

TALLINN UNIVERSITY OF TECHNOLOGY
School of Information Technologies

Natalia Semjonova 221895IASM

Research and laboratory work development for the Festo tripod robot

Master's thesis

Supervisor: Valery Vodovozov
Doctor's degree
Eduard Petlenkov
Doctor's degree

Tallinn 2024

TALLINNA TEHNIKAÜLIKOOL
Infotehnoloogia teaduskond

Natalia Semjonova 221895IASM

Uuringud ja laboratoorse töö arendamine Festo kolmjalgsele robotile

Magistritöö

Juhendaja: Valery Vodovozov
Doktorikraad
Eduard Petlenkov
Doktorikraad

Tallinn 2024

Author's declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

Author: Natalia Semjonova

03.05.2024

Abstract

This thesis contributes to the development of energy-efficient pick-and-place operation techniques and enhancement of education in the field of robotics. The purpose of the study is to reduce energy consumption of a linear Delta robot and update a methodology for teaching students. To achieve this goal, three main tasks are solved: minimization of power consumed by robots in steady state, a search for the shortest route of all joint movements at which the overall energy consumption is minimal and developing a laboratory work manual for studying the Festo EXPT-45-E1 tripod robot. A new approach using neural network technology is used to create a computer model capable of simultaneously solving forward and inverse kinematics and statics problems in robotics. The methodology is developed based on experimental data collected at the Festo EXPT-45-E1 Tripod robot and MATLAB simulation tools. The results demonstrate the effectiveness of the neural network-based model in optimizing robot paths and reducing energy consumption. Furthermore, the laboratory work manuals developed as part of this thesis facilitate practical learning for students by integrating theoretical knowledge with practical application.

This thesis is written in English and is 33 pages long, including 6 chapters, 14 figures and 6 tables.

Annotatsioon

Uuringud ja laboratoorse töö arendamine Festo kolmjalgsele robotile

Robotikast ja automaatikatehnoloogiast on saanud kaasaegsete tööstus- ja hariduskeskkondade lahutamatu osa, mis soodustab innovatsiooni, tõhusust ja õppimist erinevates valdkondades. Kogumis- ja paigutamistoimingud on peamised tööstusliku automatiseerimise ülesanded, sealhulgas objektide liigutamine ühest kohast teise. Kuna tõhus tootmine on kaasaegse maailma oluline osa, muutub energiatarbimine selliste toimingute puhul üheks peamiseks probleemiks. Käesolev lõputöö aitab kaasa energiasäästlike kogumis- ja paigutamistoimingute meetodite arendamisele ning robotikahariduse täiustamisele. Uuringu põhieesmärk on vähendada lineaarse Delta roboti energiatarbimist ja uuendada üliõpilaste õpetamise metoodikat. Selle eesmärgi saavutamiseks lahendatakse kolm peamist ülesannet. Esimene ülesanne on stabiilses olekus robotite tarbitava võimsuse minimeerimine. See probleem on oluline selliste toimingute puhul nagu kokkupanek, keevitamine, pakendamine, kvaliteedikontroll või laadimine, mille puhul komplekteerimistsükli asetamise ja hoidmise faasid kestavad palju kauem kui korjamine. Teine ülesanne on kõikide liigete liikumiste lühima marsruudi otsimine, mille puhul üldine energiatarve on minimaalne. Viimane ülesanne on laboratoorse töö juhendi väljatöötamine Festo EXPT-45-E1 kolmjalgse roboti uurimiseks. Kuna traditsioonilised robotite füüsikalised ja matemaatilised mudelid ei ole keskendunud energia optimeerimisele, uudet närvivõrgutehnoloogiat kasutavat lähenemist kasutatakse arvutimudeli loomiseks, mis suudab samaaegselt lahendada edasi- ja pöördkinemaatika ja staatika probleeme robotikas. Metoodika on välja töötatud Festo EXPT-45-E1 kolmjalgse roboti ja MATLAB simulatsioonivahenditega kogutud eksperimentaalsete andmete põhjal. Tulemused näitavad närvivõrgupõhise mudeli efektiivsust robotite liikumiste optimeerimisel ja energiatarbimise vähendamisel. Lisaks hõlbustavad selle lõputöö raames välja töötatud laboratoorsete tööde juhendid üliõpilaste praktilist õppimist, integreerides teoreetilisi teadmisi praktilise rakendusega.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 33 leheküljel, 6 peatükki, 14 joonist, 6 tabelit.

List of abbreviations and terms

CNN	Convolutional Neural Networks
DOF	Degree of freedom
FCT	Festo Configuration Tool
FK	Forward kinematics
FNN	Feedforward Neural Networks
FTL	Festo Teach Language
IK	Inverse kinematics
IRL	Industrial Robot Language
JK	Joint configuration
LDR	Linear Delta robot
MSE	Mean squared error
NN	Neural network
PC	Personal computer
PnP	Pick-and-place
RL	Reinforcement learning
RNN	Recurrent Neural Network
TFC	Tool flange centre

Table of contents

1 Introduction	10
2 Literature overview.....	13
3 Festo EXPT-45-E1 tripod robot	14
3.1 Description of the robot system.....	14
3.2 Operating the robot.....	16
4 Development of the neural-network model of a tripod robot.....	18
4.1 Overview of neural network modelling.....	18
4.2 Data acquisition	19
4.3 Design and training the neural network model.....	19
4.4 Workspace evaluation.....	21
5 Research in energy-efficient pick-and-place operation on the robotic station	23
5.1 Search for joint configurations with the least power demand	23
5.2 Planning an energy-optimal path for joints	26
5.3 Analysis of energy consumption in pick-and-place operation	27
6 Laboratory work development.....	30
6.1 Teaching and programming Festo EXPT-45-E1 Tripod robot	30
6.2 Programming Festo EXPT-45-E1 Tripod robot in CIROS Studio	36
6.3 Laboratory work conduction	42
7 Results	44
8 Summary.....	46
References	47
Appendix 1 – Non-exclusive licence for reproduction and publication of a graduation thesis	49

List of figures

Figure 1. Festo EXPT-45-E1 tripod robot with vacuum gripper.....	14
Figure 2. CDSA teach pendant.....	17
Figure 3. Neural network model.....	20
Figure 4. Festo EXPT-45-E1 workspace.....	22
Figure 5. The shortest path.....	27
Figure 6. Experimental plot of power consumed in a single phase.....	28
Figure 7. Work environment.....	31
Figure 8. Algorithm of the task for laboratory work “Teaching and programming the Festo EXPT-45-E1 Tripod Robot”.....	33
Figure 9. Example of variables declaration in FTL language.....	34
Figure 10. Example of commands in FTL language.....	34
Figure 11. Example of GRAFCET sequential function chart.....	35
Figure 12. Algorithm of the task for laboratory work “Programming Festo EXPT–45–E1 Tripod robot in CIROS Studio”.....	38
Figure 13. Work environment in CIROS Studio.....	40
Figure 14. Program example in IRL language.....	40

List of tables

Table 1. Specification of the Festo EXPT-45-E1 tripod robot.....	15
Table 2. Technical characteristics of Festo EXPT-45-E1 tripod robot	15
Table 3. Several solutions of the IK problem with power data	24
Table 4. Orientation angels of the tool flange	38
Table 5. Instructions for IRL and FTL languages	41
Table 6. Comparison of NN model and CIROS Studio model	44

1 Introduction

Robotics and automation technologies have become integral components of modern industrial and educational environments, driving innovation, efficiency, and learning in a variety of fields. The unique linear Delta robot (LDR) architecture offers a variety of capabilities in a wide range of applications, from industrial automation to research in challenging environments [1]. However, LDRs are not without their complexities and limitations. Understanding and exploiting their capabilities is not an easy task, and this is where the thesis finds its purpose. The Festo EXPT-45-E1 tripod robot [2] is used for research in this work.

Pick-and-place (PnP) operations serve as fundamental industrial automation tasks, including moving objects from one place to another. Since efficient production is an important part of the modern world, energy consumption becomes one of the major concerns in such operations.

The purpose of this thesis is to reduce energy consumption of an LDR and to advance a methodology of teaching students in energy saving when performing PnP operations.

The LDR is considered as a rigid body with three degrees of freedom (DOF) machine joint dynamics of which are governed by the Newton–Euler equation [3]:

$$\tau_j = \tau_{jf} + kq + b\dot{q} + J\ddot{q} \quad (1)$$

where τ_j is the joint torque applied to j^{th} joint; τ_{jf} – its fraction directed to overcome external disturbances; k – joint stiffness dependent on the internal body mass resistance, b – damping factor, J – moment of inertia, and q, \dot{q}, \ddot{q} – vectors of joint positions, velocities, and accelerations.

The electromagnetic fraction of torque generated by an electric motor with flux linkage ψ and supply current I is:

$$\tau_j = \psi I \quad (2)$$

At the given supply voltage U , this yields in the following electrical power required to keep the joint:

$$P_j = UI = \frac{U\tau_j}{\psi} \quad (3)$$

with energy

$$E_j = P_j t \quad (4)$$

consumed during the PnP cycle time t .

According to (1), the torque τ_j developed by the joint motor is composed of two parts, namely, the steady state torque τ_{jstat} needed to withstand constant external and internal influences and the dynamic torque τ_{jdyn} required to accelerate and decelerate the motion due to robot inertia. The current study considers two research problems, and two different solutions may be found. In the first case, the focus is on the retention of the processed part in the target position, and the problem is reduced to solving (1) for τ_{jstat} only. In the second case, the total energy consumed by the robot is in the focus.

