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A holistic approach of stability using material parameters of manipulators

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ABSTRACT

The demand for a comprehensive method to assess stability using manipulator material parameters is high. Various material parameters, such as the Young modulus, which represents stiffness, damping, and deflection, influence the material of the robot manipulator. The correlation between robot stability and these characteristics remains unclear, as prior studies have not yet examined the collective impact of these parameters on robot manipulators. This work considers two sophisticated manipulators, namely ABB and FANUC. The main objective of this research is to construct a stability model that considers the material properties of stiffness, damping, and deflection to assess the manipulator's stability level, which may be categorized as low, medium, or high. Furthermore, the presented stability model examines and employs numerous modified and conventional formulas for material properties to determine the level of stability. The findings show that stiffness significantly influences the stability of robot manipulators, a relationship that applies to all the examined manipulators. We also emphasize that the choice of manipulator materials significantly impacts stability maintenance. These findings are expected to enhance the design and advancement of novel robot manipulators within the industry.

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1. INTRODUCTION

In the field of robotics and automation, achieving stability in manipulator systems has long been a primary goal [1]. To ensure safe and effective functioning, these systems must remain stable as they become more complex and widespread in a variety of industrial and commercial applications [2]. However, attaining stability in manipulator systems necessitates a complex interaction between a wide range of elements, including environmental variables, control algorithms, material properties, and structural design [3]. This research effort emphasizes the material properties, delving into the intricate relationship between material parameters and manipulator system stability [4].

This research takes a more holistic approach, acknowledging the importance of material properties in shaping manipulators' overall stability characteristics, as opposed to traditional methods that mainly concentrate on structural design and control procedures. This work pursues to offer a thorough understanding of how material selection might impact the stability performance of manipulator systems by methodically investigating and assessing the influence of material factors such as stiffness, damping, and deflection.

We regard the mechanical stiffness of a manipulator as a significant characteristic for evaluating robot performance [5]–[7]. Industrial robots have historically experienced static and dynamic deformations, as well as chatter vibrations, due to their comparatively low stiffness. External forces acting on the end-effectors during the milling process induce these deformations and vibrations. For optimal performance, a robot with high rigidity is essential, whereas low stiffness is necessary for safety purposes [8], [9]. Damping capacity refers to a material's capability to disperse elastic strain energy when subjected to mechanical vibration or wave propagation [10]. High-damping materials are only necessary in certain situations because they diminish physical and mechanical properties [11]. When a force is applied, the robot manipulator arm's end-point will deflect, and the extent of deflection depends on the arm's stiffness and the magnitude of the force applied [12].

The research explores the relationship between material properties and stability metrics, using theoretical analyses, simulations, and experimental validations. It aims to improve manipulator technology design, optimization, and control, resulting in safer, more reliable, and more efficient robotic systems.

This study makes several significant contributions towards stability considering the material parameters of robot manipulators as follows.

- We examine the stability of robot manipulators using material properties like Young's modulus, which affect stiffness, damping, and deflection.
- In this research, we focused on advanced manipulators like ABB and FANUC, emphasizing the importance of material selection for stability and improving robotic technology design.
- A stability model is developed, classifying stability levels as low, medium, or high.
- The study reveals that stability is directly related to stiffness and inversely related to damping and deflection.
- The importance of stability is highlighted in both existing and new robots.

The paper is structured as follows. The second section of the article describes the literature review on this topic. Section 3 presents the research methodology. Section 4 represents the results and discussion. Section 5 presents the final conclusions of this work.

2. LITERATURE REVIEW

The stiffness properties of industrial robots are very significant for many industrial applications and low stiffness causes imprecise products, due to the robot deflections during the robotic task. The stiffness of a system influences the acceleration that may be achieved while moving toward a target point. This helps to prevent unwanted displacements induced by the inertia forces that occur during rapid manipulations. Hence, improving the stiffness sustains the stability [13]–[16]. To maintain stability when the stiffness is increased, the modulation is controlled by an energy-tank-based law [17].

