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Field Systems Engineering

# PhD THESIS
## – ABSTRACT –

## Advanced control techniques for CNC machines

**PhD Student:**
**Dora – Laura Sabău**
**(căs. Morar)**

**PhD Supervisor:**
**Prof. Eng. Petru DOBRA, PhD**

**Examination committee:**
Chair: Prof. Eng. **Honoriu VĂLEAN**, PhD – Technical University of Cluj-Napoca;
PhD Supervisor: Prof. Eng. **Petru DOBRA**, PhD – Technical University of Cluj-Napoca;
Members:
- Prof. Eng. **Radu-Emil PRECUP**, PhD – Politehnica University Timişoara;
-Prof. Eng. **Octavian PĂSTRĂVANU**, PhD – "Gheorghe Asachi" Technical University of Iași;
- Assoc. Prof. Eng. **Paula RAICA**, PhD – Technical University of Cluj-Napoca;

**– Cluj-Napoca –**
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str. Memorandumului nr. 28, 400114 Cluj-Napoca, România
tel. +40-264-401200, fax +40-264-592055, secretariat tel. +40-264-202209, fax +40-264-202280
www.utcluj.ro

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# 1 Introduction

The processing and manufacturing industry is increasingly dependent on numerically controlled machines and this is due to the fact that, with the evolution of technology, they have become easier to use and more advantageous. The advantages of using a numerically controlled machine (CNC) are demonstrated by the fact that they are easy to use, increase production capacity, can reduce costs and production time and, last but not least, complex operations can be performed. These advantages have led to the use of these types of machines by manufacturers in various fields and not only in the industrial field. Among them are activities in the field of engraving, wood processing, etc. In recent years, the challenge is to optimize process parameters, especially to maximize the precision.

In literature, there are a lot of research papers on CNC control techniques and mechanical positioning systems in general. From classical control methods to adaptive, optimal or fuzzy control methods, they are all found in recent work on this topic. The research done in the doctoral studies led to the design, simulation and testing of advanced control methods for a CNC machine. The motivation for these studies is that, although many studies have shown that modern control techniques outperform PID controllers, the latter are predominantly used in industry, mainly due to their easy implementation. The thesis proposes several advanced control methods whose structure is adapted to the classic cascade control scheme used in industry.

The thesis consists of 7 chapters, where the theoretical aspects of control methods for CNCs and the numerical results obtained from their design are presented.

# 2 Synthesis of control strategies for numerically controlled machines

## 2.1 Considerations regarding mathematical models

Regarding the mathematical models used in literature, several approaches are used, depending on the type of machine, the number of axes and the control structure that can be implemented. Thus, state-space models obtained either by identifying the parameters or on the basis of the equation of motion or the electro-mechanical analogy are used. Also, many studies present transfer function models then used later for the design of control strategies.

## 2.2 Considerations for control methods for numerically controlled equipment

The control systems of numerically controlled machines are divided into two main groups: open loop control and closed loop control. Open loop control is suitable for point-to-point systems and in 90 % of cases different closed loop control methods are used.

According to the works in the literature, for CNC control various algorithms are used, from classical Proportional-Integrative-Derivative (PID) controllers, to state feedback control algorithms, optimal control, fuzzy-logic controllers and even more advanced control algorithms, such as genetic and adaptive ones [1].

# 3 Modeling, identification and analysis

The experimental machine chosen for the case study is represented by a CNC equipment with 3 orthogonal axes, which performs movements of translation in the 3 directions. The X and Y translation axes (those in the table plane) are controlled by servomotors, respectively the

Z axis (the one perpendicular to the table plane) is controlled by a stepper motor. The motors are controlled using the MC206X controller from the Motion Coordinator family and is programmed using the TrioBasic programming language. Among the categories of motion control functions provided by TrioBasic, the linear, circular and helical interpolation functions and the acceleration and deceleration functions are the most used in order to obtain complex trajectories. Fig. 1 shows an image of the experimental stand.

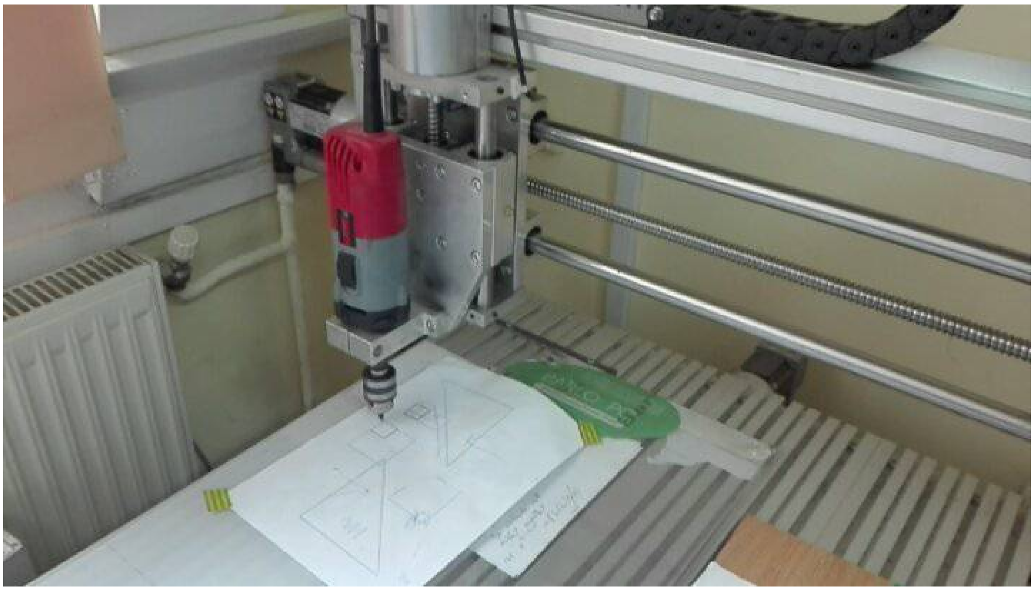

Figure 1: Experimental machine

Regarding the control of the actuators, there are 5 parameters of control. Based on these parameters, the output voltage is modified such that the necessary speed is obtained. Based on the control diagram illustrated in the user manual [2], we can implement a PID controller for the position outer loop and a P controller for the speed inner loop. Also, there is a possibility of adding a feed-forward compensator.

In order to obtain the mathematical model for the equipment, two approaches are proposed: the first one consists on finding SISO models for each axis, and the second one consist in determining a MIMO model that includes the mutual effect between the two axes. For the first case, the effect between the axes is seen as a disturbance.

## 3.1 SISO approach

Regarding the first case considered, a SISO model for each axis, the structure proposed in Fig. 2 is considered, where the relationship between the input signal and the speed is approximated by a first-order transfer function, and the speed-position relationship by an integrator. Based on the experimental data in Fig. 3 and Fig. 4, the model model parameters are identified using the Matlab System Identification Toolbox [3].