When looking for solutions, it should be borne in mind that the total power P_T and energy E_T consumption of the n -DOF robot depend on not only the common joint power and energy but on the additional parts P_{sys} and E_{sys} associated with the losses in motors and gears, power converter, fans, sensors, control equipment, and other needs of the robot system, that is:

$$P_T = P_{sys} + \sum_1^n P_j; E_T = E_{sys} + \int_0^t \sum_1^n E_j dt \quad (5)$$

This means, the power consumption of the robot depends on both the joint configuration (JK), that is a series of locations that robot joints may take while setting the tool in a target position, and other factors, and it is quite a complex problem to assess the ratio of system and joint power and energy components. In this research, this ratio is seeking experimentally.

Once the consumed power and energy (5) are found, the objective function of this research is represented as

$$P_{opt} = \min P_T, E_{opt} = \min E_T \quad (6)$$

To achieve the goals, the thesis is structured around three main tasks related to the optimal configuring of robot joints in PnP processes. The first task is to minimise the power consumed by the robot in steady state. This problem is actual in such operations as assembling, welding, packaging, quality control, loading, or wrapping, in which the placing and holding phases of the PnP cycle continue much longer time than picking. The next task is to search for the shortest path of the joint movement at which the overall energy consumption is minimal. This problem is essential for systems that require the fastest PnP cycles. The third task is the development of a laboratory practice on the LDR study and control.

Since the conventional physics-mathematical robot models are not oriented on energy optimization, a new computer model is required, which could support simultaneous solving both the forward kinematics (FK), inverse kinematics (IK) and statics problems of robotics. Neural network (NN) technology was chosen as the basis of such a model [4].

By addressing these tasks, this thesis aims to contribute to the advancement of research of LDRs by developing NN-based computer model of the LDR and manuals for laboratory work on the LDR.

In Chapter 2, literature review of previous study is presented. Chapter 3 includes description of the Festo EXPT-45-E1 tripod robot and methodology of operating the robot. In Chapter 4 development of NN model of a LDR is presented. Chapter 5 describes research in energy-efficient PnP operation on the robotic station. Chapter 6 presents development of laboratory work for the Festo EXPT-45-E1 tripod robot. In Chapter 7 the results of work are presented. Finally, Chapter 8 concludes the thesis.

2 Literature overview

The literature overview provides an exploration of existing research, with a specific focus on studies related to LDRs, and particularly to the Festo EXPT-45-E1 tripod robot.

Numerous researches are devoted to the use of NNs in solving kinematic problems in robotics. As an instance, the NN was used by Almusawi et al. [5] to find a solution of the IK problem of a Denso VP6242 robot, thereby demonstrating the effectiveness of NN-based approaches in addressing kinematic challenges. Similarly, Hasan et al. [6] in their study focused on a kinematics solution for a FANUC M-710i robot. In another study, Aggarwal et al. [7] developed an IK solution by training the NN for a PUMA 560 robot. All these studies showed the potential of NN algorithms in tackling complex robotic kinematic. However, the application of such methodologies to LDRs, and specifically to the Festo EXPT-45-E1 tripod robot, remains relatively unexplored, serving as a primary objective of this thesis.

Additionally, several studies have investigated various aspects of LDRs. For instance, Dehong et al. [8] introduced the structure design of a new type of LDR aiming to reduce the cost of production, thus highlighting the ongoing efforts. Ahangar et al. [9] studied the characteristics of the robot during PnP operations to save energy consumption. In another research, Liu et al. [10] analysed LDR workspace on the basis of the FK solution, contributing valuable insights into the spatial capabilities of these robotic systems.

Thus, although existing researches have made significant advances in understanding and optimizing the performance of robotic systems, a gap remains in the application of methodologies to LDRs, especially to the Festo EXPT-45-E1 tripod robot. By exploring similar methodologies and based on previous research, this thesis aims to contribute to the development of LDR technology and its applications.

3 Festo EXPT-45-E1 tripod robot

This Chapter provides an information of the Festo EXPT-45-E1 tripod robot, offering insights into its description, components, and operational principles. In Section 3.1 description of the robot system is presented. Section 3.2 introduces the methodologies for operating the robot.

3.1 Description of the robot system

The studied LDR contains a fixed base platform, three identical arms, and a mobile tool flange. Figure 1 shows the picture of the Festo EXPT-45-E1 tripod robot.

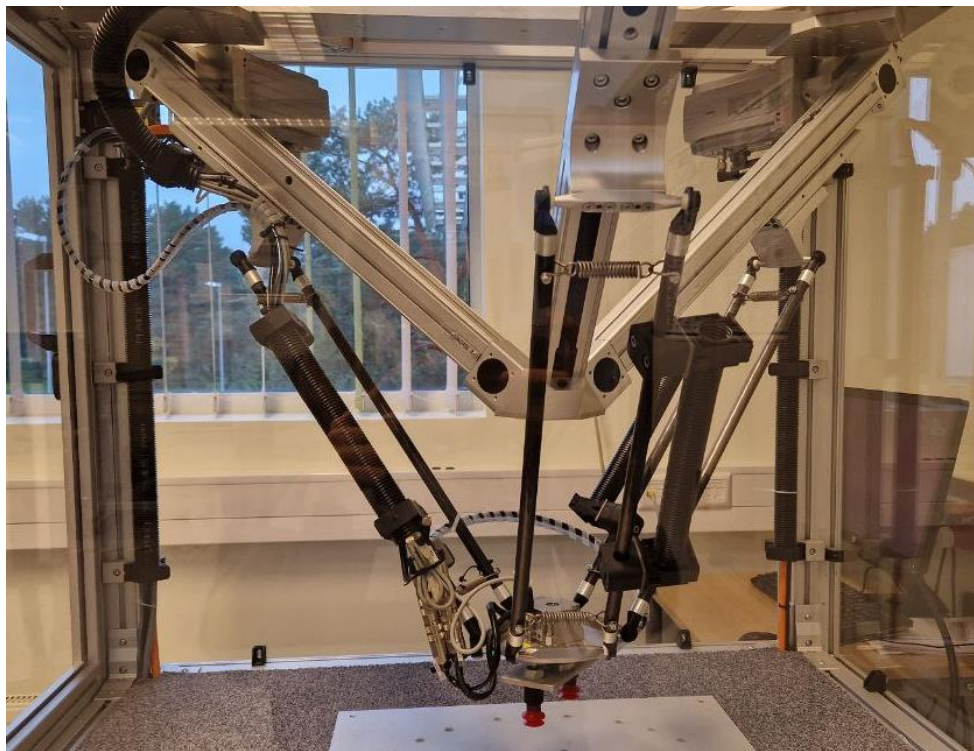


Figure 1. Festo EXPT-45-E1 tripod robot with vacuum gripper

Each arm has a parallelogram rod driven by one of three linear axes: A1, A2, or A3. These rods are accompanied by three passive joints, which collectively enable movement of the tool flange along the Cartesian XY axes parallel to the base platform, as well as along the Z axis vertically [11]. Each axis is driven by a servo motor featuring an absolute displacement encoder.

An additional rotational joint A4, equipped with a rotary actuator with an incremental encoder, facilitates the tool flange turning around an axis intersecting the tool flange centre (TFC). The tool itself is equipped with two suction cups located on both sides of the TFC at a distance of 45 mm.

Table 1 shows specifications of the Festo EXPT-45-E1 tripod robot.

Table 1. Specification of the Festo EXPT-45-E1 tripod robot

Component		Actuator	Control system
Linear axes DGE-25- 224-ZR- RF-LK-RH- SA	A1	Servo motors EMMS-AS- 100-S-RMB	Servo controller CMMP- AS-C5-3A
	A2		Servo controller CMMP- AS-C5-3A
	A3		Servo controller CMMP- AS-C5-3A-M0
Rotational axis A4		FHA-xC Hollow Shaft Actuator	Servo controller CMMP- AS-C5-3A

To facilitate seamless operation, a control cabinet housing controllers, electrical components, and pneumatic equipment is securely mounted beneath the robot.

The Festo EXPT-45-E1 tripod robot technical characteristics are presented in Table 2.

Table 2. Technical characteristics of Festo EXPT-45-E1 tripod robot

Parameter	Value
Workspace diameter	450 mm
Base platform shoulder, B1	0.549 m
Linear rail of upper sub-arm, B2	From 0 to 0.224 m

Parameter	Value
Parallelogram rod length, B4	0.738 m
Tool flange shoulder, B6	0.200 m
Maximal payload	5 kg
Maximal velocity	7 m/s
Maximal accuracy	0.0005 m
Maximal Z force	1300 N
Servomotor EMMS-AS-100-S-RMB of every arm	360 V; 3.8 A; 1497 W; 3.76 – 4.71 Nm
Maximal power consumed by robot	4900 W
Minimal power consumed by robot	320 W

3.2 Operating the robot

The LDR EXPT-45-E1 contains also a teach pendant CDSA-D1-VX [12] linked to a personal computer (PC) equipped with Festo Configuration Tool (FCT) software for operating and programming the LDR.

The teach pendant (Fig. 2) is used for jogging and LDR programming by teaching, observing system state, and diagnostics. Its touch screen features a *Status* line at the top and a *Menu bar* at the bottom. Additionally, it includes a *Mask panel* positioned to the left and a *Jog panel* to the right. A *Deadman switch* located on the back of the teach pendant ensures safe control during operation.

