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FORCE BASED IMPEDANCE CONTROL OF 5-BAR PARALLEL ROBOT MANIPULATOR

Eray YILMAZLAR*

Kırklareli University, Technical Sciences Vocational School, Electronics and Automation, Kırklareli, Türkiye

Keywords	Abstract
Impedance Control, Parallel Robot, Damping-Stiffness Analysis, Robot Interaction.	The interaction of robots with the environment is increasing in many sectors. In particular, position and force-dependent interactions are frequently used in sensitive applications. In this interaction control, impedance control method answer the need. The parallel robot manipulator is one of the models that is widely used in this field and constitutes the basic of many robot designs. In this study, an exemplary 5-limb robot manipulator is designed. Position change according to the amount of load applied on this manipulator was realized with impedance control. Force amount measurement was applied using loadcell. The position change was calculated with the forward kinematic calculations of the manipulator. This calculation and control process was realized on the Arduino Mega embedded system board. With this experiment application study, the behaviour analysis of the robot manipulator was examined according to the stiffness and damping coefficients that affect the impedance control, and the ideal coefficients for the designed manipulator were determined.

5-BAR PARALEL ROBOT MANİPÜLATÖRÜNÜN KUVVET BAZLI EMPEDANS KONTROLÜ

Anahtar Kelimeler	Öz
Empedans Kontrolü, Paralel Robot Manipülatör, Sönümleme-Sertlik Analizi, Robot Etkileşimi.	Robotların çevre ile etkileşimleri birçok sektörde yaygınlaşarak artmaktadır. Özellikle Pozisyon ve kuvvete bağlı etkileşimler hassas uygulamalarda sıkılıkla kullanılmaktadır. Bu etkileşim kontrolünde empedans kontrolü ihtiyacı karşılamaktadır. Paralel robot manipülatörü ise bu alanda yaygın kullanılan ve birçok robot tasarımının temel örneklerini oluşturan modellerden biridir. Bu çalışmada örnek bir 5 uzuvlu robot manipülatörü tasarlanmıştır. Bu manipülatörün üzerinde uygulan kuvvet miktarına göre pozisyon değişimi empedans kontrolü ile yapılmıştır. Kuvvet miktarı ölçümü yük hücresi kullanılarak gerçekleştirilmiştir. Pozisyon değişimi ise manipülatörün ileri kinematik hesaplamaları ile hesaplanmıştır. Bu hesaplamalar ve kontrol işlemi gerçek zamanlı olarak Arduino Mega gömülü sistem kartı üzerinde yapılmıştır. Bu uygulama çalışması ile empedans kontrolünü etkileyen sertlik ve sönümleme katsayılarına göre robot manipülatörünün davranış analizi incelenmiş ve tasarlanan manipülatör için ideal katsayılar belirlenmiştir.

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* İlgili yazar / Corresponding author: eray.yilmazlar@klu.edu.tr, +90-288-214 18 45

FORCE BASED IMPEDANCE CONTROL AND ANALYSIS OF 5-BAR PARALLEL ROBOT MANIPULATOR

Eray Yılmazlar†
Kırklareli University, Technical Sciences Vocational School, Electronics and Automation, Kırklareli, Türkiye

Highlights

- Force-based impedance control of the parallel manipulator robot.
- Robot motion control in robot human-environment interaction.
- Control coefficients in impedance control.