- For X axis:

$$H_{\omega_x u_x}(s) = \frac{K_{M_x}}{T_{M_x} s + 1} = \frac{1054}{s + 40.85} \tag{1}$$

having $K_{M_x} = 25.8017$ and $T_{M_x} = 0.0245$ [s].

$$H_{\theta_x \omega_x}(s) = \frac{0.9992}{s + 10^{-7}} \approx \frac{1}{s} \tag{2}$$

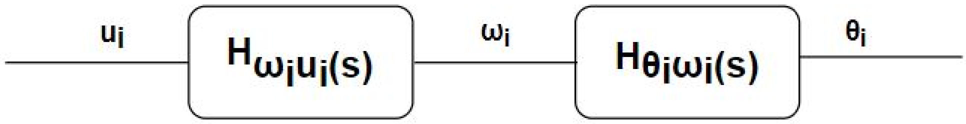


Figure 2: SISO model for one axis

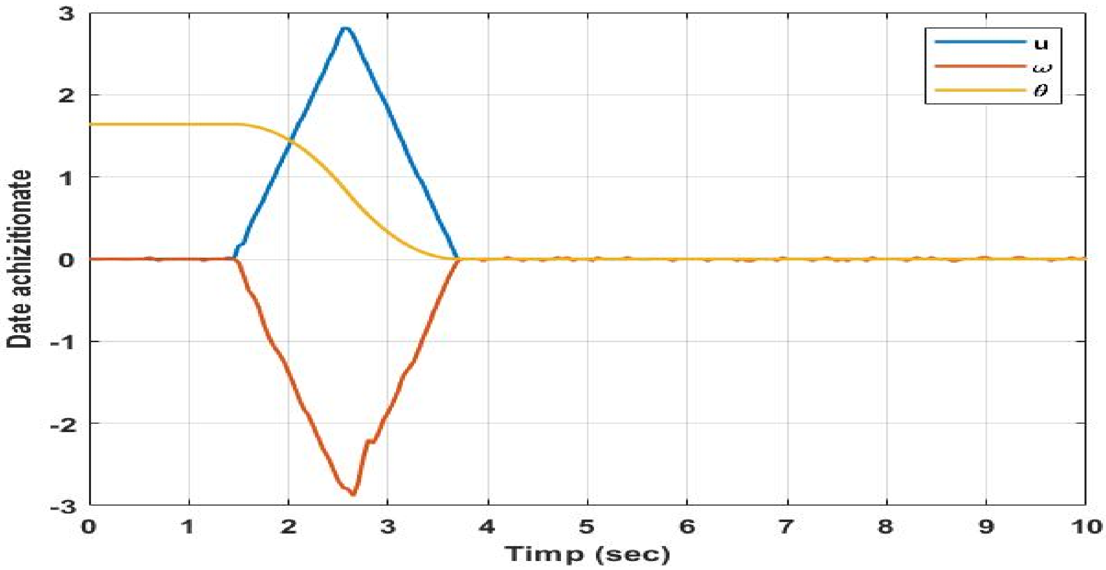


Figure 3: Experimental data for X axis

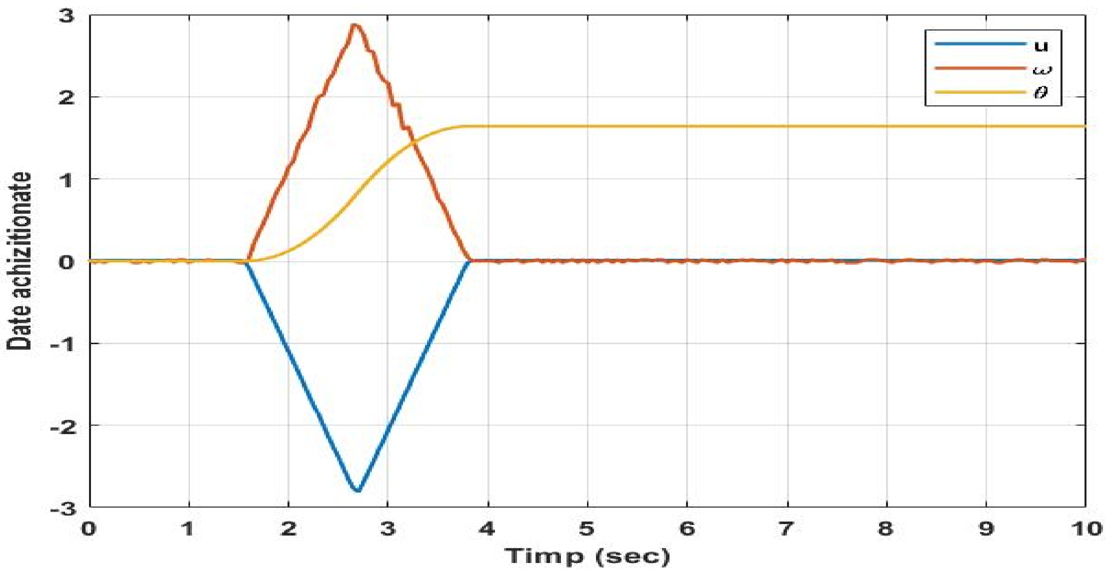


Figure 4: Experimental data for Y axis

- For Y axis:

$$H_{\omega_y u_y}(s) = \frac{K_{M_y}}{T_{M_y}s + 1} = \frac{2188}{s + 87.81} \tag{3}$$

having $K_{M_y} = 24.9174$ and $T_{M_y} = 0.0114$ [s].

$$H_{\theta_x \omega_x}(s) = \frac{0.9887}{s + 2.9 \times 10^{-7}} \approx \frac{1}{s} \tag{4}$$

Also, the state space model is obtained, using the diagram in Fig. 2 and the transfer functions obtained.

$$G_i : \begin{pmatrix} \dot{\omega}_i(t) \\ \dot{\theta}_i(t) \\ \hline y_i(t) \end{pmatrix} = \left(\begin{array}{cc|c} -\frac{1}{T_{Mi}} & 0 & \frac{K_{Mi}}{T_{Mi}} \\ 1 & 0 & 0 \\ \hline 0 & 1 & 0 \end{array}\right) \begin{pmatrix} \omega_i(t) \\ \theta_i(t) \\ \hline u_i(t) \end{pmatrix}, \tag{5}$$

where $i \in \{X, Y\}$.

### 3.2 MIMO approach

The second approach regarding the mathematical model used is to obtain a model with two inputs, $u_x$ and $u_y$, and two outputs, represented by the positions for each of the two axes. In addition to the case presented previously, the interconnection between the two axes is taken into consideration and the influence of one on the other, which occurs in particular when a movement which requires the movement of both axes is needed.

The block diagram for the MIMO system is illustrated in Fig. 5, where the term illustrating the influence of the input corresponding to the X axis at the speed of the Y axis was denoted by $H_{\omega_x u_y}$ and by $H_{\omega_y u_x}$ for the Y axis input on the X-axis velocity. These terms are also determined using the identification toolbox and the obtained values are: $H_{\omega_x u_y} = 15$ and $H_{\omega_y u_x}$ =24.5.