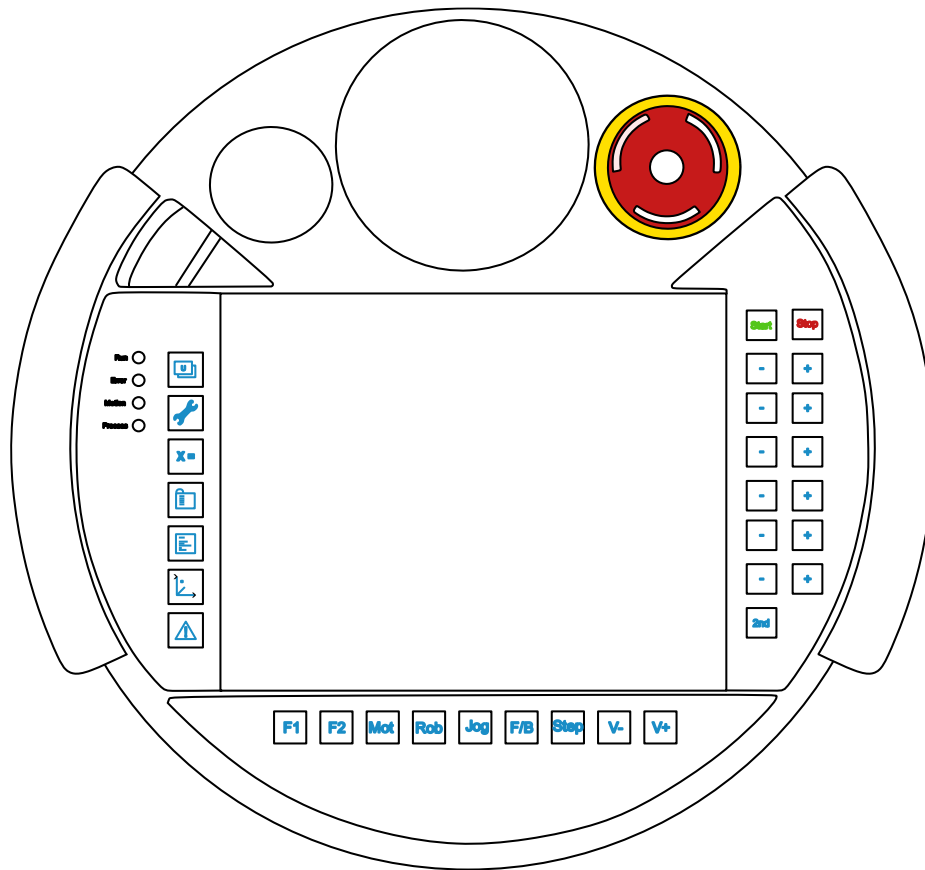


Figure 2. CDSA teach pendant

The LDR operates in manual and automatic modes. The manual mode is used to manually move the LDR, check the system, test, and commission the programs. Each axis can be moved individually in a joint frame, and the robot can be jogged linearly in a world frame. The zeroing of the 4th axis is accomplished by the homing program. Rotation of the tool is restricted between -90 and +270 degrees. The speed is limited to maximum of 250 mm/s.

To operate in automatic mode, a Festo Teach Language (FTL) is used [13]. Programming can be done from the teach pendant or from a PC with an FCT software installed.

4 Development of the neural-network model of a tripod robot

This Chapter describes creation of a NN model for the Festo EXPT-45-E1 tripod robot. In Section 4.1 overview of NN modelling is presented. Section 4.2 describes acquisition of data. Section 4.3 describes design and training the NN model using MATLAB, and finally, in Section 4.4, workspace evaluation is brought up.

4.1 Overview of neural network modelling

The NNs, inspired by the structure and function of the human brain, offer a powerful framework for modelling complex relationships and making predictions based on input data. Developing a NN model for a robot is useful for unlocking its full potential and allowing it to operate effectively in dynamic and complex environments.

Feedforward Neural Networks (FNN) are the most common type of NNs in which information flows in one direction, from input to output. They are well suited for problems related to pattern recognition and function approximation [14].

Recurrent Neural Networks (RNN) are designed to process sequential data and have circular connections, which allow them to exhibit temporal dynamic behaviour. Although RNNs are effective for tasks such as time series forecasting and natural language processing, they may not be the most suitable choice for modelling the kinematics of a robotic system such as an LDR.

Convolutional Neural Networks (CNN) are primarily used for image processing tasks, where they excel at feature extraction and pattern recognition. Since the LDR model focuses on kinematics rather than visual data, CNNs are not the optimal choice for this particular task.

Reinforcement learning (RL) is a type of machine learning in which agents learn to make decisions by interacting with the environment to maximize rewards. Although RL has been successfully applied to a variety of robotics problems, including robot control and navigation, it may not be the most suitable approach for modelling the kinematics of an

LDR, as RL often requires a large number of interactions with the environment. It may also provide a less transparent understanding of the learned policy compared to simpler NNs [15].

Therefore, FNNs offer a simpler and more efficient approach to model development and training. MATLAB has built-in application called The Neural Net Fitting, which specializes in creating and training FNNs, making it a suitable choice for developing models for the Festo EXPT-45-E1 tripod robot.

4.2 Data acquisition

The initial step in developing an accurate NN is the collect and preprocess the relevant data. The required input data that needs to be collected to create the NN model of the robot are the positions of the joints, the positions of the tool in the Cartesian coordinate system, and consumed power.

To collect data on joint positions, Cartesian coordinates of the TFC, and consumed power, the workspace of the robot was first divided into a set of 496 constituent cells. When systematically moving the tool in the joint frame along these cells, data on the positions of joints and Cartesian coordinates were read from the teach pendant. The frequency of data collection is approximately 30 mm. The maximum joint parameter is 224 mm, since in order to avoid collisions with the walls of the box in which the robot is located, it has this limit.

To measure consumed power and estimate energy, Fluke 1745 power quality logger with PQ Log software was applied [16]. The PQ Log software prepares the device for use and downloads data from the Logger to the connected PC. Power was measured with and without additional load.

4.3 Design and training the neural network model

The collected data was divided into predictors and responses for FK problem solving: 3 joint positions in joint frames A1, A2 and A3, representing predictors, and 3 tool positions in Cartesian frame X, Y and Z with corresponding power values P, representing responses. For IK problem data was divided into predictors and responses as follows: tool

positions in Cartesian frame resent predictors, and joint positions with power represent responses.

Next step is to import a set of predictors PRED (496x3 double) and a set of responses RESP (496x4 double) in the Neural Net Fitting app. These datasets are then partitioned into training, validation, and test sets as follows: 70% for training, 15% for validation, and 15% for testing.

The NN is trained using the Levenberg-Marquardt gradient descent algorithm with random data division and evaluating performance based on mean squared error (MSE). A synthesized double-layer FNN architecture comprises 10 neurons with sigmoid activation functions in a hidden layer and 4 linear output neurons. Figure 3 shows the NN architecture.

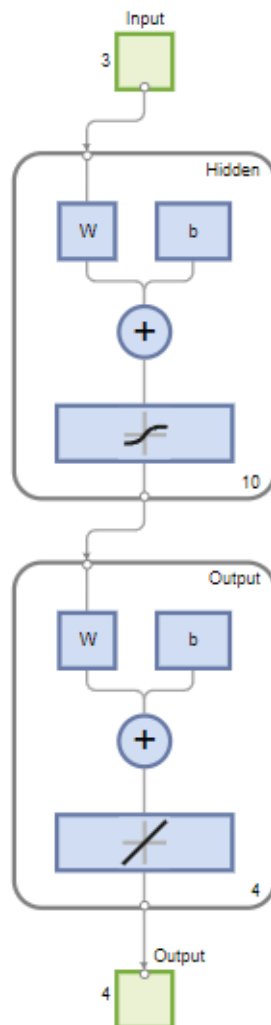


Figure 3. Neural network model

The following results were obtained:

- In training: MSE = 0.00715 and regression R = 0.9986
- In validation: MSE = 0.000012 and R = 0.9983
- In testing: MSE = 0.00036 and R = 0.9972

After training, the NN codes generated by the app are forwarded to MATLAB for their use as an NN-based LDR model for subsequent solution of the FK and IK with power consumption problems in the full spectre of all required PnP operations.

4.4 Workspace evaluation

To validate the developed robot model as an FK solver, the following procedure is performed. First, an $\{n \text{ to } 3\}$ -size joint array (JOINT) is generated, where n is a number of permissible A1, A2, A3 joint positions, $n \gg 496$. Using the NN model, this array is transformed to another $\{n \text{ to } 4\}$ -size array of Cartesian tool coordinates X, Y, Z and consumed powers P (CARTP). A minor part of the JOINT and CARTP arrays fits in earlier observed data whereas their majority is intended to predict possible LDR states and behaviour.

The obtained CARTP array is suitable for estimating the robot workspace, i.e. a set of all spatial positions that a tool might reach without collisions and singularities. To identify the workspace, the FK problem is solved repeatedly while every joint cyclically increases its position value within the prescribed limits and the appropriate Cartesian tool coordinates are defined using the NN model of the LDR. The robot workspace plotted with the help of the designed FK solver is displayed in Fig. 4.

