PREAMBLE

1. The urgency of the thesis

In many working parameters of the system, the robot's accuracy is classified as a loss over time, meaning it gradually loses as the mechanism wears out and degrades. Maintaining equipment accuracy is a necessary condition to continue exploiting robots in current work. If it is possible to calibrate the robot to regain its accuracy after each maintenance cycle so as not to have to replace equipment, it will be of great economic and technical significance. This is a process that requires minimal cost and minimal process but must maintain the robot's accuracy. The feedback control loop is only effective within each link of the robot, so calibration must ensure that even errors outside the feedback loop are detected and recalibrated accurately. These constraints make the problem of precision calibration an academic and practical challenge. For that reason, the PhD student chose the topic "***Research on the method of calibrating industrial robots based on alternative trajectories*** ".

2. Research purposes

Measure the total error of the manipulator on the TCP;

Build an error interpolation model and compare it with the measurement results, use this model after removing the measuring device after calibration is complete;

Develop an algorithm to compensate for regular errors in terms of minimal costs (time costs, system resource costs, measurement costs) keeping the operator's equipment operating habits intact. This process must have high practical applicability, proven by simulations and experiments.

3. Research methods and scope

Research method: Mathematical models are built on the basis of theoretical research, combined with self-built software, numerical simulations and experimental experiments are performed to to verify the accuracy.

Research object: Chain robots, hybrid robots.

Research scope: Error calibration problem

4. Scientific and practical significance

4.1 Scientific significance

The error interpolation model in the working space based on the combination of independent measuring devices such as 3D cameras or laser trackers using shape functions is a new contribution, it allows calibration to work accurately throughout the entire maintenance cycle even after the measuring device is removed;

The calibration algorithm using the alternative trajectory method is also another contribution, it allows long-term robot accuracy to be maintained without changing the hardware or software, with only minor process changes that are quite easy to grasp.

4.2 Practical significance

The results of this research can be immediately applied into practice without any special requirements.

As the number of robots used in industrial production is increasing, the application of this calibration process is necessary. Mastering these skills ensures manufacturers maintain equipment with the required precision at minimal cost, an engineering team that cannot be replaced through simple closed-loop control strategies.

5. New contributions of the thesis

The thesis has two new contributions:

- Error model based on the theoretical and experimental shape function;

- The alternative trajectory method using error calibration (both chain robots and hybrid robots) has been proven to effectively reduce post-calibration errors by over 40%.

6. Structure of the thesis

In addition to the introduction, conclusion, recommendations and appendices, the thesis is structured with four chapters as follows:

Chapter 1: Overview of the errors and the error calibration. In this chapter of the thesis, an overview of the errors and the sources of errors at the TCP of the robot is presented. Domestic and international research on error measurement using independent measuring equipment and calibration options have been available up to this point.

Chapter 2: Equipment and techniques for measuring errors in robot calibration. This chapter presents the basic theory in applying different measurement technologies to detect errors on the final link (TCP) of robots, the advantages and disadvantages of each measurement, and the technological capabilities of each measurement. Error interpolation techniques using the theoretical and experimental shape functions to reduce measurement costs are also presented in this chapter.

Chapter 3: Calibration of industrial robot errors. This chapter presents the calibration procedure and the content of the alternative trajectory method for string and hybrid robots. The method of synchronizing the measurement data of the measuring device is independent of the robot's measurement data, which is done by the robot's encoders to be ready for the problem of error detection when comparing two measurement channel data.

Chapter 4: Simulation and experiment. This chapter presents calculation, simulation and experimental results associated with the theories presented in previous chapters. There are two methods illustrated experimentally with measuring equipment from Cognex and Leica, the remaining method is verified by simulation and also presented in this chapter.