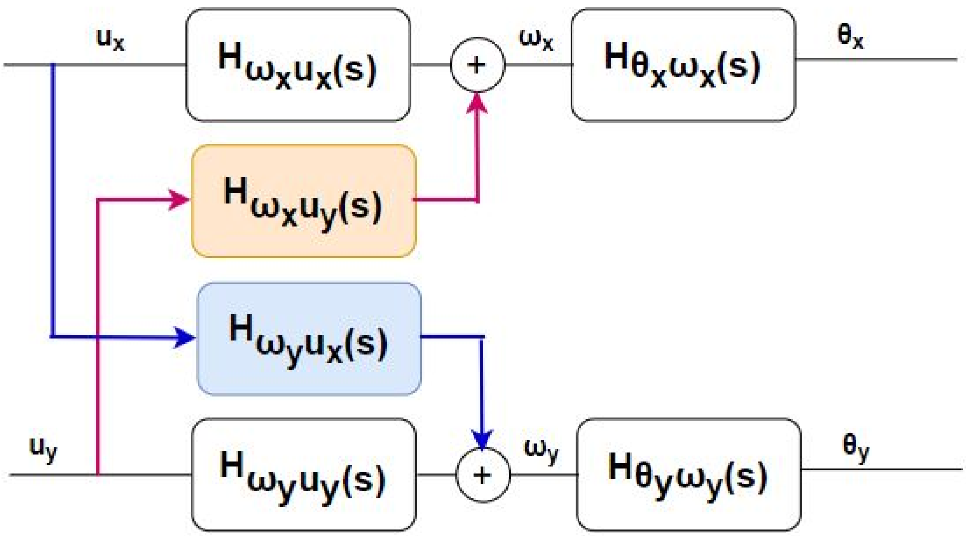


Figure 5: Block diagram for the MIMO system

The state space model for the system is presented in (6).

$$G_{MIMO} : \begin{pmatrix} \dot{\omega}_x(t) \\ \dot{\theta}_x(t) \\ \dot{\omega}_y(t) \\ \dot{\theta}_y(t) \\ \hline y_x(t) \\ y_y(t) \end{pmatrix} = \left(\begin{array}{cccc|cc} -\frac{1}{T_{Mx}} & 0 & 0 & 0 & \frac{K_{Mx}}{T_{Mx}} & H_{\omega_x u_y} \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{Mx}} & 0 & H_{\omega_y u_x} & \frac{K_{My}}{T_{My}} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ \hline 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{array}\right) \begin{pmatrix} \omega_x(t) \\ \theta_x(t) \\ \omega_y(t) \\ \theta_y(t) \\ \hline u_x(t) \\ u_y(t) \end{pmatrix}, \tag{6}$$

# 4 Classical control techniques

This chapter presents the main classical control methods used for CNC systems. The first approach is to determine a P, PI or PID controller, without taking into account the speed loop. The controllers are designed using the Ziegler-Nichols and relay method. The simulations performed with the obtained controllers show that the closed loop step response does not meet the required performances, the main problem being caused by the appearance of the overshoot in all three cases. These controllers were adjusted by changing each parameter. This approach is, however, a laborious one, and the results are not always satisfactory, as the simulations show. After adjusting the parameters, it is possible to completely eliminate the overshoot with a P controller, but with an increase in the setiling time compared to the one initially obtained. The disadvantage of this regulator is that the disturbance is not rejected. A PI or PID controller is required to cancel the disturbance, but the disadvantage of these two controllers, whose parameters have been calculated with the ZN method and then adjusted, is the large overshoot. The table shows the performances obtained after the simulations performed.

| | X Axis | | Y Axis | |
|---|---|---|---|---|
| Controller type | Settiling time | Overshoot | Settling time | Overshoot |
| P | 0.18$s$ | 20% | 0.1$s$ | 8% |
| Modified P | 0.25$s$ | 1% | 0.18$s$ | 0% |
| PI | 0.3$s$ | 28% | 0.12$s$ | 36% |
| Modified PI | 0.6$s$ | 20% | 0.5$s$ | 19% |
| PID | 0.22$s$ | 28% | 0.17$s$ | 25% |
| Modified PID | 0.81$s$ | 20% | 0.6$s$ | 21% |

Table 1: Comparison of the performance of the proposed P, PI and PID regulators for each axis

The second common control method is the cascade control. This involves finding two controllers: one for the speed loop and one for the external loop, the position loop. Many papers [4] present simulations using different types of controllers for the cascade structure. Several comparisons between different combination of controllers shows that a PI controller for the speed loop is mostly indicated in order to obtain good performances and disturbance rejection. However, the CNC equipment, controlled using MC206X allows only the implementation of a P controller on the speed loop. Thus, the thesis presents the analysis, implementation and simulation of the cascade scheme with a P controller on the speed loop and a P, PI or PID controller on the position loop. The simulations also show that each combination has advantages and disadvantages. The advantage of the P-P structure is not causing overshoot, performance not fulfilled in the case of PI-P or P-PID combination, which, however, have the advantage of rejecting disturbances, unlike the first one. All these aspects can be seen in Fig. 6.

The third approach consists on using state feedback controller. State feedback control can be used if the system is controllable and the values of the state variables (position and speed) are accessible either physically or using an observer. For our system, state-feedback controller can be designed using pole placement method for identified the state space model. Using this method, both cases are analysed - the control for each independent axis and for the MIMO system. For the SISO case, the performances increased by up to 20% than the performances obtained by PID or cascade control approach. In order to implement these controllers on the machine, it is necessary to modify the classic state feedback control diagram in order to obtain a P-P cascade control structure. The step response corresponding for each subsystem, obtained by implementing these controllers, is depicted in Fig. 7.