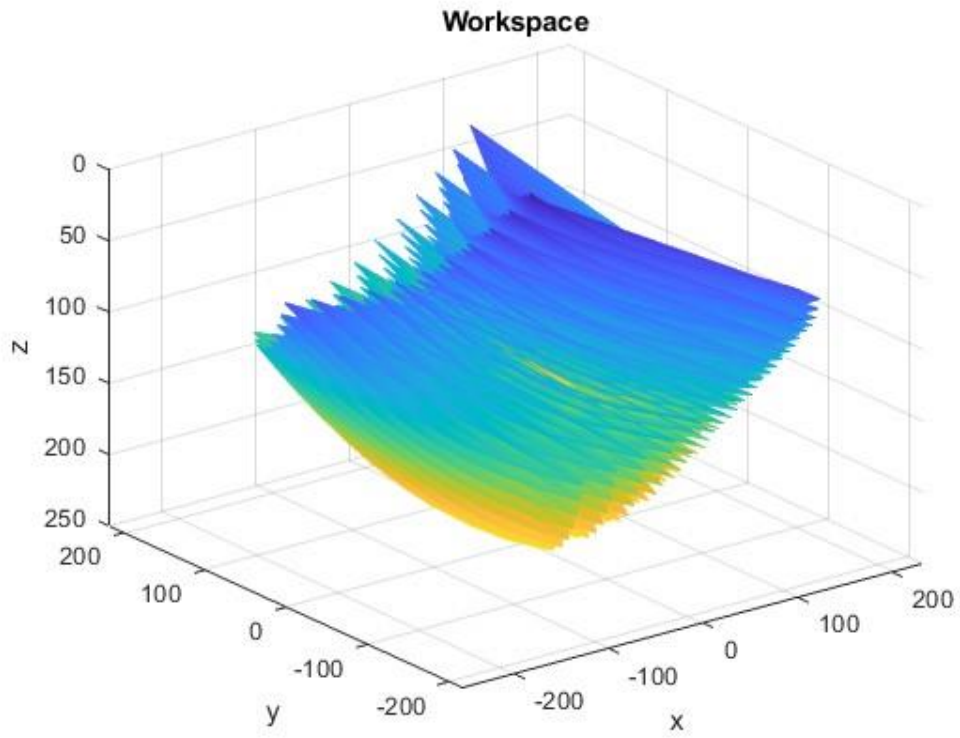


Figure 4. Festo EXPT-45-E1 workspace

5 Research in energy-efficient pick-and-place operation on the robotic station

This Chapter describes research in energy-efficient PnP operation. Section 5.1 introduces search for joint configurations with the least power demand. In Section 5.2 planning an energy-optimal path for joints is presented. Section 5.3 presents analysis of energy consumption in PnP operation.

5.1 Search for joint configurations with the least power demand

LDR accuracy must always exceed the tolerance of PnP operations this robot performs. This tolerance takes into account factors such as mechanical inaccuracies, sensor noise, and environmental variations that may affect the robot's performance. Using such a tolerance as a certain degree of flexibility, it is suitable to ensure that the tool reaches the target position with acceptable accuracy. Thus, every joint location in the JOINT array may result in a number of similar Cartesian locations in the CARTP array. This means that different power amounts can be consumed while the tool achieves the same Cartesian positions at different JKs. Consequently, a search for JKs with the least power demand may be chosen as the key factor of the optimisation procedure in the steady state.

The proposed method for searching the best JKs tends to the common solution of the IK and inverse statics problems. Various algorithms are known in robotics to generate IK problem solutions. Usually, they employ iterative gradient-based optimization algorithms that start with an initial guess about the solution and seek to reduce a specific cost function. Since most of them fail with some combinations of the initial assumption and target tool positions, not all IK and power estimation requirements can be met with their help. This is especially important for LDRs that are the 3-DOF machines of parallel architecture. Taking into account this issue, another solution of the inverse problems is applied in this work using an LDR model generated in the previous Chapter to resolve the IK problem along with power optimization. To find the best JKs, the IK problem is solved for each required Cartesian position of the tool. Since not only the Cartesian

coordinates are stored in the CARTP array but also information about consumed power, the optimal JK may be selected in such a way as to ensure minimum power consumption.

Table 3 illustrates a case study, in which a specific PnP process is described by 10 targets corresponding to 10 Cartesian positions X, Y, Z by which the tool passes with a 5% tolerance. In this example, every target can be reached at one of four JKs with different A1, A2, A3 joint coordinates and power demands P that were found as solutions of the problem. The JKs with minimal consumed power are highlighted. In the last column, amounts of saved power are calculated for each target. This PnP case study shows that by choosing an optimal JK, it is possible to reduce the static power consumption of the LDR quite slightly, mostly less than 3%. Such reduction looks rather small compared to 18% savings achieved in 6-DOF robots of serial architecture [17].

Table 3. Several solutions of the IK problem with power data

Target	X	Y	Z	A1	A2	A3	P	ΔP
1	-85	21	70	109.1480	28.2801	13.5913	208.9	5.5 (2.7%)
				108.3571	38.1076	15.8222	207.0	
				108.3166	48.9107	19.0117	205.2	
				108.9727	60.3681	22.9802	203.4	
2	91	-39	140	63.1707	115.8895	157.2348	224.4	3.7 (1.7%)
				66.7210	127.2989	161.4614	222.9	
				70.2313	137.8271	165.5269	221.7	
				73.5232	147.3962	169.4440	220.7	
3	172	124	115	9.6362	204.0779	112.7080	230.8	4.3 (1.9%)
				14.7359	211.2865	118.5259	229.7	
				20.2409	217.3044	123.6276	228.2	

Target	X	Y	Z	A1	A2	A3	P	ΔP
				26.0494	222.5902	128.3271	226.5	
4	57	9	70	12.9823	60.9977	61.1159	224.9	1.9 (0.8%)
				15.0695	72.9794	65.7687	224.4	
				17.4864	84.5425	70.5770	223.7	
				20.1748	95.5695	75.4588	223.0	
5	-19	125	140	134.6042	157.4037	42.8794	204.4	4.9 (2.4%)
				137.8368	169.1124	50.2885	202.6	
				141.3662	182.1996	58.6999	200.9	
				145.2806	195.2227	67.1115	199.5	
6	90	-143	120	62.6975	55.1792	201.8083	218.4	3.5 (1.6%)
				64.2962	69.4399	205.2912	217.3	
				66.4443	83.9062	209.0288	216.2	
				68.9115	98.1500	212.8591	214.9	
7	-50	-50	100	110.2935	18.5455	89.3192	226.5	0.7 (0.3%)
				108.6405	29.0561	91.5000	227.0	
				108.0820	40.7031	94.5768	227.2	
				108.3553	52.9375	98.1988	227.2	
8	51	-87	72	30.4995	12.8139	117.9472	206.2	4.9 (2.4%)
				29.2389	23.4756	120.0357	204.4	
				28.9284	35.0994	122.9182	202.8	

Target	X	Y	Z	A1	A2	A3	P	ΔP
				29.4046	47.3212	126.3841	201.3	
9	37	-33	164	112.9763	120.6523	155.4786	227.1	0.7 (0.3%)
				115.3915	130.9105	158.7555	227.6	
				117.4830	139.9556	161.7388	227.8	
				119.1707	147.8480	164.4924	227.6	
10	107	-4	161	75.5419	150.3808	160.9952	208.7	5.3 (2.6%)
				78.5913	159.3254	165.3428	206.9	
				81.1656	168.3225	170.2553	205.1	
				83.2178	177.9274	176.0893	203.4	

5.2 Planning an energy-optimal path for joints

In accordance with (6), another way to save power is by minimization of the total joint route through all targets considering all possible JKs at which the overall energy consumption becomes minimal as a result of reducing the time of the PnP process.

The following solution is offered to this aim. In the case study of the previous Section, the desired PnP route passes via 10 targets, each of those can be achieved using one of 4 possible JKs. A $\{10 \text{ to } 4^2\}$ -size array represents all possible distances between the candidate joints. Each distance is calculated as a maximal offset between conforming positions of joints A1, A2, A3 in the neighbour targets and labelled as “11”, “12”, ..., “1p”, “21”, ..., “104” where the first digit specifies the target number and the second one – its JK number in this target. To search and plot the shortest path, the “*shortestpath*”, “*digraph*”, “*highlight*”, and “*printpath*” MATLAB functions are applied.

Figure 5 shows the shortest path that MATLAB reproduces for a given PnP operation. The path starts and ends at the zero position. Here, 10 rows represent 10 targets and 4

nodes in each row represent 4 possible JKs for each target. The shortest path is highlighted with a thick line.

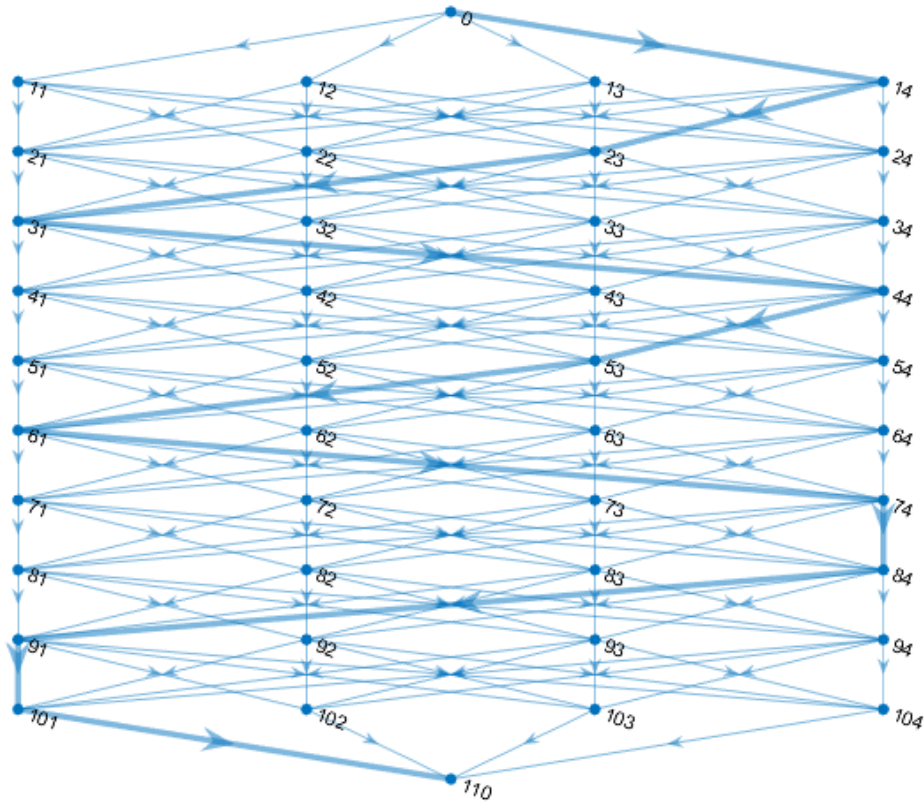


Figure 5. The shortest path

5.3 Analysis of energy consumption in pick-and-place operation

To validate the effectiveness of the optimized path for the robot, a program is created with the proposed joint positions. The program consisted of point-to-point movement commands for moving around 10 targets. The execution of the program is observed, and the taken time and speed are recorded. Energy consumption is calculated taking into account the time and power spent.