Graphical Abstract

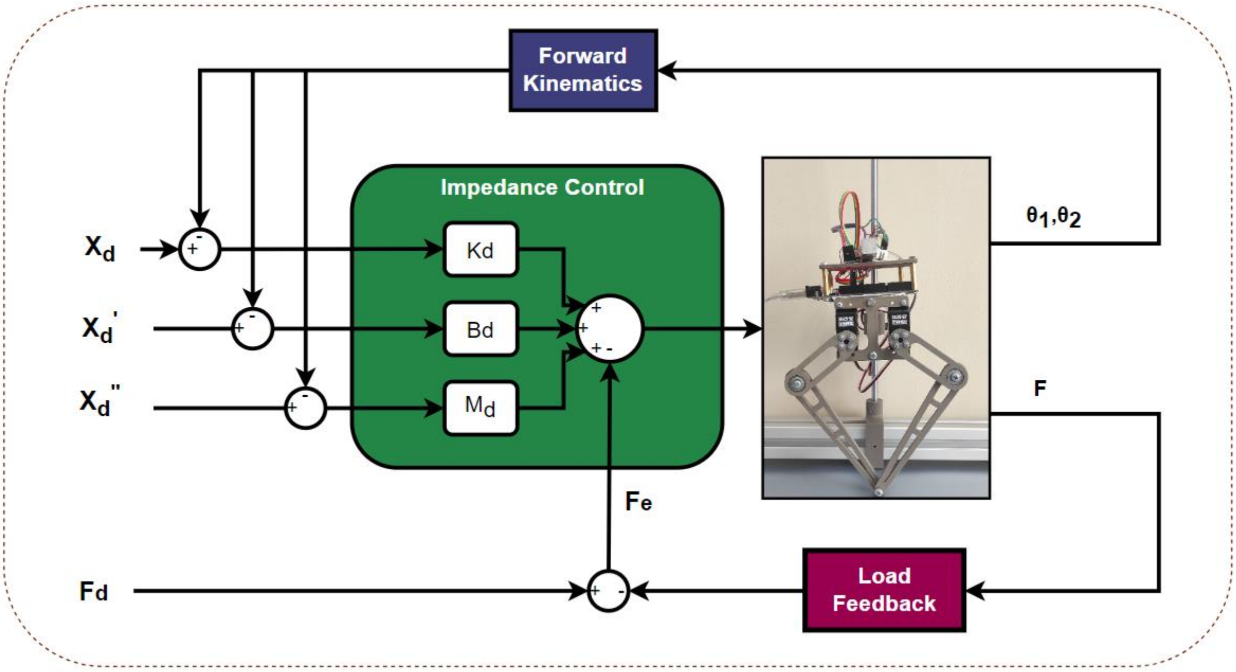

Figure. Force dependent parallel manipulator impedance control block diagram

Purpose and Scope

The main purpose of this study is to realize the environmental interaction of the 5-bar parallel robot manipulator with the impedance control method and to determine the ideal impedance control coefficients.

Design/methodology/approach

In order to reach the goal in the study, firstly, the experimental setup was designed. An impedance control algorithm based on the manipulator model was created using Arduino Mega. Applications were made at different impedance coefficients by applying loads on the Loadcell. The ideal stiffness and damping coefficients were determined by analyzing the data collected in real-time.

Findings

The ideal impedance control coefficients were determined according to the amount of force that the designed manipulator can be exposed to and the analysis of the behaviour of the manipulator in interaction with the environment.

Originality

This study presents an exemplary model for evaluating the importance of impedance control, real-time design, and the effects of impedance control coefficients used in many robot designs that interact with the environment.

† Corresponding author: eray.yilmazlar@klu.edu.tr, +90-0288-214 18 45

1. Introduction

The increase in the capacity of robots and the spread of their use are constantly increasing. Simultaneously, the contact of robots with their environment is increasing. The interaction between the objects and the robot must be controlled in a balanced. If this process is not controlled, damage to the robot or object may occur due to contact. Impedance control is one of the commonly used methods in this control process. In impedance control, the contact force or distance is measured and controlled. And thereby, contact damage is avoided. In other control methods, the command requested from the robot is realized regardless of position, movement, or force value. It does not take into account the problems that may occur in the object opposite(Buchli et al. 2011; Song, Yu, and Zhang 2017).

Impedance control has many advantages, some of which are: it can be used in many sectors in interaction with the environment and humans in the robotic field, the sensitivity can be adjusted according to the material to be contacted, more reliable force and torque movements instead of old-style spring-loader mechanical control methods and it can be used with other control theories. (Ba and Yu 2018; Xu et al. 2020) Disadvantages of impedance control is that the values of the damping and stiffness coefficients used must comply with the limits and performance of the controlled unit otherwise instability may occur in applications where high damping is required. The model dynamics of the unit to be compatible for impedance control and should not be affected by external factors. Sensitive sensors are required for torque and force feedback. With these advantages it provides impedance control, it is used in many areas today(Abu-dakka and Saveriano 2020). Examples of areas where impedance control is used are precision movement and handling, gripper mechanisms, assembly processes, and surgical procedures(Jiao et al. 2022; Ji et al. 2021; Palma, Seweryn, and Rybus 2022).