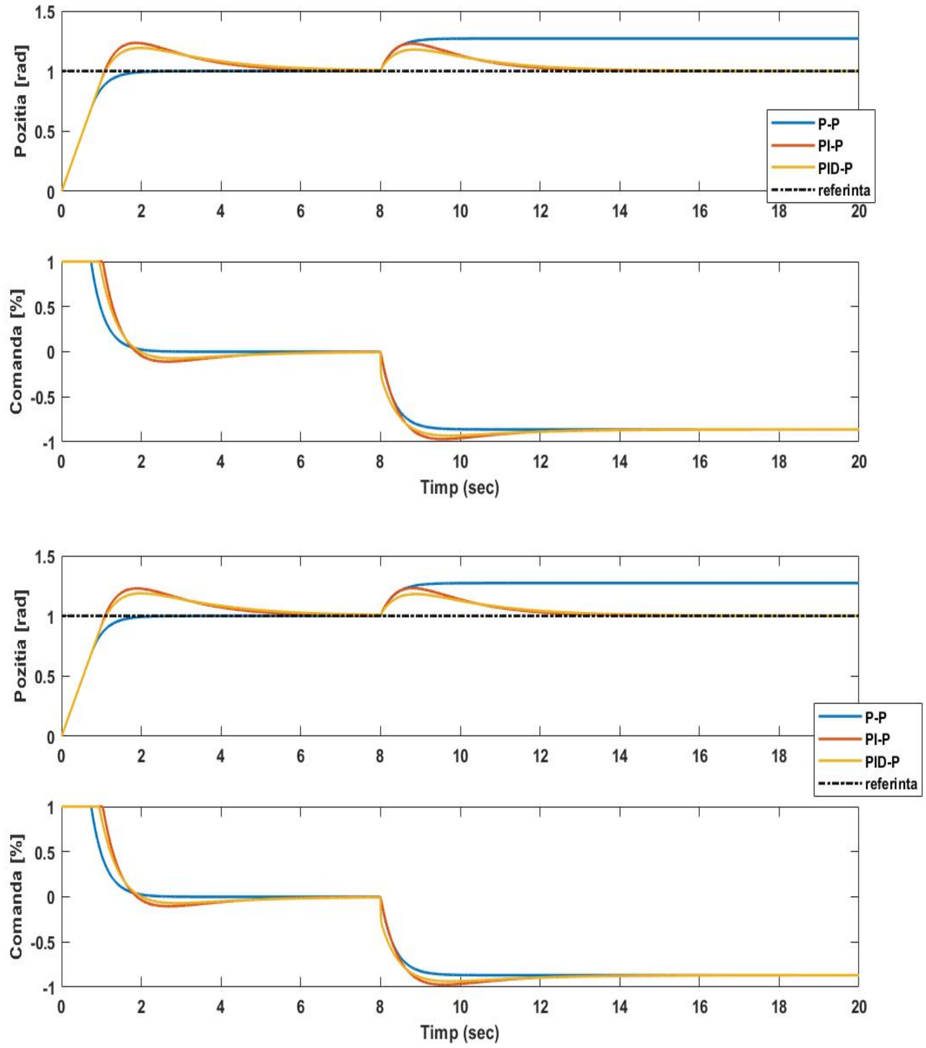


Figure 6: Step response using P controller on the speed loop and P, PI and PID controller on the position loop a) X axis b) Y axis

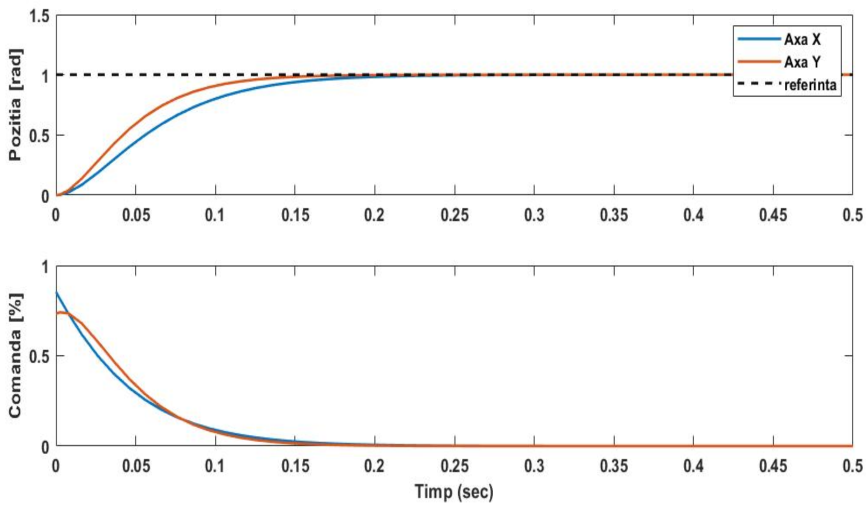


Figure 7: Step response for each axis using state feedback controller -pole placement methos

# 5 Advanced control techniques

## 5.1 Optimal control - LQR

The thesis presents, in the fourth chapter, some advanced control techniques, which can be adapted to the imposed control scheme that can be implemented on the CNC machine. Also, it is desired to obtain better performance. The first method is LQR, which is based on minimizing a cost function in order to obtain the optimal state feedback controller. LQR design involves choosing the weight matrices $Q$ and $R$. The first simulations are based on choosing $Q$ and $R$ in the classical way, using "trial and error" approach. This mechanism can be time consuming. One of the main objectives of this thesis consists on finding a way to choose the weights for these two matrices such that better performances are obtained and mainly to avoid "trial and error". So, I proposed a method that consists on defining $Q$ matrix based on the total energy of the system.

Having the state variables $\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \omega_i \\ \theta_i \end{bmatrix}$, the equation for the total energy (7) and the term corresponging to the states in the cost function (8), the necessary weights can be identified.

$$E = \frac{1}{2}(J_i \omega_i^2 + k_i \theta_i^2) \tag{7}$$

$$\mathbf{x}^T Q \mathbf{x} = \begin{bmatrix} x_1 & x_2 \end{bmatrix} \begin{bmatrix} q_{11} & 0 \\ 0 & q_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = q_{11} x_1^2 + q_{22} x_2^2 \tag{8}$$

$$Q = \begin{bmatrix} J_i & 0 \\ 0 & k_i \end{bmatrix} \tag{9}$$

## 5.2 PI controller design using state feedback

The simulations and results obtained in the previous chapters show that the state-feedback control methods give good performances in terms of settling time, overshoot and command. The classic structure with state feedback can be modified to obtain the cascade control configuration required for the implementation of the control scheme on the physical process. Thus, a cascading structure is obtained with a P controller on the speed and position loop also. Following the simulations for different possible cascade configurations, it was found that, in order to eliminate the disturbances on the speed signal that may occur due to the interconnection between the axes, the integrator element on the position loop is needed.

A methodology for obtaining the transient performances given by the state-feedback controller and the capacity to reject the disturbances given by the integrator is proposed below.

The authors in [5, 6, 7] presents some applications of the state-feedback control problem using pole placement, while adding the integrator element in the process. Also, in [8, 9] the same technique of adding an extra integral element and computing the state feedback matrix using LQR is presented. Studies show that adding the integral action gives better performances, especially regarding steady state error and disturbance rejection capacity. The papers [10, 11] presents a method of obtaining PI controllers based on state feedback techniques.

