cycle	**Position of Robot**	**Velocity**	**Cycle Time (s)**	**Energy Consumed (Simulation Results) (J)**	**Energy Consumed (Experimental Results) (J)**
7	Home to Pick	12%	12.785	762.0418	882.85
	Pick to Wait	20%			
	Wait to Leave	35%			
	Leave to Home	50%			
8	Home to Pick	50%	3.980	654.6950	772.664
	Pick to Wait	75%			
	Wait to Leave	80%			
	Leave to Home	100%			
9	Home to Pick	30%	6.720	687.6411	800.354
	Pick to Wait	40%			
	Wait to Leave	50%			
	Leave to Home	60%			
10	Home to Pick	60%	8.140	705.0970	827.360
	Pick to Wait	35%			
	Wait to Leave	20%			
	Leave to Home	50%			

E. Uniform velocity test with an arbitrary weight of 3.36 kg

Table 7 Results from uniform velocity test with an arbitrary weight of 3.36 kg

Cycle	Position of Robot	Velocity	Cycle Time (s)	Energy Consumed (Simulation Results) (J)	Energy Consumed (Experimental Results) (J)
1	Home to Pick	12%	23.475	944.0108	1086.35
	Pick to Wait	12%			
	Wait to Leave	12%			
	Leave to Home	12%			
2	Home to Pick	20%	14.115	811.9725	935.562
	Pick to Wait	20%			
	Wait to Leave	20%			
	Leave to Home	20%			
3	Home to Pick	35%	8.090	727.5421	845.062
	Pick to Wait	35%			
	Wait to Leave	35%			
	Leave to Home	35%			
4	Home to Pick	50%	5.685	694.3118	817.158
	Pick to Wait	50%			
	Wait to Leave	50%			
	Leave to Home	50%			
5	Home to Pick	80%	3.575	667.4263	810.946
	Pick to Wait	80%			
	Wait to Leave	80%			
	Leave to Home	80%			
6	Home to Pick	100%	2.875	659.0123	798.158
	Pick to Wait	100%			
	Wait to Leave	100%			
	Leave to Home	100%			

F. Tool weight investigation

Table 8 Results from the test investigating the energy saved per kilogram weight added to the gripper

Velocity	Cycle Time (s)	Weight of gripper (kg)	Energy Consumption (J)	Quadratic Curve Fit
25%	11.305	1	376.3668	0.84*x^2+5.75*x+370
		5	419.5502	
		10	511.3371	
		15	645.1324	
		20	820.9353	
50%	5.685	1	193.2754	0.45*x^2+4.30*x+189
		5	221.2233	
		10	276.5374	
		15	354.4948	
		20	455.0957	
100%	2.875	1	103.971	0.34*x^2+4*x+100
		5	127.8317	
		10	173.3859	
		15	235.6101	
		20	314.5037	