The advantages of the impedance control method have been preferred in order to prevent damage to both the robot mechanism and the object in the contact of a sample robot leg with the environment and to provide adjustable force transfer between them. In this study, it is aimed to use position and force-dependent impedance control as a hybrid. In order to realize this application, single leg of the prototype robot was designed and an experimental setup was created. In this study, in addition to similar studies, the behavior of the robot leg mechanism according to different force loads and different stiffness and damping coefficients was analyzed and contributed to the determination of the ideal coefficients for the application.

2. Material and Method

Impedance control is a type of force or position-dependent control. In this study, a force-based control type is based. Impedance control dynamically adjusts the relationship between robot motion and contact force through a mechanical impedance. The impedance control model is expressed by equation 1(Hogan 1985).

$$F = M(\ddot{\theta} - \ddot{\theta}_d) + B(\dot{\theta} - \dot{\theta}_d) + K(\theta - \theta_d) \qquad (1)$$

In the equation, the impedance parameters M, B, K represent the inertia matrix, damping matrix and stiffness matrix, respectively. θ stands for current position, θ_d stands for targeted position. In equation 2 The force applied to the robot manipulator system is F, the desired force value is F_d, and the force difference F_e occurs between.

$$F_e = F_d - F \qquad (2)$$

In impedance control, stiffness and damping parameters are defined to control how the robot interacts with its environment. This interaction occurs with the displacement of the robot's limbs in the control process. With displacement, the force applied to the robot's limb reaches the reference value. And thus, the force applied to the robot manipulator is adjusted to reference level and equilibrium is achieved in contact with the object.

The manipulator with 5 connectors designed in figure 1(a) is shown. The five-link parallel manipulator appears in many examples in robotic applications with different designs. It represents the single leg of the robot, one of the robotic design examples. 5 bar parallel manipulators have a symmetrical structure. P_{xy} is the end-effector of the parallel manipulators. The manipulator has the ability to with the servo motor at θ_1 and θ_2 as active joints, and θ_3 and θ_4 as passive joints. The manipulator moves vertically on the slide shaft axis. (Lara-molina and Takano 2018; Duperret and Koditschek 2015; He et al. 2021) Forward kinematic solutions are used to calculate the coordinates(x,y) of point P. These solutions appear in equation 3-6. Active changes at θ_1 and θ_2 cause the movement of the l limbs and change the position of the p point (Lou et al. 2004;Le, Kang, and Doan 2013).