So, the proposed method aims to determine the needed controllers in the PI-P cascade configuration based on the two state-feedback approaches: pole placement and LQR. In order to do this, the state space model corresponding to an axis is augmented, by adding an extra state, representing the integral of the position, as it is shown in Fig. 8.

$$G_i^* : \left(\begin{array}{c} \dot{\omega}_i(t) \\ \dot{\theta}_i(t) \\ \dot{z}_i(t) \\ \hline y_i(t) \end{array}\right) = \left(\begin{array}{ccc|c} -\frac{1}{T_{Mi}} & 0 & 0 & \frac{K_{Mi}}{T_{Mi}} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \hline 0 & 1 & 0 & 0 \end{array}\right) \left(\begin{array}{c} \omega_i(t) \\ \theta_i(t) \\ z_i(t) \\ \hline u_i(t) \end{array}\right), \tag{10}$$

Thus,the new SISO (10) system has 3 state variables, instead of two and the state feedback matrix $K$ has a gain for each of these states. Having the control law for the state-feedback

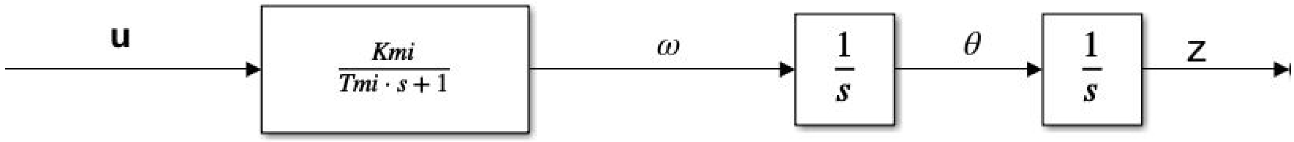


Figure 8: Diagram of the augmented system

approach (11) and the control law for the proposed cascade configuration (12) the relationship between the state feedback gains and the PI and P controllers' parameters can be identified, as shown in (13).

$$u(t) = \theta^{\star}(t) - K\mathbf{x}(t) = -k_1\omega(t) - k_2\theta(t) - k_3 z(t) = \\ = \theta^{\star}(t) - K\mathbf{x}(t) = -k_1\omega(t) - k_2\theta(t) - k_3 \int \theta(t)dt \tag{11}$$

$$u(t) = P_v(-\omega(t) - P_p\theta(t) - I_p \int \theta(t)dt + P_p\theta^{\star}(t) + I_p \int \theta^{\star}(t)dt) \tag{12}$$

$$\begin{cases} P_v = -k_1 \\ P_p = \frac{k_2}{k_1} \\ I_p = \frac{k_3}{k_1} \end{cases} \tag{13}$$

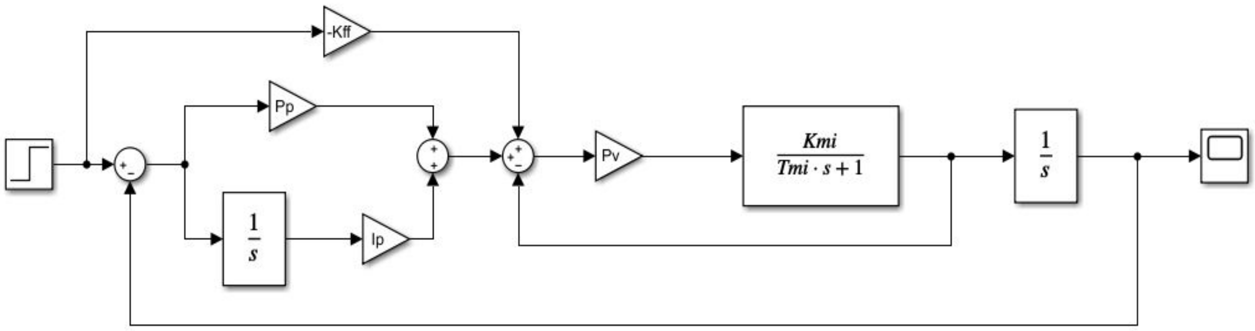


Figure 9: CNC cascade configuration using PI and P controllers with additional feed-forward term

An additional analysis of the closed loop transfer function for both control strategies shows the introduction in the system of a transmission zero that may cause performance changes. To mitigate this effect, a feed-forward gain is proposed and the final control scheme is presented in Fig. 9. The simulations show that this approach gives better performances than the one obtained using ZN design method. In Fig. 10 and 11 are depicted the step responses for each axis, making a comparison between the obtained results using pole placement method and LQR. Better performances are obtained using pole placement technique, but the results depends on the weights selection of the matrices $Q$ and $R$.

## 5.3 Fractional PID controllers design using $\mu$ synthesis - MIMO approach

The paper [12] proposes a method of designing a controller, with a fixed structure, using robust control techniques, $\mu$ synthesis respectively. The chosen fixed structure is a PID regulator, of

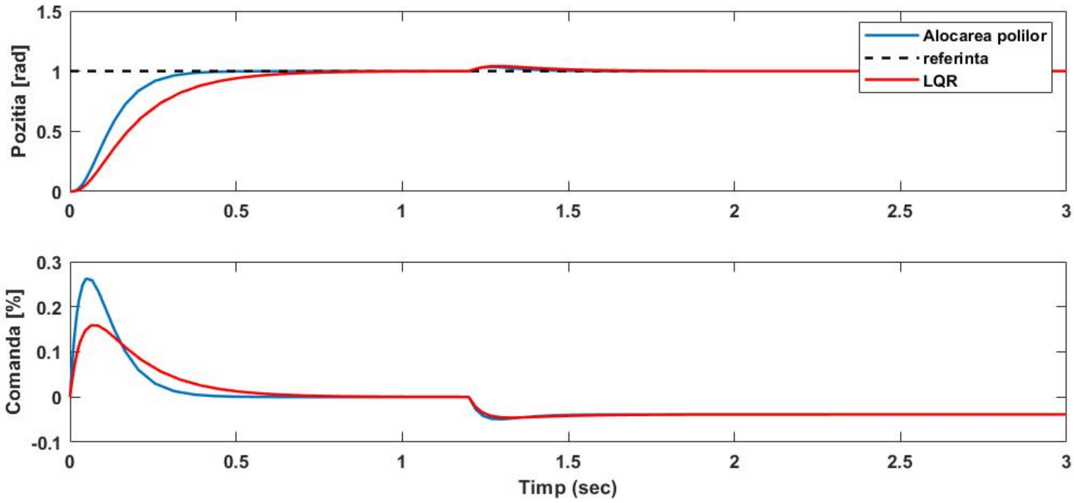


Figure 10: Step response using PI-P cascade configuration with feedforward - X axis

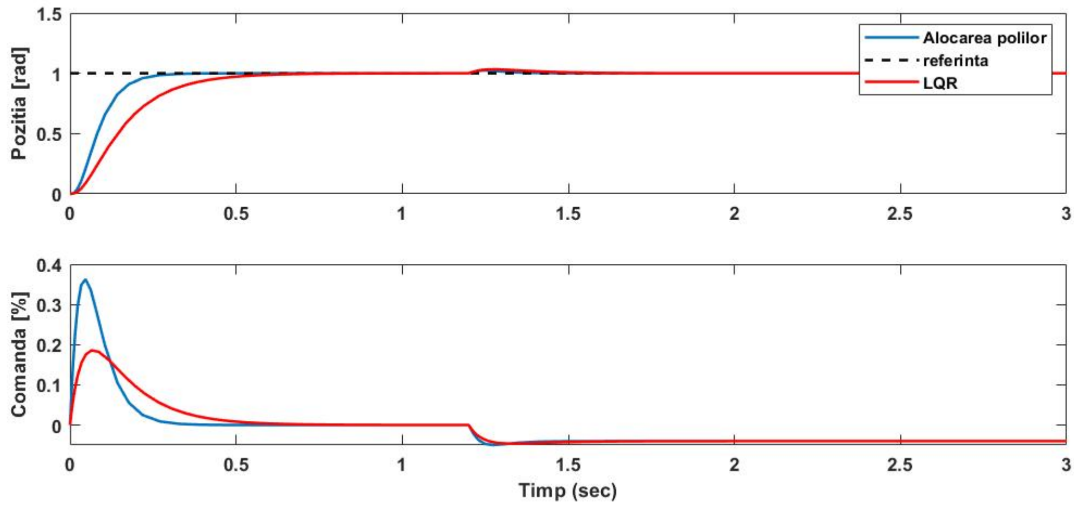


Figure 11: Step response using PI-P cascade configuration with feedforward - Y axis