CHAPTER 1: OVERVIEW OF THE ERRORS AND THE ERROR CALIBRATION

1.1 Development trends of industrial robot applications

World Robotics' latest report shows an all-time high of 517,385 new industrial robots installed in 2021 in factories around the world. Asia is the world's largest market for industrial robots, in recent years in Vietnam, the number of newly installed robots has increased sharply. According to statistics from the digital economic magazine, Vietnam is still at the bottom of the global value chain, the main reason is that we mainly perform the assembly stage in product completion chains, this is the profitable part. very low in the 4.0 value chain, one of the main difficulties here is that the quality of Vietnam's labor force only reaches 3.39 points on a scale of 10. Because of the above reasons, the implementation of related research Mastering the techniques of design, manufacturing, and especially the exploitation and maintenance of industrial robots for Vietnam at this time is extremely important and urgent. It is also appropriate at the right time because this is the time when the industries High technology requires high quality labor. In the general goal of quickly mastering robotics techniques and turning them into key labor tools in the 4.0 revolution, this project aims to calibrate accuracy. of industrial robots, that is, improving the accuracy of the robot right after leaving the factory and during use through the techniques proposed by the author.

1.2 Some terms and concepts about accuracy and repeatability

An industrial robot is characterized by important parameters divided into two groups as follows:

The first group includes the number of degrees of freedom, load capacity, working area including shape and working volume, ability to perform peripheral connections.

The second group includes the robot's accuracy and repeatability

Here are some concepts and terms:

Error

Accuracy

Repeatability

The main sources of error in this working space of the robot can be divided into three groups:

Geometric and kinematic errors

Errors in the control system

Errors caused by environment

1.3 Calibration of industrial robots

Calibration is the use of software, rather than changing the mechanical structure or design of the robot itself, to improve the accuracy of the robot's position. Calibration can be classified into two types, non-kinetic calibration and kinematic calibration

Non-kinetic calibration

Kinematic calibration: Kinetic calibration consists of four sequential steps:

- *Modeling:*
- *Measure:*
- *Parameter identification:*
- *Compensation:*

Based on measurement methods, kinematic calibration can be divided into two types:

Open loop calibration:

Closed-loop calibration:

1.4 Research related to the topic

Although there have been many studies done on kinematic calibration, both in terms of measuring equipment and data processing methods, and in subsequent calibration methods such as compensation for generalized coordinates, compensationon DH size, but in this topic the author proposes to use a new method, namely:

- Replace trajectory and error approximation with a shape function model;

- Trajectory substitution method and superposition principle applied to hybrid robots.

1.5 Research scope of the thesis

To calibrate the robot, external measurement tools are needed, such as a laser tracker or camera. In this thesis, an optical measuring device from Leica is used. The robot used in the experiment is Coloborative.

Introducing a methodology for the calibration of parallel robots in cases where they are used as specialized jigs to expand the technological capabilities of machine tools.

Conclusion

The author chose a calibration method that replaces the TCP's trajectory combined with error interpolation based on the shape function to reduce measurement costs as well as have a basis for intervention for many different trajectory types in the work area after just one measurement – error identification.

CHAPTER 2: EQUIPMENT AND TECHNIQUES FOR MEASURING ERRORS IN ROBTO CALIBRATION

The most common measuring devices commonly used in robot's TCP error measurement techniques are very diverse. According to the development of technology, the following measuring devices are most commonly used in robot calibration:

- Comparison table and probe;
- CMM;
- CCD camera;
- Laser tracker;
- 3D camera.

2.1 General principles when setting up a measurement system

Basic technical features of a measuring system used in robot calibration include:

- Accuracy;
- Resolution;
- Working field of measuring instrument (shape, volume);
- Measurement method (contact, non-contact);
- Ability to automatically convert scales and dimensions;
- Ability to automatically compensate for errors and receive coordinate origin to represent measurement data as specified.

In principle, to detect measurement errors, all methods measure two channels simultaneously, the robot channel and the independent external measuring device channel, then compare the measurement results of these two channels with each other, in which the measurement value of an independent measuring device is used as the standard. Both measurement channels must be referenced to a single origin before comparison, this needs to be done right during the process of setting up the measurement system.