The program execution took 67 seconds at a speed of 21.67 *mm/s*.

Figure 6 shows the power measurements during program execution. The average power of one phase is 70 *W*. The total power of three phases is 210 *W*.

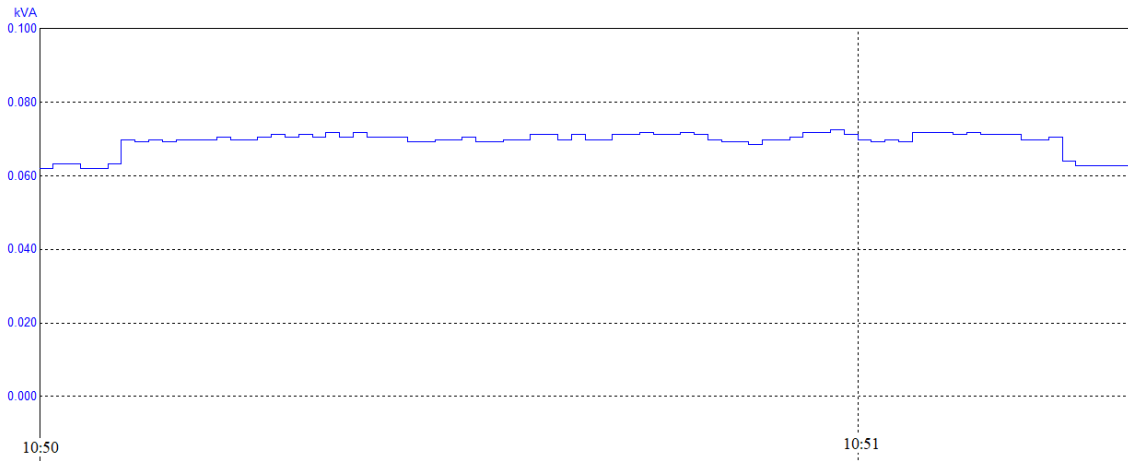


Figure 6. Experimental plot of power consumed in a single phase

Energy consumption (4):

$$210 \text{ W} * 67 \text{ s} = 14070 \text{ Ws}$$

In order to check that this path was the shortest, another program was compiled with different joint positions, within a tolerance of 5%. The program execution took 74 seconds with the same speed as for the previous program.

Energy consumption of the second program:

$$210 \text{ W} * 74 \text{ s} = 15540 \text{ Ws}$$

The analysis shows significant energy savings of 9.5% using the optimized path, highlighting the effectiveness of the proposed methodology in reducing energy consumption and increasing operational efficiency.

The same programs were created for CIROS Studio to check the result in a simulation environment. These programs consisted of linear movement command for moving around the same 10 targets.

Execution of the program with the joint positions that MATLAB found most efficient took 65 seconds.

A program with different joint positions was also created for CIROS Studio to check that the path generated by MATLAB was the shortest. This program execution took 71 seconds.

An analysis reveals savings of 8,5% when using the optimized path, highlighting the effectiveness of the proposed methodology in reducing energy consumption.

6 Laboratory work development

This Chapter describes two laboratory exercises developed to familiarize students with the Festo Tripod robot [18]. In Section 6.1 laboratory work “Teaching and programming the Festo EXPT-45-E1 Tripod Robot” is presented. Section 6.2 introduces laboratory work “Programming Festo EXPT–45–E1 Tripod robot in CIROS Studio”. In Section 6.3 results of laboratory work conduction are brought up.

6.1 Teaching and programming Festo EXPT–45–E1 Tripod robot

The purpose of the laboratory work “Teaching and programming Festo EXPT–45–E1 Tripod robot” is to familiarize students with the LDR equipped with a double-vacuum gripper and teach them how to control and operate it with a teach pendant and program it by specialized software FCT.

For this laboratory task, students are equipped with essential tools, including the Festo tripod robot, which includes a vacuum gripper and a teach pendant. Additionally, they work with cylindrical workpieces and utilize a circular playground divided into eight sectors, each with circular cells equally spaced from one another. Moreover, they utilize a PC with the FCT program installed to create robot control programs. Figure 7 shows work environment.

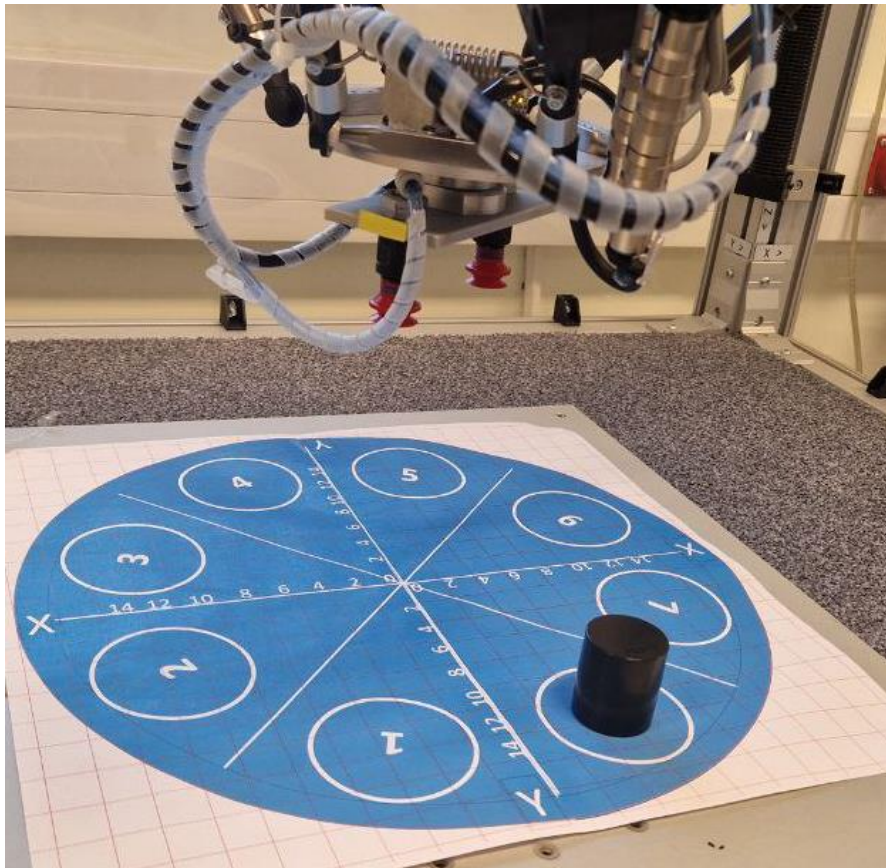


Figure 7. Work environment

Before starting to work with the robot directly, students need to understand the equipment that they will be using and the purpose of the laboratory work. Therefore, the initial section of the manual provides the objective of the work and a brief overview of the robot and its components, enabling students to get acquainted with the theory before proceeding further.

Once students have acquainted themselves with the robot and have checked safety conditions, students can proceed to the first part of robot control, which is called Jogging. In this section students learn how to operate the robot in *Joint* frames and *World* frame using the teach pendant.

Now, when students are familiar with operating the robot and have reviewed the sample program, they are prepared to begin the laboratory assignment and develop their own program. The next chapter of the manual is the description of the task that students are required to perform. Students are expected to implement the following PnP duty cycle (Fig. 8):

- The robot should transport a workpiece from a feeding cell to an interim cell located on the playground two sectors away or at an angle of 90° from the feeding cell and then return to the home position.
- The robot shall transport this workpiece to the receiving cell located two sectors further or at the angle of 180° from the feeding cell and then return to the home position.

To complete this task, the TFC locations of the feeding and interim cells must be found experimentally and taught by using the teach pendant, whereas the TFC location of the receiving cell needs to be specified by calculation.

Before and after gripping and releasing the workpiece, the robot must move higher (decreasing the Z coordinate) while maintaining the same X and Y coordinates so as not to break the workpiece or the gripper, so there is a need for additional targets above the feeding, interim and receiving cells.