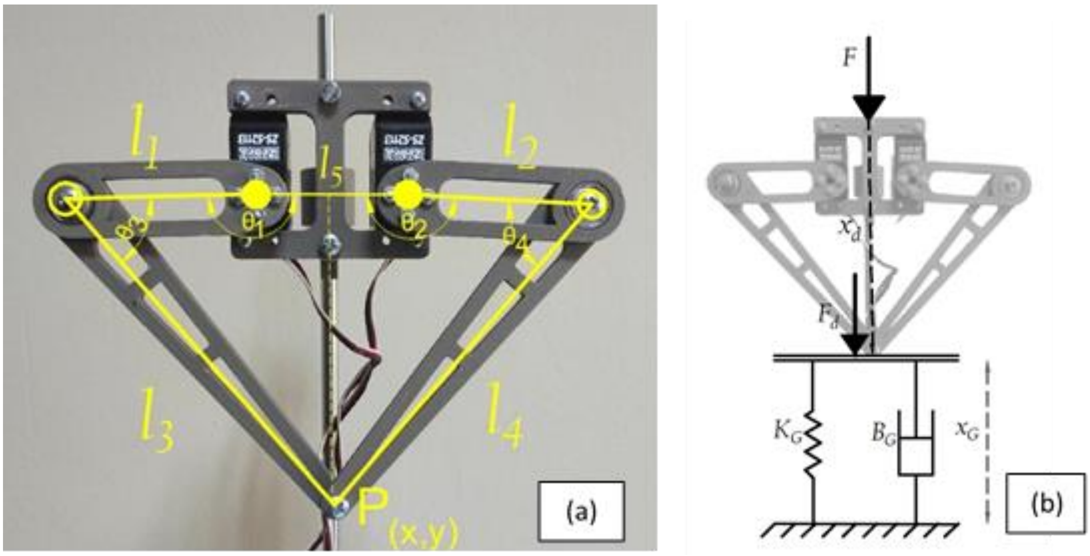

Figure 1. (a) The 5-bar planar parallel robot and (b) schematic of robot spring-damper system

$$x = l_1 cos\ \theta_1\ + l_3 cos\ \theta_3 - l_5/2 \tag{3}$$

$$x = l_2 cos\ \theta_2\ + l_4 cos\ \theta_4 + l_5/2 \tag{4}$$

$$y = l_1 sin\ \theta_1\ + l_3 sin\ \theta_3 \tag{5}$$

$$y = l_2 sin\ \theta_2\ + l_4 sin\ \theta_4 \tag{6}$$

In figure 1b, the spring-damper model of the surface contacted by the 5 bar robot is shown. In the model, B_G and K_G represent the ground spring and damper coefficients. x_G represents the ground height and there is also the independent mass M_G. In force-based Impedance control, the F force applied to the robot is requested to be transmitted to the ground at the desired reference (Fd). For this purpose, the robot manipulator changes its position with the change of angle (θ_1, θ_2). When there is an interaction originating from the surface, the equation shown in equation 7 is used to reach the desired force value F_d . With this equation, the difference force F_e sensed by the robot manipulator is gradually brought to the reference value Fd with the impedance control.

$$F_d = M_G \ddot{x}_G + B_G \dot{x}_G + K_G x_G = M\left(\ddot{\theta} - \ddot{\theta}_d\right) + B\left(\dot{\theta} - \dot{\theta}_d\right) + K(\theta - \theta_d) + F_e \tag{7}$$

In impedance control, the inertia matrix M shown in the equation is explained by the equation 8. Calculations of matrix elements between 8-13 equations are shown. In equations, the j_1, j_2, j_3, j_4 appearing represent the inertia matrices of the connections, m represents limb mass and l represents limb size. M inertia, B dumping, K stiffness matrices in equation 8 consist of 4 rows and 4 columns since the manipulator in figure 2 has 4 moving joints (Rigatos and Abbaszadeh 2022).

There are 3 basic parameters in impedance control. The first of these parameters is the inertia matrix (M). M varies according to the level of force applied to the unit and the dynamics of the controlled unit. The other 2 parameters are stiffness and damping matrices. These two parameters can be changed according to the user's preference. High stiffness coefficient is preferred in applications where the force applied to the unit is to be transmitted to the surface or the robot remains stable. High damping coefficient is preferred when it is desired not to transmit the force to the surface and to be damped by the unit. The motion behavior of the robot unit is consist on according to the values of the stiffness and damping coefficients.

$$M(\theta) = \begin{matrix} m_{11} & 0 & m_{13} & 0 \\ 0 & m_{22} & 0 & m_{24} \\ m_{31} & 0 & m_{33} & 0 \\ 0 & m_{42} & 0 & m_{44} \end{matrix} \tag{8}$$

$$m_{11} = m_1 \left(\frac{l_1}{2}\right)^2 + m_3 \left({l_1}^2 + \left(\frac{l_3}{2}\right)^2 + 2 l_1 \frac{l_3}{2} cos(\theta_3) \right) + j_1 + j_3 \tag{9}$$

$$m_{13} = m_{31} = m_3\left(\left(\frac{l_3}{2}\right)^2 + l_1\frac{l_3}{2}cos(\theta_3)\right) + j_3 \quad (10)$$

$$m_{22} = m_2\left(\frac{l_2}{2}\right)^2 + m_4\left(l_2{}^2 + \left(\frac{l_4}{2}\right)^2 + 2l_2\frac{l_4}{2}cos(\theta_4)\right) + j_2 + j_4 \quad (11)$$

$$m_{24} = m_{42} = m_4\left(\left(\frac{l_4}{2}\right)^2 + l_2\frac{l_4}{2}cos(\theta_4)\right) + j_4 \quad (12)$$

$$m_{33} = m_3\left(\frac{l_3}{2}\right)^2 + j_3 \qquad m_{44} = m_4\left(\frac{l_4}{2}\right)^2 + j_4 \quad (13)$$