2.2 The measuring equipment group uses a comparison table and probe

People attach a probe to the robot arm and use it as the robot's TCP. The reference table is a precisely manufactured reference surface used to calibrate the probe when it touches it. The comparison table and probe act as electrodes that when in contact will close the circuit by an electric current that lights up the indicator device, which is an LED bulb, which is the moment the probe touches the comparison table. This method has the advantage of being cheap, but its disadvantage is that it limits the direction of TCP that can be measured and the accuracy is not high.

2.3 The measuring equipment group uses CMM

The CMM consists of a structure that moves in three dimensions, a probe attached to the structure, and a computer-controlled recording system (Figure 2.4). All CMMs work the same way: the probe touches points on the object to be measured and the position of the structure is recorded. Each measurement point is described by X, Y, and Z coordinates. All measured points for an object are combined into a 3D CAD file called a point cloud. The point cloud can be compared to 3D design drawings to determine if the object has been manufactured to the correct dimensions.

There are different types of CMMs on the market including tactile and optical CMMs. With the high cost of CMMs, these many options make it difficult to choose a suitable CMM for a given measurement.

At a minimum, there are five aspects that need to be considered to select the most suitable CMM for specific applications.

- Accuracy of CMM
- CMM tool characteristics
- CMM's software
- Sampling strategy of CMM

2.4 The measuring equipment group uses laser tracker

Laser tracker is a non-contact optical measuring device, based on two basic techniques: using a laser interferometer to measure distance and using two encoders to measure the angle of two beam steering mirrors. A measuring point is represented by a distance (radius) and two angles in spherical coordinates

Laser trackers measure the three-dimensional position of a moving target with an accuracy of a few microns, over ranges of tens of meters.

Advantages:

Disadvantages:

2.5 The measuring equipment group uses industrial camera and 3D camera

In essence, the camera measuring device will be based on techniques to determine the depth of marked points called makers (reflective points) on the model, from these 2D images to model the real object into a 3D image. All dimensions of the object are then measured on this virtual model without the need for the real object.

To further enhance the quality of the 3D model, an advanced technique called structured light or its higher order light coding is used, which projects a binary sequence that highlights the spatial characteristics during image recording (structuring) or point cloud generation (encoding) (Figure 2.15). The light encoding technique essentially increases the number of markers to an extremely large number (cloud) to thereby improve reconstruction accuracy.

Advantages:

Disadvantages:

2.6 The measuring equipment group uses 3D laser scanning sensor

3D scanning sensors sample many points at the same time, essentially reducing sampling time and increasing model accuracy. This is a type of non-contact measurement.

Conclusion

The most common methods of measuring the position and direction of industrial robots are using laser trackers and high-resolution cameras, although they are very expensive (about > 80,000 USD). These are non-contact measuring devices with high precision (micrometers) and are capable of quickly collecting data with large data density, so they can provide detailed images during robot operation. In addition, modern cameras and laser trackers can often be connected to industrial robots to automatically determine the axis transition matrix between the two reference frames of the robot and the measuring device.

With these advantages, Leica's laser tracker (accuracy +/-15µm) and Cognex's 3D camera (accuracy +/-55µm) were chosen to be used for experiments to determine errors of the survey points of industrial robots requires precision calibration in research. This error is then used as a basis for calculating an alternative trajectory. The effectiveness of alternative trajectory will be verified using these same devices.

CHAPTER 3: CALIBRATION OF INDUSTRIAL ROBOT ERRORS

3.1 Software for checking and calibrating tolerances

Supervisory feedback control by encoders is a very popular strategy to intervene to eliminate the gap of mechanical transmission in the mechanism. However, if two links are adjacent and the generalized coordinates connecting them are not wrong compared to the calculation, the TCP's position is still wrong due to reasons such as their assembly error, elastic deformation of those two links, wear of the joints, … All of these factors are outside the encoder's feedback loop so it cannot be detected. This is the reason why when applying an independent measuring device to the final link, the error is always greater than the initial announcement.