The impact of various cross-sections and layups on the dynamic performance of a robot arm for agricultural monitoring is evaluated by manipulating vacuum pressure within the particle chamber [18], [19]. Self-excited vibration in systems is due to damping, and external loads compensate for deflection Therefore, model-based approaches analyze robot manipulator parameters using mathematical methods [20], [21]. The deflection of a cantilever beam due to force, transforming it into a two-point boundary value problem and a one-parameter eigenvalue optimization problem using a heuristic cuckoo search algorithm, is evaluated for its validity [22], [23].

Various issues in the field of robotics have been investigated through the examination of alternative control strategies, materials, manufacturing methods, and mechanical modeling [24]. Xu *et al.* [25] presented a methodology for the modeling of stiffness for heavy payload industrial robots by consideration of various aspects of the robot's links. Yang *et al*. [26] created three techniques for a robotic machining procedure, but did not consider deflection factor for improved stiffness model precision. Van Quyen *et al*. [27] outlined a methodology for calculating the dynamic stability control and inverse dynamics of a single-link flexible manipulator using numerical simulation. The application of flexible multi-link manipulators can enhance robot dynamic stability with an additional feedback controller, but reducing the controller duration can cause instability [28]. A controller has been developed [29] by incorporating dynamic behavior through a feedback linearization method that was then evaluated on a universal robot (UR5). The evaluation of robot stability considers both straight and non-straight designs [30], [31]. After reviewing the background and present state of the problem of this domain, it has been found that most of the researchers have investigated single link, one degree of freedom, heavy-duty robots, controllers, and modeling only stiffness or damping or deflection, as summarized in Table 1.

In our study, a combination of stiffness, damping, and deflection parameters for a six-degree-of-freedom multilink manipulator has been considered to formulate a new mathematical model of stability. To mitigate the issue of stability in robot manipulators and compensate for current challenges, it is essential to undertake the modeling of manipulator parameters. This modeling process is focused on the aspect of the optimized method of stability considering link-material in terms of stiffness, damping, and deflection.

Table 1. Comprehensive investigation of the research domain to explore the research gap

S/No	Model/Type of Robot	Parameters considered in analytical model	Number of robotic links	Degree of freedom	Level of Payload (kg)	Ref.
1	Planar serial robot	Stiffness	4	-	Not specified	[7]
2	Omron Adept Viper s650	Stiffness and damping	<1	6	Not specified	[13]
3	Standard rigid-body robot	Stiffness	<1	-	Not specified	[14]
4	Inverse Dynamics Flexible Manipulator	Stiffness	1	Not specified	0.1	[27]
5	UR5 robot	Controller related parameters	6	6	5	[29]
6	Elastosil M 4601	stiffness (k), damping coefficient (D 0),	<1 fixed length	N degree of freedom	1.5	[32]
7	two-link flexible manipulator model	Bending Stiffness	2	<1	Not specified	[33]
8	Two-Link Flexible manipulator	Damping	2	6	Not specified	[34]
9	Flexible Single-Link Manipulator (FSLM)	Damping	1	1	Not specified	[35]
10	Not Specified	radial stiffness, axial stiffness, torsional stiffness, and deflection	Not Specified	Not Specified	Not Specified	[36]
11	ABB IRB6640	Stiffness	6	6	heavy	[37]
12	HH-150 robot	Stiffness, deflection	2	2	heavy	[38]

3. RESEARCH METHODOLOGY

The methodology utilized in this work, in the beginning, was to comprehensively examine modern robot manipulators with modest payload capacities to determine their fundamental characteristics.

In the next step, a quantitative method with a specific technique is used to calculate and analyze the numerical data, which guarantees transparency and trustworthiness in the research process by providing a thorough explanation of the method. Furthermore, examine the correlation between the stability of a robot manipulator and its material properties to establish a stability model. The proposed approach can be linked with the study's aims and enables the achievement of significant findings to address the research topic effectively.