fractional order. The authors propose a different problem-solving approach from the classical one, in which the non-convex part of the problem is solved using metaheuristic optimization algorithms. The details of the proposed method are exemplified in the cited paper, and this was tested for the MIMO model of the CNC equipment. An uncertainty range was considered for each parameter that varies by $pm10\%$ from the nominal values.

The proposed method consist of solving the "*mixed-sensitivity fixed structure μ-synthesis*" problem, resulting the controller:

$$K^{\theta^\star}(s) = \begin{pmatrix} 0.2229 + 5.9392 \cdot s^{-0.7792} & 0 \\ 0 & 0.3949 + 10 \cdot s^{-0.9733} \end{pmatrix}. \tag{14}$$

In Fig. 12 are represented the step responses, corresponding to each axis. The performances in the time domain obtained can be correlated with the performances in the frequency domain. The minimum bandwidth values are above the required values. The related rise time is $0.248s$ for the nominal subsystem $r_x \to \theta_x$ and ranges from $0.227s$ to $0.281s$, and the settling time for the nominal system is $0.558s$ and ranges from $0.496s$ to $0.664s$. In the case of the $r_y \to \theta_y$ subsystem, the rise time varies from $0.19s$ to $0.235s$ and is $0.211s$ for the nominal system, and the settling time is $0.405s$ and varies between $0.363s$ and $0.454s$. Regarding other performance,

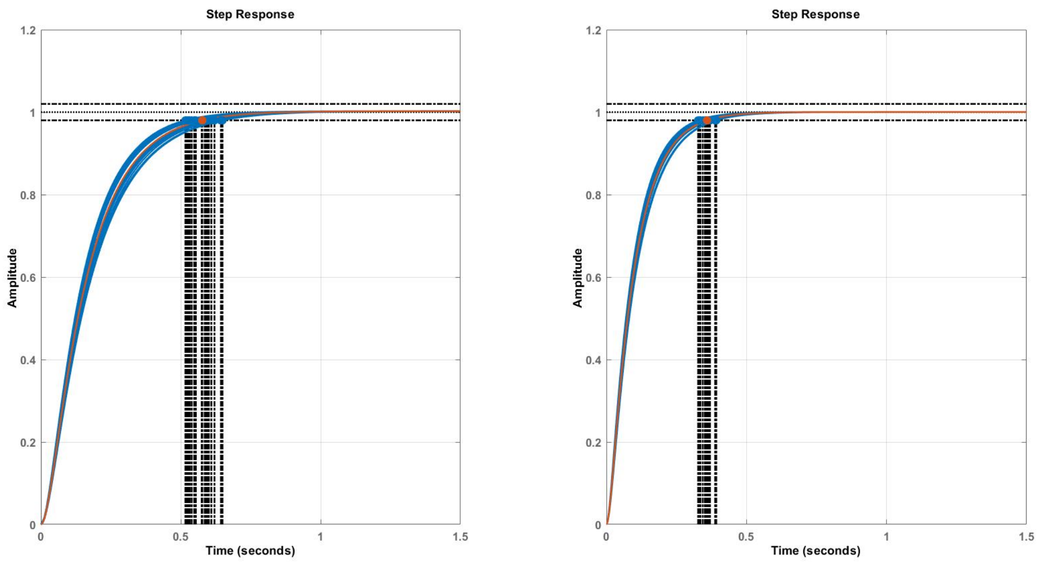


Figure 12: Step response for the two subsystems ($r_x \rightarrow \theta_x$ și $r_y \rightarrow \theta_y$)

the system does not have overshoot and stationary error.

An advantage of this method, compared to the method based on unstructured $\mu$ synthesis, is the order of the controller. For comparison, a controller was designed for the same system, using Matlab functions, and the obtained controller is non-implementable, of order 66.

Also, in order to compare the results and performances from a theoretical point of view, based on the simulations, it was proposed to determine a robust regulator, with a fixed structure, using the classical method, namely the structured $\mu$ synthesis. For this, the cascade structure was proposed, with PI regulator for position and P for speed. The design of the controller was done using Matlab functions, and the optimal obtained controllers are:

- For the first subsystem - X axis:

$$H_{PI,\theta} = 1.339 + \frac{0.0063}{s} \qquad H_{P,\omega} = 0.1548 \tag{15}$$

- For the second subsystem - Y axis:

$$H_{PI,\theta} = 0.429 + \frac{0.00064}{s} \qquad H_{P,\omega} = 0.9205 \tag{16}$$

The simulations were performed on the MIMO system with uncertainties, using the same weighting functions as in the case of fractional regulators. The step responses are illustrated in Fig. 13.

Based on the simulations performed, it is observed that fractional regulators lead to slightly improved performance, with a settling time smaller by $0.1[s]$. Their disadvantage, from the point of view of the physical process used, is that they cannot be implemented, due to the imposed control structure.

# 6 CNC state feedback control methods optimization

The chapter presents two approaches for optimizing the previously presented control methods. The first is to implement an optimization algorithm for selecting the $Q$ and $R$ matrices required

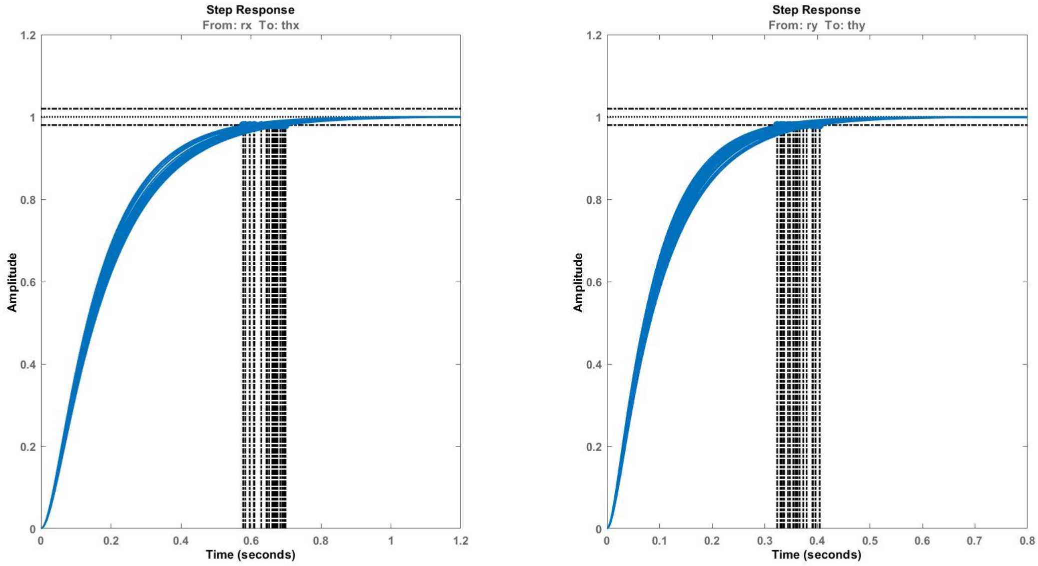


Figure 13: Step response for the two subsystems ($r_x \rightarrow \theta_x$ și $r_y \rightarrow \theta_y$) using the robust controllers in the cascade configuration