Error is composed of two types including regular error and irregular error. In which, measuring the final error with an independent measuring device always detects the sum of both types, but the compensable part is only the regular part.

Under ideal conditions, the function between these two quantities is calculated based on the ideal model without errors.

$$x_i = f(\mathrm{u}_i) \quad (3.1)$$

Rule identification can be built in the form of point-to-point mappings and use interpolation algorithms to calculate the entire work trajectory.

3.2 Robot calibration methods

3.2.1 The chain robots

Suppose the ideal kinematic equation of the robot in general form is:

$$f(\mathrm{x}_i, \mathrm{y}_i, \mathrm{z}_i, \mathrm{q}_i, \mathrm{a}_i, \mathrm{d}_i, \beta_i) = 0 \quad (3.2)$$

Assuming that a highly accurate independent measuring device is used to check and detect errors at the ith survey point, equation (3.2) actually has the following form:

$$f(\mathrm{x}_i, \mathrm{y}_i, \mathrm{z}_i, \mathrm{q}_i, \mathrm{a}_i, \mathrm{d}_i, \beta_i) = \delta r_i \quad (3.3)$$

To error $\delta r_i \rightarrow 0$ from (3.2) there can be the following solutions:

- The first plan: Adjust TCP's actual coordinate group to another alternative coordinate and leave the remaining parameter groups unchanged
- The second plan: Change the DH parameter group $(\mathrm{a}_i, \mathrm{d}_i, \beta_i)$ from its nominal size to its actual size.

3.2.2 The hybrid robots

In some systems, hybrid systems are often formed for the reason of expanding the technological capabilities of the device to solve a specific task that requires a large number of degrees of freedom. This system usually consists of a machine table acting as a base that is coupled in series with a robot (series or parallel, usually a parallel robot) to expand the movement capabilities of the system. These systems often have large degrees of freedom but the dynamic chain is long, so the accumulated error in the chain is very larg.

This calibration method is performed by assigning an intermediate point in the kinematic chain to divide its into upper and lower parts. The lower part has the function of eliminating errors of the machine table, the upper part has the function of implementing the working trajectory. Due to participating in two different movements, the robot mechanism here has two inputs and one output, it acts as a differential mechanism that must synthesize the movements through it.

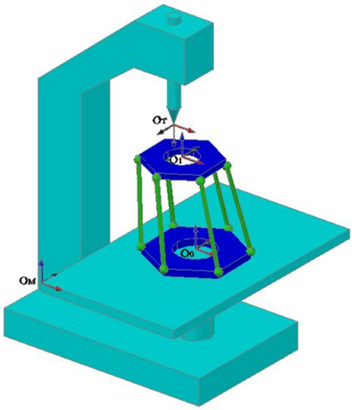


Figure 3.2 *Equipment layout and basic reference systems*

The desired trajectory of the machine table is shown as follows:

$$f_3(\text{xyz})^{O_M} = 0 \quad (3.14)$$

The real trajectory of the machine table including its kinematic error is shown as follows:

$$f_4(\text{xyz})^{O_M} = 0 \quad (3.15)$$

Instead of moving in an ideal trajectory in (3.14), due to the influence of position error, the machine table moved along trajectory in

(3.15). The hexapod robot itself has very high rigidity, so the error of the jig can be ignored. Therefore, to achieve the desired accuracy in shaping, the errors of the machine table need to be compensated. There are two ways to do this:

- The first method: Calibrate the machine table itself so that the actual orbit (3.15) returns to the ideal orbit (3.14). This option requires intervention in the hardware of the machine tool and cannot completely and permanently eliminate machine table errors. Therefore, it is not the subject mentioned in this study.

- Second way: Accept the error of the machine table, the real trajectory of the machine table is now (3.15). Because hexapod robots have extra degrees of freedom, they can be used to create compensating movements to eliminate errors from the machine table. At the same time as error compensation, the robot also combines with the machine table to create working movements according to (3.12) to complete its task. Thus, the robot's movement now has two functions, both creating shapes through combination with the movement of the machine table and eliminating errors created by the table.