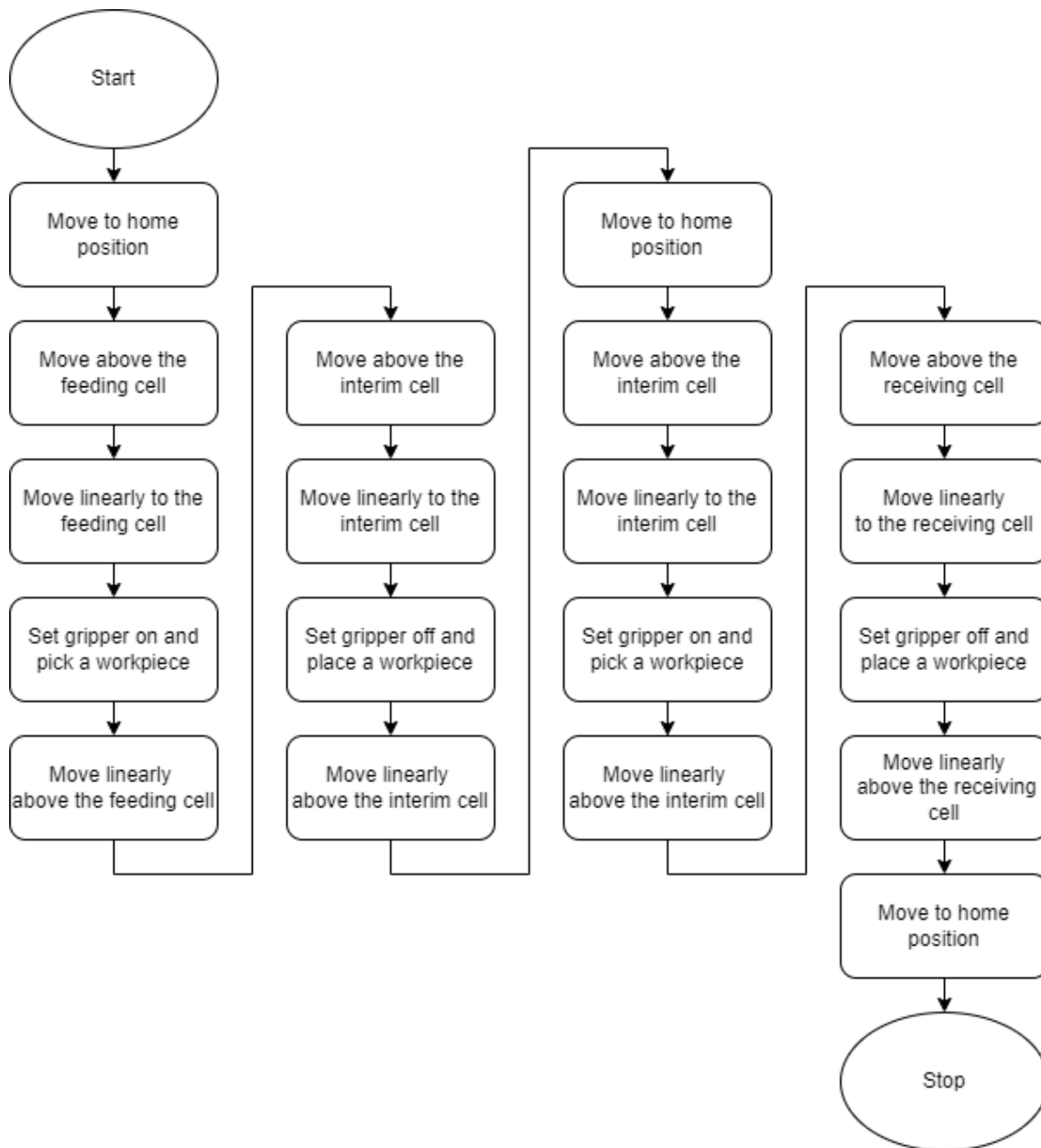


Figure 8. Algorithm of the task for laboratory work “Teaching and programming the Festo EXPT-45-E1 Tripod Robot”

The next section describes how to specify positions through which the robot will be moved. The method for it is called *Teaching*, it saves the coordinates of the current position of the robot. In order to manipulate variables, students are required to create a program file within the preexisting project named *Students*. Upon loading the created program, they can then generate new variables and store needed positions. These position variables can be established using Cartesian coordinates or axis coordinates. The variable type AXISPOS contains the data of the positions of the robot's four axes, representing its movement along the A1, A2, A3, and rotational A4 axes. The variable type CARTPOS

is dedicated to storing data of Cartesian coordinates, representing the robot's position in three-dimensional space along the X, Y, and Z coordinates, and rotational A4 axes.

Once variables for the feeding and interim cells are ready, students can proceed to the programming. The programming part must be done on a PC using the FCT software.

The short program sample in FTL is shown below divided into local variables part (Fig. 9) and program part (Fig.10):

Local variables:

```
// Joint coordinates
Home_P : AXISPOS := (0, 0, 0, 0, 0, 0, 0, 0, 0)

// Cartesian coordinates
P01 : CARTPOS := (-14.7001, 147.278, 95.1616, -89.7931, 0,
0, 0, 0, 0)
P02 : CARTPOS := (-14.7038, 147.277, 130.994, -89.7915, 0,
0, 0, 0, 0)

// Gripper declaration
Gripper1      :      DOUT      :=      (-1,      FALSE,
MAPX("_system.PLC_sreg_free2"))
```

Figure 9. Example of variables declaration in FTL language

Program:

```
Ptp(Home_P) // Point-to-point movement
Ptp(P01) // Point-to-point movement
Lin(P02) // Linear movement
Gripper1.Set() // Gripper on
WaitTime(500) // Delay
Lin(P01) // Linear movement
```

Figure 10. Example of commands in FTL language

Once the program is completed it can be loaded into the robot and can be run for testing.

The next step is to calculate coordinates for the receiving cell and add new variables and commands into the program. The calculation of the coordinates of the TFC must be done based on the suction cup coordinates x_c, y_c that can be found from the playground coordinate system, its linear offset $d_c = 45 \text{ mm}$ from the TFC, degree of the fourth axis, and angular tool flange offset dA from -X Cartesian axis, that students have to measure themselves:

$$x = x_c + d_c * \cos(A4 + dA); y = y_c - d_c * \sin(A4 + dA) \quad (7)$$

As the zero position of the fourth axis is shifted to the left from the y axis, therefore the fourth axis calculation methodology was developed. For calculating the fourth axis parameter the angular flange offset that is 30 degrees must be subtracted from the orientation angel.

After testing the program and completing the laboratory work, students are required to write a report containing the following information:

- Robot name, its degree of freedom, body names, and joint types.
- GRAFCET sequential function chart of the robot operation. Figure 11 shows a short example of the GRAFCET sequential function chart.

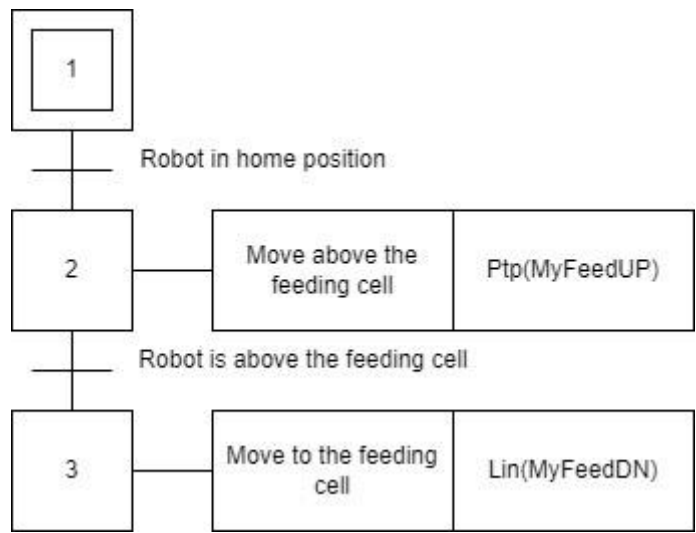


Figure 11. Example of GRAFCET sequential function chart

- Calculation of x_c, y_c coordinates of feeding, interim and receiving tool locations, and receiving x, y coordinates of TFC.

- A table of the taught and calculated $x, y, z, A4, x_c, y_c$ coordinates of feeding, interim, and receiving tool locations.
- Program text with comments.
- Conclusions on robot control, programming, debugging, and calculation.
- Video of the robot operation

The laboratory work "Teaching and programming Festo EXPT–45–E1 Tripod robot" has achieved its goals: familiarize students with the Festo tripod robot equipped with a double vacuum gripper, and to provide the necessary skills to control, operate, and program it. Through hands-on exercises with the teach pendant and the FCT software, students have gained practical knowledge and experience in operating the robot's functions, understanding its programming interface, and performing tasks.

6.2 Programming Festo EXPT–45–E1 Tripod robot in CIROS Studio

The purpose of the laboratory work “Programming Festo EXPT–45–E1 Tripod robot in CIROS Studio” is to introduce students to the operational functionalities of the Festo tripod robot equipped with a double vacuum gripper and teach them how to create programs using CIROS Studio to simulate robot movements within a virtual environment, modifying code to adapt to the real robot, and evaluating the program's effectiveness through practical experimentation.

For this laboratory work, students utilize a PC with the CIROS Studio program installed to simulate robot within virtual environment. Additionally, they work on a PC with the FCT software installed to create the real robot control programs. Moreover, students are equipped with the Festo tripod robot, which includes a vacuum gripper and the teach pendant, to be able to evaluate the program's effectiveness. Robot’s work environment also has cylindrical workpieces and a circular playground divided into eight sectors, each with circular cells equally spaced from one another.

For simulation the Festo tripod robot students are required to use CIROS Studio, a platform for creating and using 3D models for automation technologies. The need to learn how to work in CIROS Studio is due to several factors. First, there is a need to diversify

programming skills by learning another programming language that CIROS Studio provides. This allows students to expand their knowledge of robotics programming tools and techniques. The ability to translate commands, instructions, and code from one language to another is important for future works in robotics. Second, CIROS Studio offers graphics and video capabilities needed to simulate and visualize robotic operations in a virtual environment. This aspect enhances students' understanding of robot behaviour and interaction.

However, it is important to note that CIROS Studio has limitations, one of which is the lack of a fourth axis. This limitation limits the robot's movement to three-dimensional space, potentially limiting the complexity and realism of simulated robotic tasks.

The task of the laboratory work is to design a program of the TFC motion for the following PnP duty cycle (Fig.12):

- Start from a home position.
- Pick a workpiece from a given feeding cell.
- Place the workpiece to a receiving cell located on the playground three sectors away or at the angle of 135° from the feeding cell.
- Return the TFC back to the home position.

This task differs from the “Teaching and programming Festo EXPT–45–E1 Tripod robot” laboratory work’s task in that there is no interim cell for this task and robot moves straight to the feeding cell from the receiving cell. The simulation model of the robot does not have gripper and additional rotational axis, meaning that program for CIROS Studio must be created without gripper commands and later these commands must be added into the program for the real robot.