3. Impedance Control

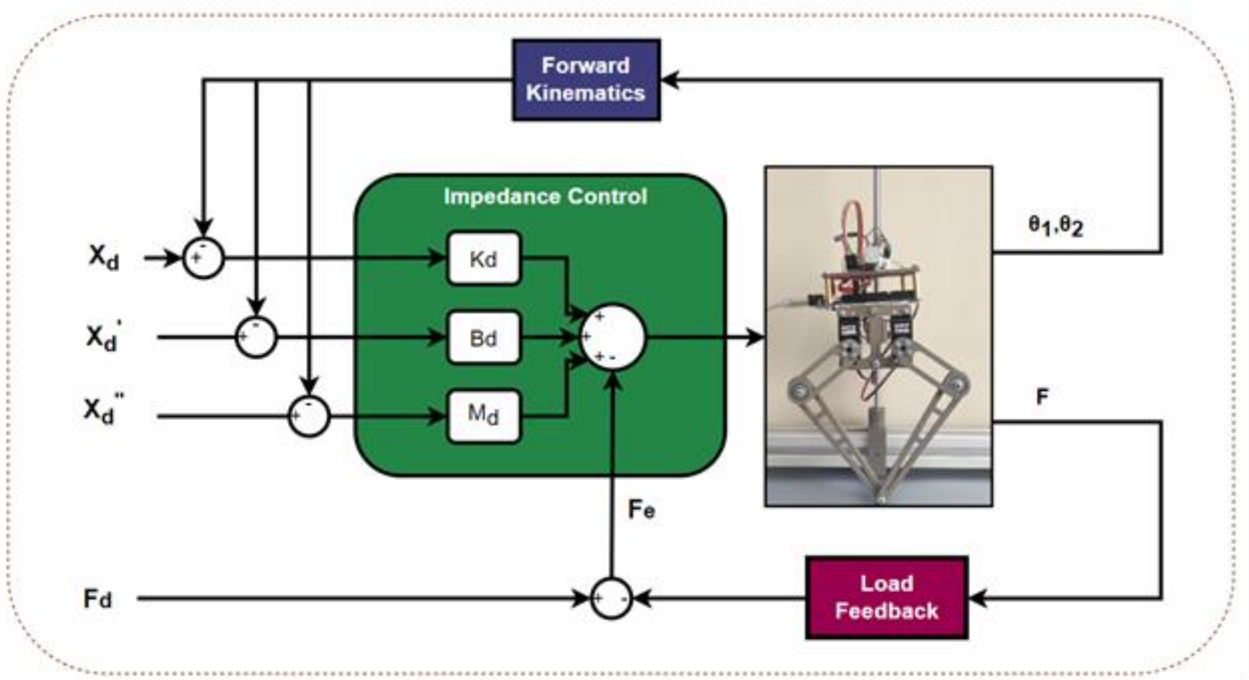

Figure 2. Force dependent parallel manipulator impedance control block diagram

The control diagram in figure 2 shows the inputs of robot height and force value to be applied to the manipulator. These inputs was determined as reference. These values are calculated during the impedance control process and transmitted to the manipulator motors. The movement of the robot occurs with the change of motor angles. This motion turns into height feedback with forward kinematics calculation and is included in the impedance control process. The force control process calculate by comparing the reference value with the force applied on the robot manipulator. This feedback process was realized with loadcell and included in the control process. These operations are calculated and controlled using an 8-bit Atmega2560 microcontroller(Campus 2021; Zhan-xi et al. 2021; Arevalo and Garcia 2012).

Reference inputs and outputs appear in algorithm 1. When the basic loop is examined, the E error is calculated depending on the impedance control as long as the force is applied to the manipulator. This error value is calculated with the motor angles and rearranges the x and y positions (Table 1).