3.3 Transfer coordinates in the working space

3.3.1 Transfer potential between two endpoints

3.3.2 Transfer measurement data by camera

3.4 Basis of alternative orbital formation

3.4.1 One-point reverse conversion of real and alternative trajectories

3.4.2 Reverse conversion all real trajectories to alternate trajectories

3.4.3 Solve the inverse kinematics problem using the Generalized Reduced Gradient numerical method (Generalized Reduced Gradient - GRG)

Conclusion

While the direct trajectory replacement method leads to changing the generalized coordinates, which affects the inputs to correct the error of robot’s TCP, the method of changing the DH parameter will indirectly affect the generalized coordinates. The principles of these two methods are similar in that they must affect the generalized coordinates while the calculation process leading to these changes is different. The mathematical basis of both methods is the same because they are based on a single kinetic model.

The direct trajectory replacement method is suitable for trajectories that require high precision. However, this method is implemented for specific trajectories without compensating the entire working area like the DH parameter change method. The DH parameter change method does not have as high accuracy for each specific trajectory as the direct trajectory replacement method. In fact, due to the specialization of robots, mainly running a specific trajectory repeatedly, the direct trajectory replacement method has more applications.

The third method is applicable to multi-degree-of-freedom systems, which often involve a hybridization of two configurations. This method is less applicable because today's machine tools rarely have to be organized this way.

CHAPTER 4: SIMULATION AND EXPERIMENT

4.1 Description of error measurement experiment diagram

4.1.1 Experiment 1, Leica measuring device.

In this study, the 6 DOF Collaborative robot and the Leica's laser tracker combined with the AT960-MR probe were used to measure the errors at survey points. The error is obtained by comparing the two data channels of the robot and the laser tracker (LT) after the data are represented on the same origin of the robot. This error is then used to form an alternative trajectory, the orbit change is verified by the same laser tracker mentioned above.

Figure 4.1 *Experimental setup and the Leica laser tracker*

The kinematic diagram and DH table of the Collaborative robot are shown in Figure 4.2 and Table 4.2, respectively.

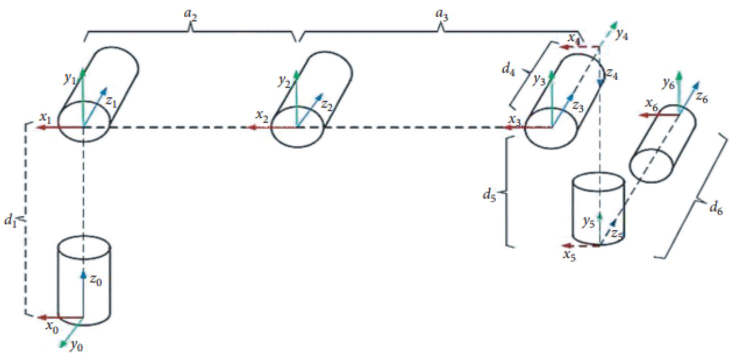


Figure 4.2 *Dynamic diagram of the Robot*

Table 4.2 *DH table*

Khớp	β_i(độ)	a_i (mm)	d_i (mm)	q_i (độ)
Khớp 1	-0.318	-7.3788	169.7586	(q_1)
Khớp 2	89.8912	-0.9163	179.4213	(q_2)
Khớp 3	-0.0217	505.5451	0.4213	(q_3)
Khớp 4	-0.1666	439.7139	0.4213	(q_4)
Khớp 5	-89.8511	0.8422	160.4283	(q_5)
Khớp 6	89.9531	-0.8371	103.4869	(q_6)

Table 4.3 *The origin coordinate O_0 of the robot in relation to the LT's coordinate O_c*

Tham số	X (mm)	Y	Z	Rx (độ)	Ry	Rz
Giá trị	-466.5649	77.5747	-127.7128	0.8936	-0.3427	9.7938