3.1. Examine contemporary robot manipulators

The article uses two industrial robots, ABB and FANUC, as case studies to examine the stability relationship between stiffness, damping, and deflection of robot manipulators. The ABB and FANUC models are shown in Figure 1. Additionally, Figure 2 also features the schematic diagram.

The basic properties of these robot manipulators such as link/arm, length, mass, inner diameter, and outer diameter have been thoroughly examined and different numerical values have been taken from the product specifications for the ABB CRB-15000 and FANUC CRX-10iA, respectively [39], [40]. Numerical estimates are provided for the stiffness, deflection, and average damping coefficient of a given material, as well as other pertinent parameters. An analysis is conducted of the various units utilized in the computation of the stiffness, deflection, and damping values for every link.

ABB FANUC

Figure 1. Model of the manipulators

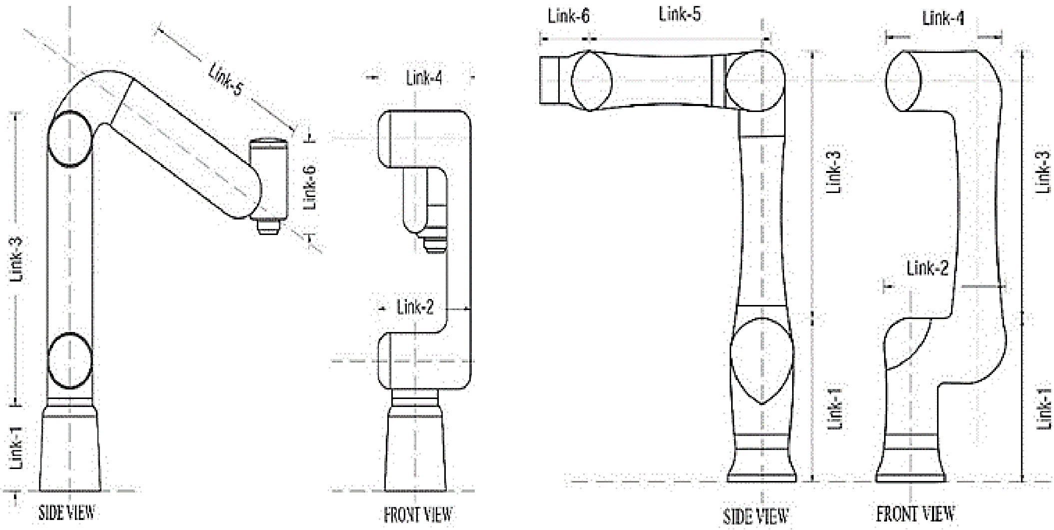

ABB FANUC

Figure 2. Schematic diagram of ABB and FANUC

3.2. Technique for computing numerical values

The stability of a robot manipulator is determined by three critical parameters: stiffness, average damping coefficient, and deflection, which are influenced by various technical factors. Given the cylindrical shape of both manipulators, the analysis of banding stiffness is the main focus of this study. According to theoretical considerations, a material's bending stiffness is largely dependent on its Young modulus. Alternative techniques that consider the radius and natural frequency of the robot manipulator's six degrees of freedom can be used to determine Young's modulus. The moment of inertia and the modulus of elasticity are directly related to stiffness. A material's stiffness can be determined by measuring its modulus of elasticity, also known as its angular frequency. It has a close relationship with both the elastic constant and natural frequency. It has been discovered that the damping coefficient is correlated with both stiffness and the reduction factor of amplitude.