Table 1. Impedance control coding algorithm

Algorithm 1: Impedance Control

Input: F_d, x_d *//Reference Force and Position*
Output: θ_1, θ_2, F *//Motor angle and Force feedback*
while $F \neq 0$ **do**
  $x = l_1 \cos\theta_1 + l_3 cos\theta_3 - l_5/2$ *//Forward kinematic position calculation*
  $y = l_1 sin\theta_2 + l_3 \sin\theta_4$
  $F_e = F_d - F$ *//Force feedback measurement*
  $E = M\left(\ddot{\theta} - \ddot{\theta}_d\right) + B\left(\dot{\theta} - \dot{\theta}_d\right) + K(\theta - \theta_d) + F$ *//Impedance error*
  $\underline{\theta}_1 = \theta_1 + E \quad \theta_2 = \theta_2 + E$ *//Error motor angle calculation*
End

3.1 Stiffness and Damping Analysis

Analysis figure 3 shows the behaviour of the manipulator according to 5 different stiffness coefficients and 100 damping coefficient value according to 100N load. In these experiments performed according to real-time impedance control according to Algorithm 1, the response of the manipulator was examined. In addition to the examples in the figure, experiments were carried out to determine the ideal impedance coefficients of the designed manipulator. The coefficients defined for these experiments and the length of the manipulator according to the applied force are shown graphically. For the behaviour analysis of the designed manipulator, 5 different stiffness coefficients and 11 damping coefficients between 1-100 were determined. At these coefficients values, forces of 10,20,40,60,80,100 N values were applied to the load cell on the robot. As a result of the applied forces, the reactions of the robot manipulator to change in length were measured in real-time and shown on the graph.

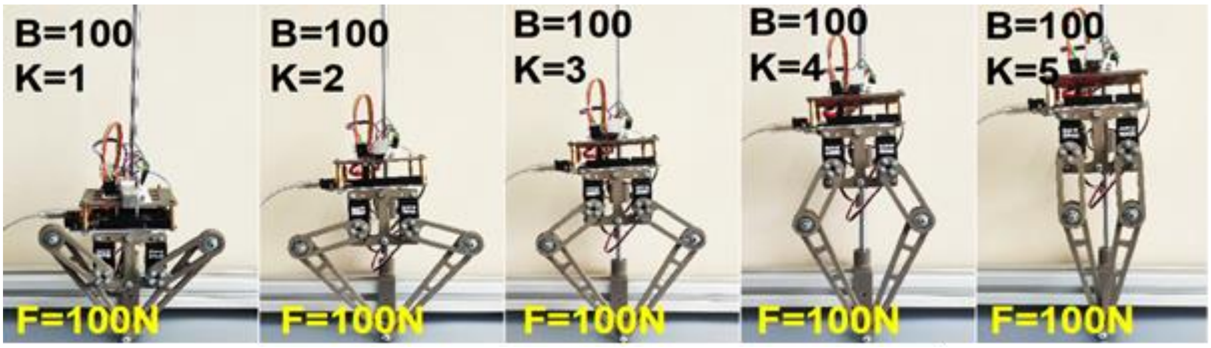

Figure 3. The 5-bar planar parallel robot stiffness analysis

After the stiffness analysis, experiments realized stiffness and damping coefficient analysis. The height curves of the robot are shown in figure 4. Figure 4 are examined; it is seen that the height of the robot manipulator changes according to the gradually changing stiffness and damping values in the different forces. The purpose of the graphics is to observe how the robot behaves in which parameters and to determine the ideal impedance coefficients according to the force to be applied to the robot. When the graphs were examined, it was shown that the robot reacted very little to the 10N and 20N forces and almost ignored the applied forces. When the applied force value is 40N and 60N, the shortening of the robot manipulator stature is observed in the stiffness coefficients of 1 and 2 and the impedance control is active. When the stiffness coefficients are between 3-5, no significant change was observed in the manipulator length. When the force value is 80N and 100N, the robot is completely in its shortest position in the 1st stiffness coefficient. If the stiffness coefficient is between 2-4, the robot manipulator has effective impedance control depending on the force applied to it. When the stiffness coefficient is 5, no movement was observed in the robot manipulator height.