Table 4.4 *Probe coordinates in the robot's TCP*

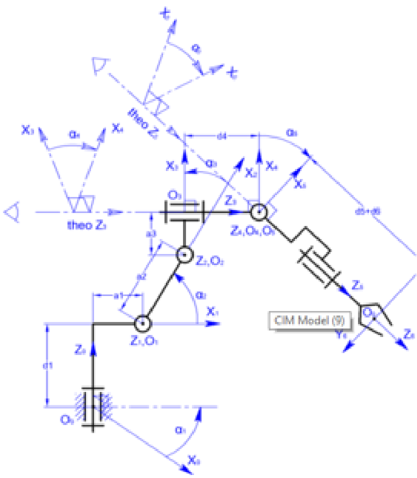
Tham số	X (mm)	Y	Z	Rx (độ)	Ry	Rz
Giá trị	7.5984	-15.8128	107.8152	90.1573	1.1997	-61.0056

T is the axis transition matrix between the LT and the experimental robot, in this case *T* is shown as follow:

$$T = \begin{vmatrix} 0.631699 & 0.334297 & 0.699401 & 550.2334 \\ 0.697931 & 0.147472 & -0.70091 & -449.973 \\ -0.33738 & 0.930947 & -0.1401 & 381.1823 \\ 0 & 0 & 0 & 1 \end{vmatrix} \qquad (4.2)$$

4.1.2 Experiment 2, Cognex's 3D camera

The system includes an 6 DOF ABB IRB1200 robot with its kinematic parameters as shown in table 4.5 and a Cognex's 3D camera - A5030 that is used to accurately record TCP's real errors with resolution in x, y, z direction is 200µm, accuracy is 66 µm. In this experiment, the camera was calibrated with RSM index = 0.02. The kinematic diagram and DH table of the Collaborative robot are shown in Figure 4.3.



Khớp	β_i	d_i	a_i	α_i
1	(α_1)	d_1	a_1	90^0
2	(α_2)	0	a_2	0
3	(α_3)	0	a_3	90^0
4	(α_4)	d_4	0	-90^0
5	(α_5)	0	0	90^0
6	(α_6)	d_5+d_6	0	0

Figure 4.3 *The kinematic diagram and DH table*

4.2 The errors interpolation

Calculated data in this section is taken from the experimental diagram according to Experiment 2 in section 4.1.2. A triangular prism with the top of 6 nodes A, B, C, D, E, F was chosen as the survey space. The experimental process is conducted on 54 grid points in this space. Two pose data at these points are recorded independently: the nominal pose is displayed on the robot controller, and the actual pose is recorded by the area scan 3D camera.

4.3 The error calibration of chain robot

4.3.1 Leica's laser tracker

4.3.1.1 First set of data (TCP's trajectory change)

4.3.1.2 Second set of data (Change the DH parameter)

4.3.2 Cognex 3D camera

4.4 The error calibration of hybrid system

4.4.1 Hexapod robot kinematic model with SPS configuration and hybrid structure

4.4.2 Machine table kinematic error

4.4.4 Tool movement

4.4.5 Synthetic motion

4.4.6 Comparison of data before and after error compensation

Conclusion

In this chapter, based on the proposed theories, the author has performed measurement procedures with high-precision laboratory equipment from Cognex and Leica. From the TCP error of the experimental industrial robot, after synchronizing the two measurement channels, the author took steps to calibrate as proposed in chapter 3.

Finally, the errors are checked again from an independent measuring system. The results shown that the errors were significantly reduced, the average errors after calibration were reduced by more than 40% of the initial measured errors. With the results proven experimentally, it can be seen that the author's proposal has high potential for application in industry because these methods do not change the usage habits of robot operators, the robot's hardware or software. Thess methods only change from the specified trajectories to the alternate ones as shown here. This is also a new point of the thesis.