Both modified and conventional derivate approaches are followed to determine robot manipulator material parameters of stiffness [41], damping [42], and deflection [43]. The formulas used for materials parameters (stiffness, damping, and deflection) are expressed in (1) to (3).

$$Stiffness = S_{stiff} = 2\pi f_c I = 2\pi\left(\frac{1}{2\pi}\times\sqrt{\frac{K}{m}}\right)\times I_{wl} = \frac{1}{2}m(r_1^2+r_2^2)\times\sqrt{\frac{K}{m}} \quad (1)$$

K is the spring constant, m is the manipulator link mass, r_1 is the inner radius, and r_2 is the outer radius.

$$Damping\ Cooficient = C_{avg} = \frac{\xi}{n};\ \xi = \frac{\delta}{C_c};\ C_c = \sqrt{4mS_{stiff}};\ ln\left(\frac{x_1}{x_2}\right) = \frac{2\pi\delta m}{\sqrt{1-\delta^2}} \quad (2)$$

C_{avg} is the average damping coefficient, ξ is the damping ratio, n is the number of damping ratio, δ is the logarithmic decrement, and $\ln\left(\frac{x_1}{x_2}\right)$ is the amplitude reduction factor.

$$Deflection = \partial_{max} = \frac{PL^3}{3EI} \quad (3)$$

P is force, L is the length of the robot link, E is the Young modulus, and I is the moment of inertia.

An iterative calculation has been completed to determine the maximum and minimum numerical values of parameters, considering the maximum and minimum Young modulus of predefined robot manipulator material shown in Tables 2 to 4.

Table 2. The numerical value of stiffness (N/m) for ABB and FANUC

Arm	Stiffness	ABB		FANUC	
		Max Stiffness (Relation with Max Young Modulus)	Min Stiffness (Relation with Min Young Modulus)	Max Stiffness (Relation with Max Young Modulus)	Min Stiffness (Relation with Min Young Modulus)
1	S_1	32.99	31.18	81.7479	77.29
2	S_2	38.54	36.42	101.6508	96.1160
3	S_3	19.12	18.07	82.5959	78.09848
4	S_4	39.67	37.48	81.166	76.7471
5	S_5	10.04	9.5	82.5959	78.09848
6	S_6	9.007	8.5	52.8689	49.9903

Table 3. The numerical value of deflection (m) for ABB and FANUC

Arm	Deflection	ABB		FANUC	
		Min Deflection (Relation with Max Young Modulus)	Max Deflection (Relation with Min Young Modulus)	Min Deflection (Relation with Max Young Modulus)	Max Deflection (Relation with Min Young Modulus)
1	δ_1	0.000001158	0.0000013	0.0000003289	0.0000003693
2	δ_2	0.00000625	0.0000070	0.000001198	0.00000134
3	δ_3	0.000000095	0.00000011	0.000005722	0.00000642
4	δ_4	0.00000741	0.0000083	0.0000016114	0.0000018097
5	δ_5	0.000000154	0.00000017	0.000005722	0.00000642
6	δ_6	0.0000000763	0.000000086	0.000000123	0.000000138

Table 4. The numerical value of damping for ABB and FANUC

Arm	Dumping	ABB		FANUC	
		Min Damping (Relation with Max Young Modulus)	Max Damping (Relation with Min Young Modulus)	Min Damping (Relation with Max Young Modulus)	Max Damping (Relation with Min Young Modulus)
1	$\mathcal{D}_1$	0.00477	0.0049	0.0035	0.0037
2	$\mathcal{D}_2$	0.002	0.002	0.0016	0.0017
3	$\mathcal{D}_3$	0.02424	0.025	0.0013	0.0014
4	$\mathcal{D}_4$	0.00195	0.002	0.0021	0.0022
5	$\mathcal{D}_5$	0.053	0.055	0.0013	0.0014
6	$\mathcal{D}_6$	0.075	0.078	0.0095	0.0097

3.3. Proposed model of stability

An industrial robot manipulator that is steady can move and position itself with stability while performing duties. Stable robot manipulators execute tasks with greater accuracy and consistency, hence enhancing the quality of output. An enduring robotic manipulator guarantees the quality of a product by consistently attaining its objectives. Manufacturers and operators of industrial robots strive for stability to improve the quality, dependability, and efficiency of production. The stability of a robot manipulator is crucial for performing subsequent actions and analyzing the numerical values of material properties. It has been observed that there is a relationship between stability and factors such as stiffness, damping, and deflection. Due to these incentives, a novel strategy has been developed to ensure the stability of robot manipulators.