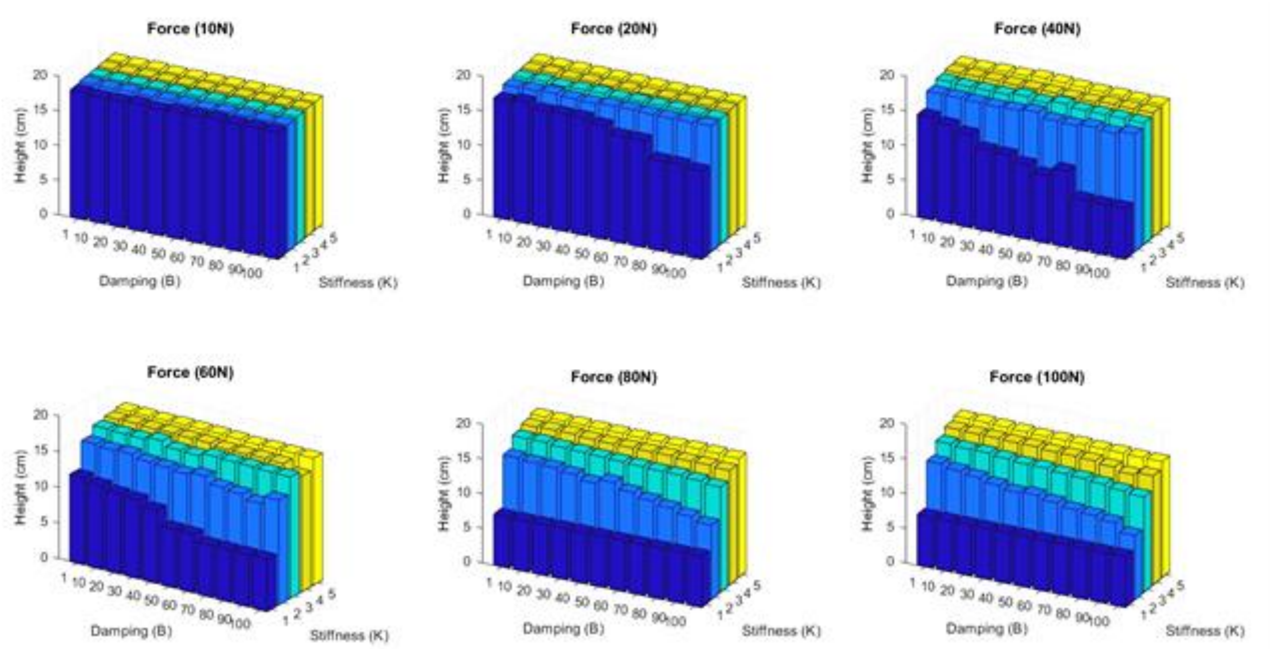

Figure 4. The 5-bar planar parallel robot height damping stiffness graphics

According to the graph of figure 4, a stiffness coefficient of 2 and damping coefficient of 40 seem ideal for impedance control at forces of 60N and above for our robot manipulator design. After defining the stiffness coefficient as 2, data were collected to determine the amount of impedance control error at different damping and force values. These data are shown in figure 5 as the amount of error in the impedance control and the percentage of displacement.