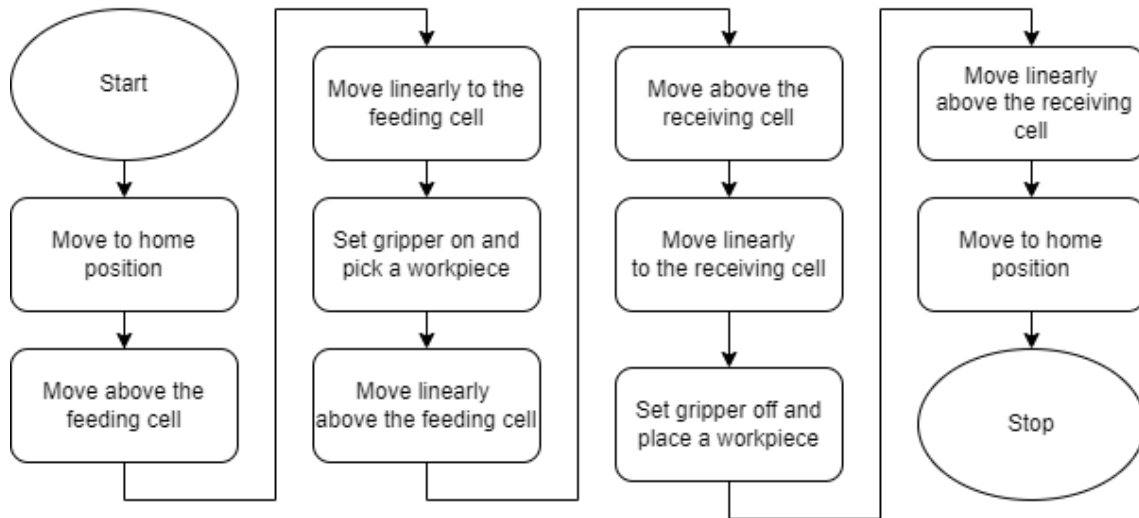


Figure 12. Algorithm of the task for laboratory work “Programming Festo EXPT–45–E1 Tripod robot in CIROS Studio”

The laboratory work starts with calculation of required coordinates. The suction cup coordinates x_{CF}, y_{CF} of the feeding cell and the receiving cell coordinates x_{CR}, y_{CR} should be calculated, therefore the table of orientation angles of the tool flange in the feeding A_F and receiving A_R cells in respect to $-X$ axis is given. Orientation angles of the tool flange are presented in the Table 4.

Table 4. Orientation angles of the tool flange

Cell	1	2	3	4	5	6	7	8
A_F	67.5°	22.5°	-22.5°	X	247.5°	202.5°	157.5°	112.5°
A_R	202.5°	157.5°	112.5°	X	112.5°	67.5°	22.5°	-22.5°

The use of the fourth cell is restricted due to limitations in the rotation of the fourth axis, implemented to prevent potential damage to the gripper.

The cells' centres are at a distance $R_C = 150 \text{ mm}$ from the playground centre. Equations for calculating the suction cup coordinates:

$$x_{CF} = -R_C * \cos(A_F) \quad (8)$$

$$y_{CF} = R_C * \sin(A_F) \quad (9)$$

$$x_{CR} = -R_C * \cos(A_R) \quad (10)$$

$$y_{CR} = R_C * \sin(A_R) \quad (11)$$

Based on the calculated suction cup coordinates students are required to calculate the appropriate x_F, y_F and x_R, y_R coordinates of the TFC that will be used in the program. The tool has two suction cups placed at $d_C = 45 \text{ mm}$ on both sides of the TFC. Equations for calculating the coordinates of the TFC:

$$x_F = x_{CF} + d_C * \cos(A_F) \quad (12)$$

$$y_F = y_{CF} - d_C * \sin(A_F) \quad (13)$$

$$x_R = x_{CR} + d_C * \cos(A_R) \quad (14)$$

$$y_R = y_{CR} - d_C * \sin(A_R) \quad (15)$$

CIROS Studio has Festo Tripod model in its model libraries, therefore students can use this model to simulate robot movement within the virtual environment and operate the virtual robot by *Teach-in* window in joint positions and Cartesian coordinates.

The world coordinates in CIROS Studio differ from the robot coordinates. Therefore, it is necessary to establish a user-defined frame, referred to as a *3D marker* in CIROS Studio, in order to design a work environment. Figure 13 shows a work environment in CIROS Studio.

CIROS Studio model libraries include geometric figures that students can use to design virtual playgrounds and workpieces. This enables them to visually verify the correct execution of their programs. As simulation robot does not have a gripper as a real robot does, the workpieces should be located at the x_F, y_F and x_R, y_R coordinates of the TFC that will be used in the program.

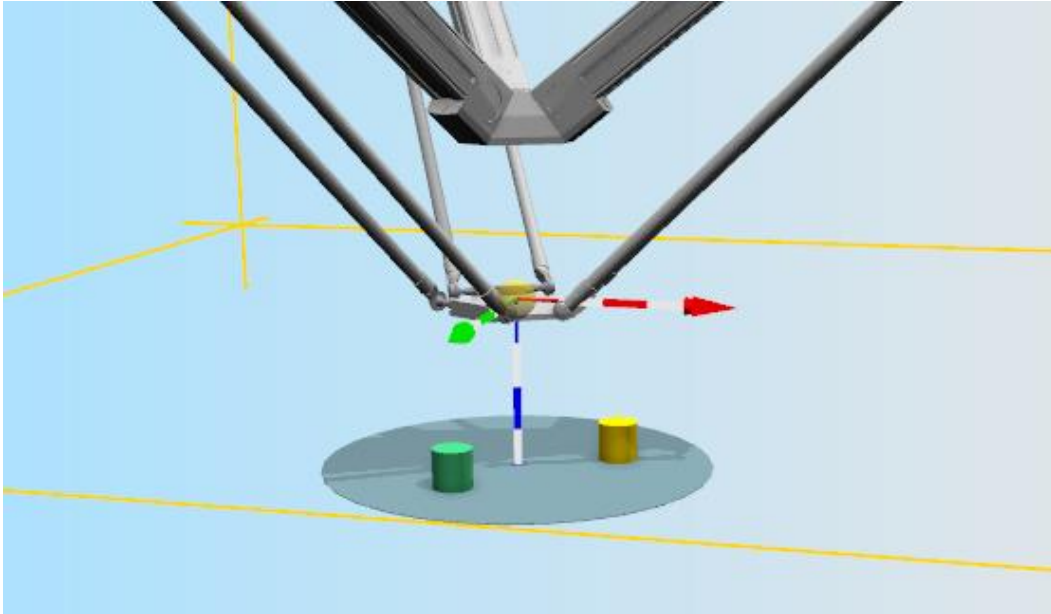


Figure 13. Work environment in CIROS Studio

CIROS Studio uses Industrial Robot Language (IRL) for programming. A short program sample is shown below (Fig.14):

```

PROGRAM main;
VAR
{axis coordinates}
MAIN_JOINT: HomePos := MAIN_JOINT (0.00, 0.00, 0.00);
{Cartesian coordinates}
POSITION: myFeedUP := POSITION (-40.00, 97.00, 100.00);
POSITION: myFeedDn := POSITION (-40.00, 97.00, 130.00);
BEGIN
MOVE PTP HomePos; {point-to-point movement}
MOVE PTP myFeedUP; {point-to-point movement}
WAIT 0.5 SEC; {wait 0.5 sec}
MOVE LIN myFeedDn; {linear movement}
ENDPROGRAM;

```

Figure 14. Program example in IRL language

After completing the program and ensuring its error-free functionality, students may then proceed to modify code for the FTL language and upload their program into the FCT for testing it on the real robot. Students are provided with a table containing instructions for both languages to facilitate the modification of the program. Table 5 shows instructions for both languages.

Table 5. Instructions for IRL and FTL languages

Industrial Robot Language	Festo Teach Language
POSITION: variable_name:= POSITION (-40.00, 95.00, 130.00)	variable_name : CARTPOS := (-40, 95, 130, 0, 0, 0, 0, 0, 0)
MAIN_JOINT: variable_name := MAIN_JOINT(10.00, 20.00, 30.00)	variable_name : AXISPOS := (10, 20, 30, 0, 0, 0, 0, 0, 0)
MOVE PTP variable_name	Ptp(variable_name)
MOVE LIN variable_name	Lin(variable_name)
WAIT 0.5 SEC	WaitTime(500)
	Gripper1.Set()
	Gripper1.Reset()
{comment}	// comment

After testing the program and completing the laboratory work, students are required to write a report containing the following information:

- Robot name, its degree of freedom, body names, and joint types.
- GRAFCET sequential function chart of the robot operation (Fig.11).
- Calculation of the feeding and receiving suction cup coordinates $x_{CF}, y_{CF}, x_{CR}, y_{CR}$ as well as x_F, y_F and x_R, y_R coordinates of TFC.

- A table of A_F, A_R and $x_{CF}, y_{CF}, x_{CR}, y_{CR}, x_F, y_F, x_R, y_R$ coordinates of feeding and receiving cell and TFC locations.
- IRL and FTL program texts with comments.
- Conclusions on robot control, programming, debugging, and calculation.
- Two videos of virtual and real robot operation.

The laboratory work "Programming Festo EXPT-45-E1 Tripod robot in CIROS Studio" has introduced students to the operational functionalities of the Festo tripod robot equipped with a double vacuum gripper and gave them with essential skills in programming using CIROS Studio. Through practical exercises in a virtual environment, students have learned how to write programs to simulate robot movements, modify code for the real robot, and evaluate the effectiveness of their programs through practical experimentation.