The novel approach can be expressed as

$$Stability \propto \left[\frac{S}{\mathcal{D} \times \delta}\right] \in [M] \cup [R]$$

where S is stiffness, D is damping, δ is deflection, M is the Young modulus of material, and R is the type of robot.

The approach indicates that stability depends on stiffness, damping, and deflection, where stability is directly proportional to stiffness and inversely proportional to damping and deflection. The relation of stability with stiffness, deflection, and damping belongs to different values of the Young modulus of materials and models of robot manipulators.

4. RESULTS AND DISCUSSION

4.1. Exploring results by numerical values

Multiple outcomes relating to stability can be created by iteratively calculating over several equations (1), (2), and (3) using varied values of material-related parameters. Real data is used to determine the stiffness, damping, and deflection parameters for each of the chosen robot manipulator models.

Regarding the material attribute of the manipulator about the Young modulus, the measurement considers both the maximum and minimum values.

Table 5 displays the values of stiffness, damping, and deflection for ABB and FANUC based on the maximum and minimum values of the relevant manipulator material's Young modulus. It has been noted that stiffness is found to be high when the Young modulus is at its highest and low when it is at its minimum. On the other hand, damping and deflection demonstrate that these two parameters are high when the Young modulus is at its minimum and low when it is at its highest. It is possible to deduce that stability is inversely related to damping and deflection and proportional to stiffness based on these facts and the new method.

Table 5. Different numerical values of ABB and FANUC for stiffness, damping, and deflection considering minimum and maximum values of Young modulus for the material type of aluminum

	Stiffness (N/m)		Damping		Deflection (m)	
	Min	Max	Min	Max	Min	Max
ABB	8.5	39.67	0.001	0.07	0.000000076	0.0000083
FANUC	49.99	101.65	0.001	0.009	0.000000123	0.00000642

An example is shown to explore one of the calculative procedures for backend calculation. It is possible to express that the total number of numerical values for each parameter is equal to 12, and the mechanism is as follows.

- For stiffness: A total of twelve (12) numerical values were found: six (06) values are considered for maximum Young modulus and six (06) values are considered for minimum Young modulus.
- For damping: A total of twelve (12) numerical values were found: six (06) values are considered for maximum Young modulus and six (06) values are considered for minimum Young modulus.
- For deflection: A total of twelve (12) numerical values were found: six (06) values are considered for maximum Young modulus and six (06) values are considered for minimum Young modulus.

After getting all twelve (12) numerical values for each parameter, it is sorted to find the lowest values as a minimum and the highest values as a maximum. Since the number of values in each parameter is twelve (12), the median value is determined in the context of an even number. It is noted that this median value is considered as the input medium value of the related parameters.

Table 6 shows the final result of all numerical values for stiffness, damping, and deflection considering minimum, median, and maximum, followed by low, medium, and high.

Table 6. Numerical values of ABB and FANUC for stiffness, damping, and deflection followed by low, medium, and high

Level	ABB			FANUC		
	Stiffness	Damping	Deflection	Stiffness	Damping	Deflection
Low	8.5	0.00195	0.000000076	49.99	0.0013	0.000000123
Medium	25.15	0.0145	0.000000664	78.098	0.00165	1.27E-06
High	39.67	0.078	0.0000083	101.65	0.0097	0.00000642

To verify the holistic approach of the proposed model of stability, the Taguchi method (L^3) is employed to generate designs encompassing all potential combinations of input variables (stiffness, damping, and deflection) classified as low, medium, and high. By utilizing the Taguchi technique, it is feasible to ascertain 27 distinct combinations of stiffness, damping, and deflection at varying degrees of low, medium, and high. Through the proposed holistic model of stability, it is possible to calculate every possible combination of Taguchi methods taken as input to get the output of stability. By applying the Taguchi method in conjunction with the stability model, it is possible to obtain 27 distinct numerical values for each robot manipulator. These values may then be arranged to find the lowest values as a minimum and the highest values as a maximum. Since there are values for stability (27), the median value is determined in the context of an even number. Given that there are 27 values for stability, the median value is calculated based on an odd number of values. This median number is regarded as a medium measure of stability. Table 7 displays various levels of stability as the output for each industrial robot manipulator, together with the matching condition of the input parameters.