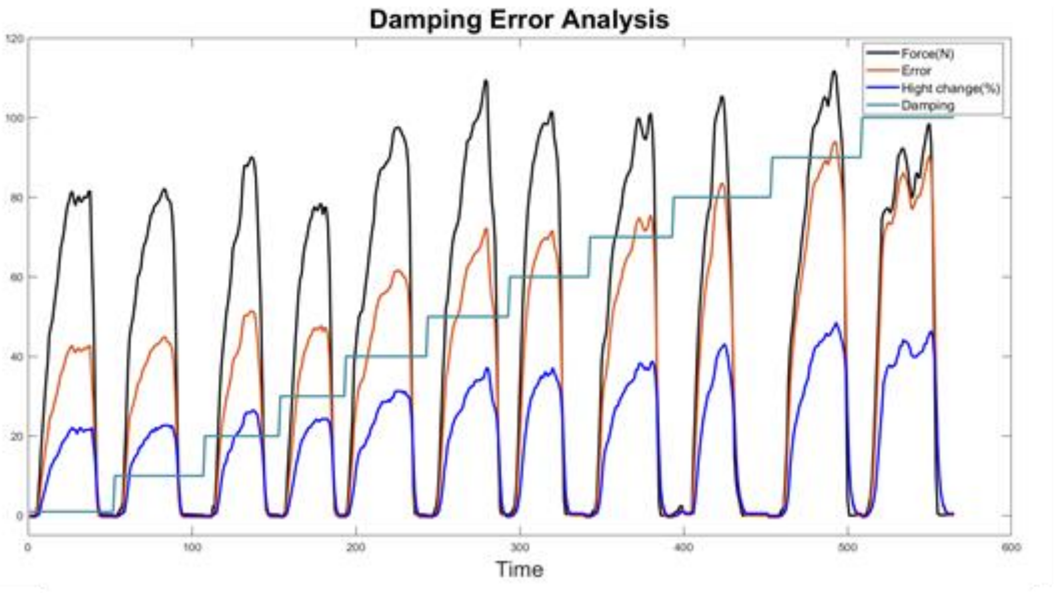

Figure 5. The 5-bar planar parallel robot impedance control damping error analysis

With the determination of stiffness and damping coefficients of 2 and 40, force-dependent damping analysis was performed to examine the analysis in more detail. In figure 5, the damping value changes gradually from 1 to 100. Forces ranging from 0N to 100N were applied on the manipulator and the percent height changes of the manipulator were measured and calculated. When the graph is examined, the error value increases as the damping value increases according to the applied force. When the error levels in the figure are examined, the error level is small when the damping coefficient is between 1 and 50. When damping coefficient values are 90-100, it is seen that the error level increases significantly and the robot manipulator moves at high rate.

4. Result and Discussion

Impedance control is characterized by three basic parameter coefficients: the inertia matrix, stiffness, and damping. The inertia matrix is constantly changing according to the model, motion and error feedback of the robot. On the other hand, the stiffness and damping coefficients are determined by the user. It is preferred at high values in applications where the stiffness coefficient increases the durability of the designed system and the movement is desired to remain constant. The damping coefficient affects the amount of flex in motion. It has been observed that at high damping coefficients, the motion changes of the robots increase. In the determination of these coefficients, it is necessary to determine the amount of interaction between the robot and its environment or the security measures. Due to the power limitation of the servo motors used in our design, 60N was preferred in the force value. Impedance coefficients set to for the stiffness coefficient as 2 and the damping coefficient as 40. These coefficients, it has been observed that the manipulator exhibits ideal behavior according to its own model.

One of the advantages of impedance control in this study is to prevent the motor equipment that provides the motion process from being damaged due to excessive force. By determining the ideal stiffness and damping coefficients according to their design and use, robots will be made more resistant to external forces. Another advantage of impedance control is that it safely responds to interactions with the environment in robot movements. Especially in applications where sensitive interaction is required, more precise control and contact can be achieved with low stiffness and high damping. In our design, it takes place depending on the force control. Force control can be performed with distance control according to the ground or with a current sensor according to the power of the robot motors in different application types. In this study, the implementation of the impedance control of a sample robot manipulator and the analysis of the impedance coefficients were carried out. In addition, it is aimed that this study will be an exemplary reference and contribute to similar applications.

Similar to impedance control, Proportional-Derivative (PD)- Gravity control of motion of robot manipulators is also a widely used method. In this method, the motion of the robot manipulator is controlled by addition the effect of gravity. It is controlled by measuring the angle and acceleration of the manipulator joints. In this method, the movement of the manipulator position against external forces can cause time delays. Therefore, position delay errors may occur. (Luca, Siciliano, and Zollo 2005; Perrusquía and Flores-campos 2020) In impedance control, the effect of gravity and the value of force applied to the manipulator are detected by the force-weight sensor and controlled in real time.This provides an advantage for the control of process speed and force reference, but requires the use of a force sensor in addition to the system unlike PD- Gravity control.

Conflict of Interest

No conflict of interest was declared by the author.

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