for LQR design. The proposed optimization algorithm is part of recent evolutionary algorithms category and is inspired by the behavior of the swarm of bees: the Artificial Bee Colony (ABC) algorithm. The proposed cost function for this algorithm includes the necessary performance parameters: settling time and overshoot. This cost function can be defined so that the optimization problem to minimize these performance indices or so that the response time is as close as possible to a required value. The integration of the selection problem of the matrices Q and R in the optimization algorithm is achieved by mapping the weights of these matrices in a vector. The algorithm is searching the best solution to minimize the cost function. A possible solution is verified by reconstructing the Q and R matrices from the current vector, computing the state reaction matrix, simulating the closed loop system, determining the performance indices and evaluating the cost function.

As for the simulations, in Fig. 14 is represented the settling time evolution after the iterations, and Fig. 15 shows the step responses at each 3 iterations (in case of changing), being highlighted the optimal step response obtained. The figures illustrate the results corresponding to the X axis.

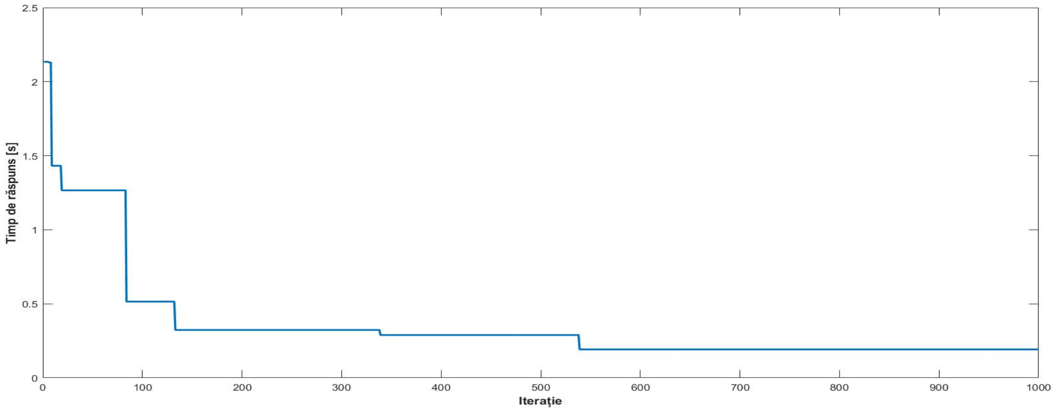


Figure 14: Settling time evolution - ABC algorithm - X axis

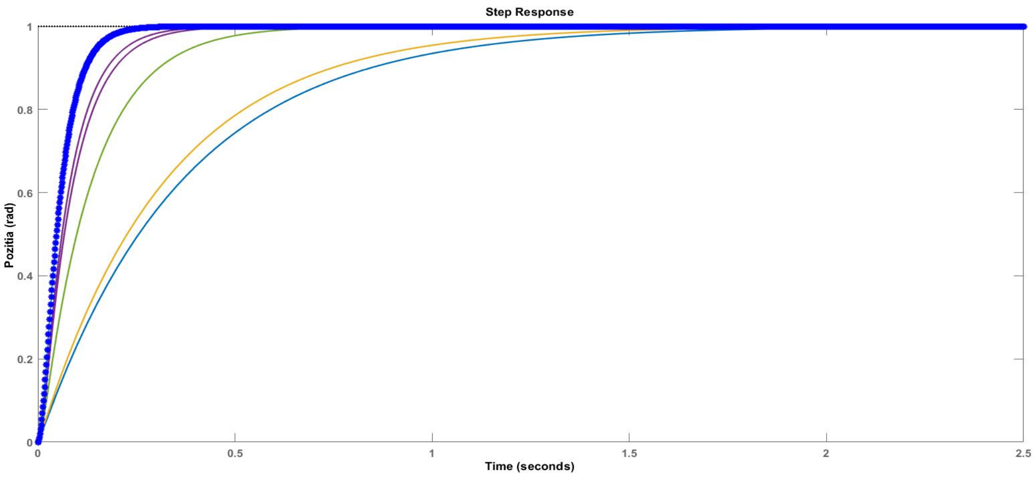


Figure 15: Step response evolution - ABC algorithm - X axis

The determination of the optimal state feedback controller, necessary to obtain the cascade control configuration. as presented in Chapter 4 is done, in the last proposed approach, using LMIs. The proposal of this method is motivated by the fact that, in the case of the LQR regulator, there is no management of the transient response performance through the matrices $Q$ and $R$. Thus, LMIs are used to define the regions in the complex plane in which the closed loop poles to be located, in order to meet the required performance. The regions proposed in the thesis are those of the vertical sector type, used to impose the settling time and the conical regions, used to impose the damping factor and, implicitly, the overshoot. The LMI system is solved in Matlab, obtaining the state feedback matrix $K$ which ensures the desired performances. Also, by using the additional state, it is possible to adapt to the cascade control scheme with a PI controller for the position loop, so that the control system has the ability to reject disturbances, the LMI approach allowing the determination of a robust controller.

The step response obtained after the simulations are illustrated in Fig. 16 și 17. The settling time has a smaller value than the imposed one, $t_s = 0.2s$, and the response has no overshoot, and the disturbance is succesfully rejected.