In all cases, the maximum stability is obtained when stiffness is high, whereas damping and deflection are low. In contrast, the minimum stability is inspected when stiffness is low, and damping and defection are high. That means the results comply with the novel model of stability for all the robots investigated, and this concept can be applied to design a new robot manipulator.

Table 7. Output values of ABB and FANUC for stability in different levels and conditions of input parameters

Level	ABB		FANUC	
	Stability (output)	Conditions for input parameters	Stability (output)	Conditions for input parameters
Low	13129440.84	When stiffness is low, damping is high, and deflection is high	802747535.1	When stiffness is low, damping is high, and deflection is high
Medium	2451034909	When stiffness is high, damping is low, and deflection is high	30302661090	When stiffness is low, damping is low, and deflection is medium
High	2.66626E+11	When stiffness is high, damping is low, and deflection is low	6.3571E+11	When stiffness is high, damping is low, and deflection is low

4.2. Validation of result using ANOVA platform under Minitab

We have statistically assessed the correlations of stability, deflection, stiffness, damping, and Young modulus and then validated the conclusions made from the observed data using the ANOVA platform under Minitab. We utilized the Minitab Statistical Software Package to reveal concealed correlations among various material properties employed in robot manipulators. The results will enhance the development of robot manipulators by informing more effective design and material selection, ultimately improving their stability.

4.2.1. Effects and Interaction of material parameters of manipulators

The ANOVA platform was configured to observe material parameters' effects and interactions. Experiments showed that increased stiffness increases stability, while decreased deflection and damping decrease stability. This highlights the importance of material parameter in stability. Figure 3 shows the main effects plot for the stability of the ABB and FANUC robot manipulators.

Furthermore, the interaction of material parameters in manipulators is crucial for achieving optimal performance, efficiency, safety, and sustainability across a wide range of robotic applications. Through the experiment to validate the interaction, it has been found that these parameters are individually affected strongly and also interact. Figure 4 shows the interaction plot of stability for the ABB and FANUC manipulators.