6.3 Laboratory work conduction

As a conclusion to the development of laboratory work manuals, laboratory works were carried out for students. The laboratory work conduction is an important part of the research to test the developed manuals in practice.

Through careful planning, detailed documentation, and practical instructions, the manuals are an important resource for helping students complete practical exercises and experiments with the Festo EXPT-45-E1 Tripod robot.

- Each manual is structured logically and intuitively, with step-by-step procedures accompanied by relevant diagrams, screenshots, and explanatory notes.
- Emphasis is placed on ensuring clarity, accuracy, and completeness, allowing students to complete the laboratory work with confidence and clarity.

Based on students' feedback, the manuals have been improved to enhance clarity, usability, and effectiveness.

- The manuals are designed to promote active student participation and facilitate meaningful learning.

- Following the instructions in the manuals, students actively participate in practical activities, conduct experiments, and analyse results, getting a deeper understanding of robotics concepts and principles.
- The structured manuals promote the development of independent learning and problem-solving skills, empowering students to take responsibility of their education.

The conduction of laboratory work is an important part of the educational experience, allowing students to bridge the gap between theory and practice and develop necessary skills to succeed in the field of robotics and automation.

7 Results

The advantages of the new model over CIROS Studio are numerous and serve to enhance its usefulness and applicability in robotics research and education. These benefits are explained in the Table 6.

Table 6. Comparison of NN model and CIROS Studio model

Property	NN model	CIROS Studio model
Kinematic problem solving	Yes	Yes
Static problem solving	Yes	No
Optimization capability	Yes	No
Calculation of trajectory points on user requests	Yes	No
Visualization	No	Yes

The new model excels at solving not only kinematic problems, such as FK and IK, but also static problems, including power and energy calculations. This comprehensive approach allows for a deeper understanding of robot behaviour and performance.

Unlike CIROS Studio, the new model offers optimization features that allow users to fine-tune the robot's movements and operations to improve efficiency and productivity. This feature is important in real-world applications where energy conservation and task optimization are required.

The new model makes it easier calculate each path point, giving users precise control over robot's movements. This level of detail improves accuracy and reliability in robotic operations, leading to more predictable outcomes.

While the new model boasts impressive computing capabilities, it lacks graphical capabilities found in CIROS Studio. Visualization is important for visualizing robotic operations and simulating real-world scenarios. Thus, its absence may limit the usability of the new model in certain contexts.

In conclusion, the new model offers a plethora of advantages that significantly expand its capabilities compared to CIROS Studio.

8 Summary

In conclusion, the study successfully achieved its goal of reducing the energy consumption of the linear Delta robot and updating the teaching methodology for students, was achieved by solving three main tasks: minimizing the power consumed by robots in steady state, finding the shortest route for all joint movements, in which the total energy consumption is minimal, and developing a laboratory manual for studying the Festo EXPT-45-E1 tripod robot.

A new approach using neural network technology is used to create a computer model that can simultaneously solve forward and inverse kinematics and statics problems in robotics. The methodology was developed based on experimental data collected using a Festo EXPT-45-E1 Tripod robot and MATLAB simulation tools. The results demonstrate the effectiveness of the neural network-based model in optimizing robot trajectories and reducing energy consumption.

In addition, the laboratory manuals developed as part of this dissertation facilitate practical learning for students by integrating theoretical knowledge with practical application.

References

- [1] T. H. T. Tran, D. S. Nguyen, N. T. Vo and H. N. Le, “Design of Delta Robot Arm based on Topology optimization and Generative Design Method,” in *5th International Conference on Green Technology and Sustainable Development (GTSD)*, Ho Chi Minh City, Vietnam, 2020.
- [2] FESTO, “Parallel kinematic system EXPT, tripod,” 2022. [Online]. Available: <https://www.festo.com/media/pim/295/D15000100122295.PDF>. [Accessed 1 May 2024].
- [3] R. Featherstone, *Rigid Body Dynamics Algorithms*, Springer New York, NY, 2008, p. 272.
- [4] A. Gholami, T. Homayouni, R. Ehsani and J.-Q. Sun, “Inverse Kinematic Control of a Delta Robot Using Neural Networks in Real-Time,” *Robotics*, vol. 10, no. 4, p. 12, 2021.
- [5] A. R. J. Almusawi, L. C. Dülger and S. Kapucu, “A New Artificial Neural Network Approach in Solving Inverse Kinematics of Robotic Arm (Denso VP6242),” *Computational Intelligence and Neuroscience*, vol. 2016, p. 11, 2016.
- [6] A. T. Hasan, N. Ismail, A. Hamouda, I. Aris, M. Marhaban and H. Al-Assadi, “Artificial neural network-based kinematics Jacobian solution for serial manipulator passing through singular configurations,” *Advances in Engineering Software*, vol. 41, no. 2, pp. 359-367, 2010.
- [7] L. Aggarwal, K. Aggarwal and R. J. Urbanic, “Use of Artificial Neural Networks for the Development of an Inverse Kinematic Solution and Visual Identification of Singularity Zone(s),” *Procedia CIRP*, vol. 17, pp. 812-817, 2014.
- [8] C. Dehong, L. Chengyao, W. Ruchao, S. Chen, T. Chang and Q. Zhijian, “Innovative Design and Realization of Lightweight Delta Robot Platform,” in *29th Chinese Control And Decision Conference (CCDC)*, Chongqing, China, 2017.
- [9] S. Ahangar, M. V. Mehrabani, A. P. Shorijeh and M. T. Masouleh, “Design a 3-DOF Delta Parallel Robot by One Degree Redundancy along the Conveyor Axis, A Novel Automation Approach,” in *5th Conference on Knowledge Based Engineering and Innovation (KBEI)*, Tehran, Iran, 2019.
- [10] C. Liu, G.-H. Cao and Y.-Y. Qu, “Workspace Analysis of Delta Robot Based on Forward Kinematics Solution,” in *3rd International Conference on Robotics and Automation Sciences (ICRAS)*, Wuhan, China, 2019.
- [11] G. Mottola, C. Gosselin and M. Carricato, “Dynamically feasible motions of a class of purely-translational cable-suspended parallel robots,” *Mechanism and Machine Theory*, vol. 132, pp. 193-206, 2019.
- [12] FESTO, “Teach pendant Assembly and installation Type CDSA-D1-VX,” 2010. [Online]. Available: https://www.festo.com/net/ro_ro/SupportPortal/Files/754895/CDSA-SY_2010-01a_560334g1.pdf. [Accessed 1 May 2024].

- [13] FESTO, “GDCCP-CMXR-SW-EN,” 2008. [Online]. Available: https://www.festo.com/net/en_sg/SupportPortal/Files/756026/CMXR-SW_2008-05_560316g1.pdf. [Accessed 1 May 2024].
- [14] M. A. Khan, D.-e.-Z. Baig, H. Ali, B. Ashraf, S. Khan, A. Wadood and T. Kamal, “Efficient System Identification of a Two-Wheeled Robot (TWR) Using Feed-Forward Neural Networks,” *Electronics*, vol. 11, no. 21, p. 9, 2022.
- [15] Y. Liu, G. Liu, Y. Wu, W. He, Y. Zhang and Z. Chen, “Reinforcement-Learning-Based Decision and Control for Autonomous Vehicle at Two-Way Single-Lane Unsignalized Intersection,” *Electronics*, vol. 11, no. 8, p. 22, 2022.
- [16] FLUKE, “1745 Power Quality Logger Users Manual,” 2006. [Online]. Available: https://www.fluke-direct.com/app/webroot/pdfs/cache/www.fluke-direct.ca/fluke/power_quality_analyzer/1745_basic/manual/fluke_1745_basic_power_quality_analyzer_manual.pdf. [Accessed 1 May 2024].
- [17] V. Vodovozov, Z. Raud and E. Petlenkov, “Intelligent Control of Robots with Minimal Power Consumption in Pick-and-Place Operations,” *Energies*, vol. 16, no. 21, p. 17, 2023.
- [18] M. Lehtla, V. Vodovozov and N. Semjonova, “Laboratory practice in creative robotics,” 2024. [Online]. Available: https://livettu-my.sharepoint.com/:b:/g/personal/nsemjo_taltech_ee/EaqPdqnMq2ZNoHWZ_8F2Y_oBYIncVkvumnJcCX_ZE1xOPg?e=cvYqTY. [Accessed 1 May 2024].

Appendix 1 – Non-exclusive licence for reproduction and publication of a graduation thesis¹

I Natalia Semjonova

1. Grant Tallinn University of Technology free licence (non-exclusive licence) for my thesis "Research and laboratory work development for the Festo tripod robot" , supervised by Valery Vodovozov and Eduard Petlenkov
 - 1.1. to be reproduced for the purposes of preservation and electronic publication of the graduation thesis, incl. to be entered in the digital collection of the library of Tallinn University of Technology until expiry of the term of copyright;
 - 1.2. to be published via the web of Tallinn University of Technology, incl. to be entered in the digital collection of the library of Tallinn University of Technology until expiry of the term of copyright.
2. I am aware that the author also retains the rights specified in clause 1 of the non-exclusive licence.
3. I confirm that granting the non-exclusive licence does not infringe other persons' intellectual property rights, the rights arising from the Personal Data Protection Act or rights arising from other legislation.

03.05.2024

¹ The non-exclusive licence is not valid during the validity of access restriction indicated in the student's application for restriction on access to the graduation thesis that has been signed by the school's dean, except in case of the university's right to reproduce the thesis for preservation purposes only. If a graduation thesis is based on the joint creative activity of two or more persons and the co-author(s) has/have not granted, by the set deadline, the student defending his/her graduation thesis consent to reproduce and publish the graduation thesis in compliance with clauses 1.1 and 1.2 of the non-exclusive licence, the non-exclusive license shall not be valid for the period.