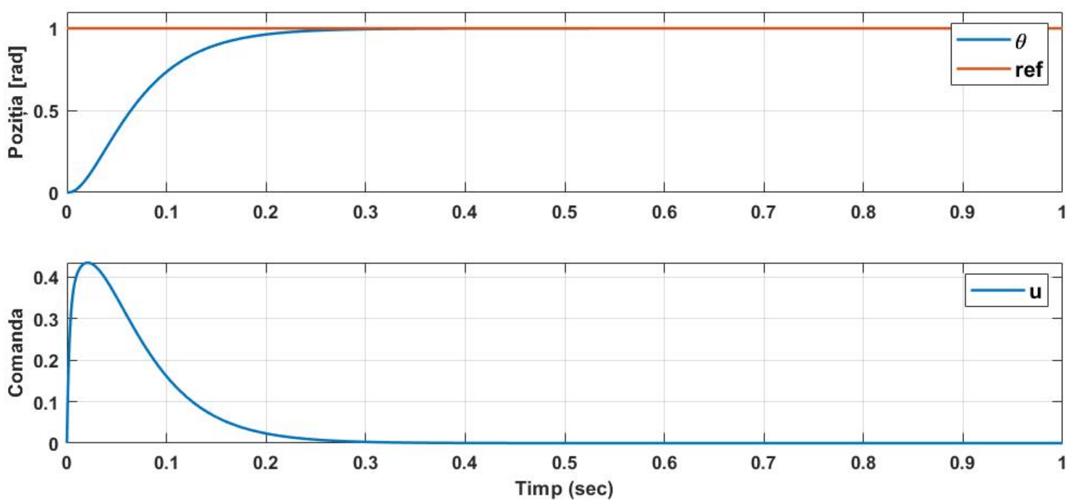


Figure 16: Control using LMIs - Y axis

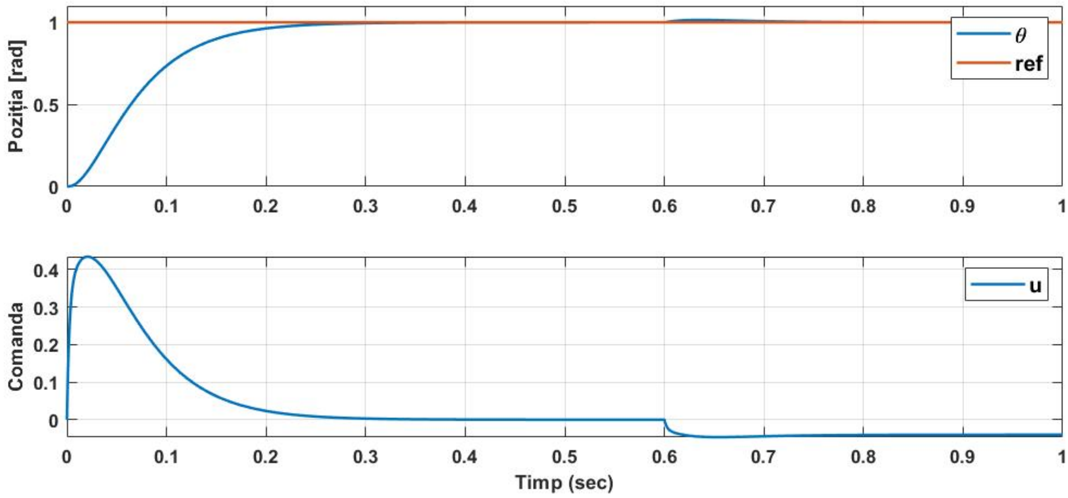


Figure 17: Control using LMIs - Y axis. Behaviour in the presence of disturbance

# 7 Experimental results

The validation chapter presents the main experiments performed on the CNC equipment,illustrating 3 of the most relevant ones. The first results presented correspond to the test without using a designed regulator, the second set of results are obtained by implementing the control scheme based on the state feedback, and the third corresponds to the experiment for which the cascade structure with feed-forward gain was used. From one experiment to another there is an improvement in the results obtained, in terms of the percentage of the fitting function of 4 to 10%. All experiments were performed by setting the parameters of the controllers for each axis and programming the machine to achieve different trajectories using the TrioBasic language.

The comparison of the results obtained from the 3 mentioned experiments was made based on an index showing the fitting of the realized trajectory, compared to the reference trajectory. For the 3 experiments, square or circle trajectories of different sizes were made. The results obtained are illustrated in the Table 2.

| | | Experiment 1 | | Experiment 2 | | Experiment 3 | |
|---|---|---|---|---|---|---|---|
| | | X axis | Y axis | X axis | Y axis | X axis | Y axis |
| Square | $L = 3cm$ | 79% | 76% | 80% | 80% | 85% | 86.4% |
| | $L = 5cm$ | 82% | 84.1% | 84.5% | 86% | 86% | 87.3% |
| Circle | $R = 1cm$ | 92% | 92.7% | 93.2% | 96% | 99.7% | 99.6% |
| | $R = 5cm$ | 93% | 97% | 95% | 98% | 99.8% | 99.7% |

Table 2: Experimental results - fitting index analysis

# 8 Conclusions

The thesis presents a research regarding control methods for CNC equipment. The existing specialized works in this field show that, although numerous studies have been performed to optimize the control algorithms for these equipments, the most used in practice are still the PID regulators. The thesis proposes the design, simulation, testing, implementation and validation of both classical control methods, used mainly in practice, but also of advanced control methods, with the role of optimizing the design process of regulators, with improved performance.

## 8.1 Personal contributions

Chapter 2 - Modeling, identification and analysis:

- Carrying out the experiments necessary to acquire the data used in the identification process.
- Identification of a transfer function model for each translation axis separately, represented by independent SISO systems.
- Identification of a MIMO model, by determining the coupling element between the two axes.

Chapter 3 - Classical control techniques

- Ziegler-Nichols with relay tuning method applied for the process chosen as a case study.
- Carrying out a comparison on the performances obtained with different regulators, using a simple structure, with regulator only on the position loop.
- Performing a series of simulations to perform a comparison of cascade control, by testing the behavior of the closed loop system with different controllers on the position loop and a P controller on the speed loop.
- State feedback controller simulation for both SISO and MIMO system.

Chapter 4 - Advanced control techniques:

- Implementation and simulation of the LQR regulator obtained by the classical method - performance analysis.
- Proposing a method of designing the LQR controller by choosing the matrices $Q$ and $R$ based on the total energy of the system. Based on mathematical relationships it is shown that the method can be suitable especially for mechanical systems.
- Proposing a method of cascade control design based on state feedback control methods. The aim was to determine a PI controller on the position loop, so that the model in the state space was extended by introducing an additional state, represented by the integral of the position.
- Adding the feed-forward gain in order to mitigate the transmission zero effect.
- Simulating the controllers obtained using $\mu$ synthesis.
- Carrying out simulations for all design methods and analyzing the results in terms of performance.

Capitolul 5 -CNC state feedback control methods optimization

- Two methods for optimizing the selection of weigt matrices $Q$ and $R$ were proposed, through the ABC optimization algorithm. In the first case, the optimization algorithm consists in minimizing the cost function, based on the time domain performances, and the second approach consists in the optimal determination of the parameters, so that the performances are as close as possible to a predetermined value. The personal contributions include the analysis of the method, the proposal of the cost functions in the two cases, the implementation of the ABC algorithm and its integration in the problem of choosing $Q$ and $R$ matrices. The implementation was done using the Matlab work environment.

- Controller design for the augmented system, using LMIs.
- Choosing and defining LMI regions.
- Simulation results analysis.

Capitolul 6 - Experimental results

- Performing experimental tests on CNC equipment, in different situations and with different control parameters.

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