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

The thesis has pointed out the limitations of calibration methods that existed up to the time the author conducted this research. On that basis, the author has proposed a highly usable calibration method that can be completely applied to actual production without changing the user's equipment operating habits. The robot's accuracy after calibration exceeds or is equivalent to research conducted to date. This study also shows that calibration errors include kinematic errors, dynamic errors, manufacturing errors, errors due to wear, heat, etc. because monitoring of these errors is done using a measurement channel independent of the robot

2. Proposal for development direction of the topic

The thesis has completely developed the theory and demonstrated experimentally the compatibility between theoretical calculations and experimental results. In the next step, the author will automate the calibration process with an intermediary application between the measuring device and the robot, aiming for widespread deployment in industry. In the coming time, the author will continue to develop the topic as follows:

1. Transfer the above research results into practice in high-tech zones that use many industrial robots.
2. Collaborate with optical measuring equipment suppliers to transfer not only measuring equipment but methods for using them on robotic systems as a standardized process.
3. Promote the application of calibration for devices with configurations similar to robots, such as chain structure numerical control machine tools, ...

LIST OF PUBLISHED WORKS OF THE THESIS

I. Articles published internationally

1. ***Thang Nguyen Huu, Khanh Duong Quoc, Thuy Le Thi Thu and Long Pham Thanh,*** Manufacturing cost of robot structures with tolerance calculated on the view of kinetic response and that of technology, International Conference on Engineering Research and Applications ICERA 2019, ISSN: 2367-3370; Scopus, p.462-470, 12/2019

2. ***Thang Nguyen Huu, Khanh Duong Quoc, Thuy Le Thi Thu and Long Pham Thanh,*** A solution to adjust kinetic of industrial robots based on alternative trajectories, International Conference on Engineering Research and Applications ICERA 2019, ISSN: 2367-3370, Scopus, p.55-65, 12/2019

3. ***Thuy Le Thi Thu, Khanh Duong Quoc and Long Pham Thanh*** Calibration of Industrial Robot Kinematics Based on Results of Interpolating Error by Shape Function, Journal of Engineering and Applied Sciences, ISSN: 1816-949X, © Medwell Journals, Q3 Scopus, Vol 15 (6), p.1451-1461, 2020

4. ***Khanh Duong Quoc, Trang Trung Thanh and Long Pham Thanh,*** Robot control using alternative trajectories based on inverse errors in the workspace, Hindawi Journal of Robotics, ISSN: 1687-9619, Q2 Scopus, Vol 2021, Article ID 9995787, 2021.

5. ***Khanh Duong Quoc, Thuy Le Thi Thu, Long Pham Thanh and Ngoc Nong Minh,*** Controlling Lai Machine Tools

Concerning Error Compensation of Chain Elements, Hindawi Journal of Robotics, ISSN: 1687-9619, Q2 Scopus, Vol 2022, Article ID 4366888, 2022.

6. ***Trang Trung Thanh, Yue Ming Hu, Thanh Long Pham, Quoc Khanh Duong,*** Design and Kinematics Analysis of 3-URS Ankle Rehabilitation Parallel Robot, ICMHI' 22: Proceedings of the 6th International Conference on Medical and Health Informatics, ISBN: 978-1-4503-9630-1, Q2 Scopus, p.163-175, 2022

II. Articles published domestically

1. ***Khanh Duong Quoc, Long Pham Thanh,*** Bài toán dung sai của cơ cấu robot dạng chuỗi hở trên quan điểm tính công nghệ gia công, Tạp chí Khoa học và Công nghệ, ISSN 1859 – 2171, 2021

2. ***Khanh Duong Quoc, Long Pham Thanh,*** Một giải pháp tính toán đảm bảo sai số khâu cuối robot nằm trong miền giới hạn định trước, Tạp chí Khoa học và Công nghệ, ISSN 1859 - 2171, 2019.

3. ***Khanh Duong Quoc, Long Pham Thanh,*** Giá thành và lựa chọn khâu, khớp hợp lý trên cơ sở điều chỉnh dung sai khi thiết kế cơ cấu robot, Tạp chí nghiên cứu khoa học và công nghệ quân sự, ISSN 1859 – 1043, 2019.