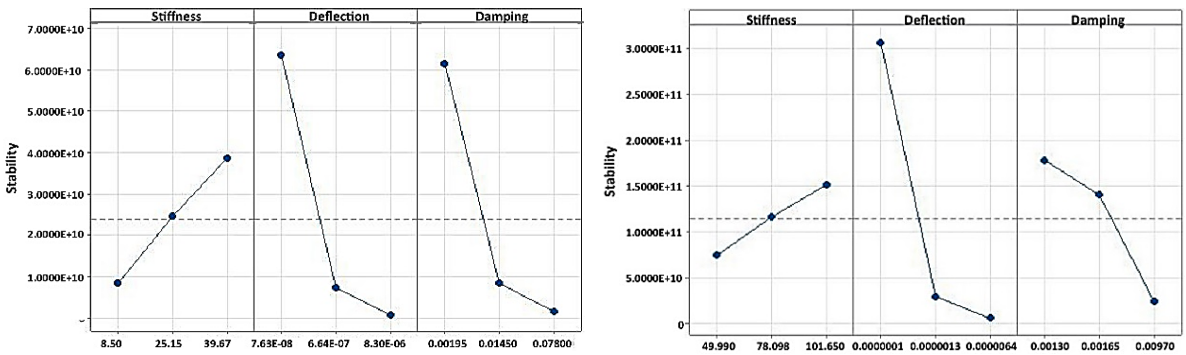

ABB FANUC

Figure 3. Main effects plot of stability for the manipulators

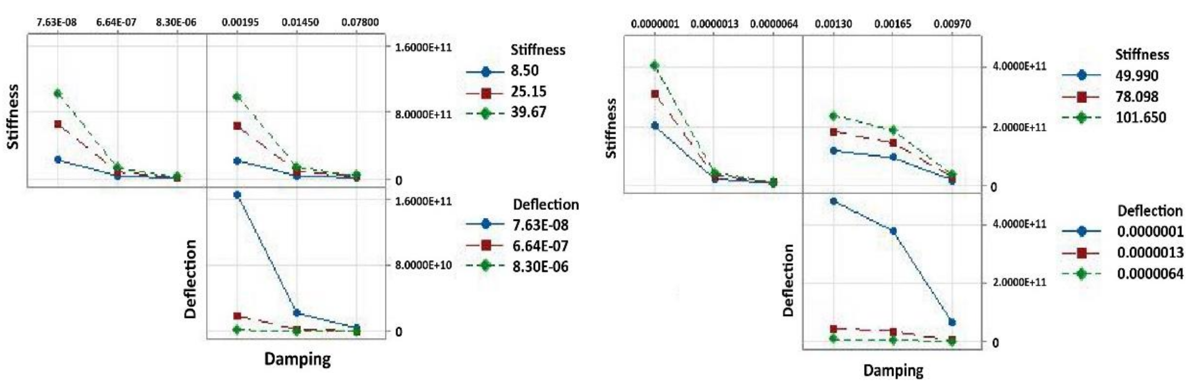

ABB FANUC

Figure 4. Interaction plot of stability for the manipulators

4.2.2. Analysis of variance for stability of ABB and FANUC manipulator

Analysis of variance is crucial for assessing and enhancing the stability of robotic manipulators based on material properties such as stiffness, deflection, and damping. A thorough analysis has been conducted using the ANOVA platform to gain insights into the relative significance of these factors and how they interact. The main focus was to understand the ratio of variability between different groups compared to the variability within each group. The F value is a crucial result of ANOVA, and it is employed to conclude the disparities among group averages. Additionally, it is utilized to compute the p-value, which represents the likelihood of detecting the data under the assumption that the null hypothesis is accurate. A smaller p-value indicates stronger evidence against the null hypothesis and in support of the alternative hypothesis. By analyzing the consequences, it has been determined that deflection is the most influential characteristic among the material properties of stiffness, deflection, and damping. The results are shown in Table 8.

Table 8. Analysis of variance for stability of ABB and FANUC

Source	DF	ABB				FANUC			
		SS	MS	F	P	SS	MS	F	P
Stiffness	2	4.14856E+21	2.07428E+21	0.90	0.421	2.67495E+22	1.33747E+22	1.18	0.328
Deflection	2	2.14782E+22	1.07391E+22	4.68	0.022	5.03703E+23	2.51851E+23	22.24	0.000
Damping	2	1.94540E+22	9.72702E+21	4.24	0.029	1.16421E+23	5.82105E+22	5.14	0.016
Error	20	4.58855E+22	2.29427E+21			2.26535E+23	1.13267E+22		
Total	26	9.09663E+22				8.73408E+23			

4.2.3. Surface plotting of stability for ABB and FANUC manipulator

To show the effect of changes in stiffness, deflection, and damping on the manipulator's stability, a stability surface plot has been made. These plots can be analyzed to identify the regions of the system that are unstable or stable. The optimal stiffness levels for stability and performance metrics can also be found using the surface plot of stability against stiffness. Additionally, the effect of structural flexibility on the system's overall stability can be assessed by examining the relationship between deflection and stability. Understanding the effect of damping on the system's ability to maintain stability in the face of external disturbances or dynamic loads requires an analysis of the stability surface of damping. Figure 5 shows the surface plot of stability for the ABB and FANUC robot manipulator. Through the figures, it can be determined the areas where the system is either stable (green) or unstable (white).

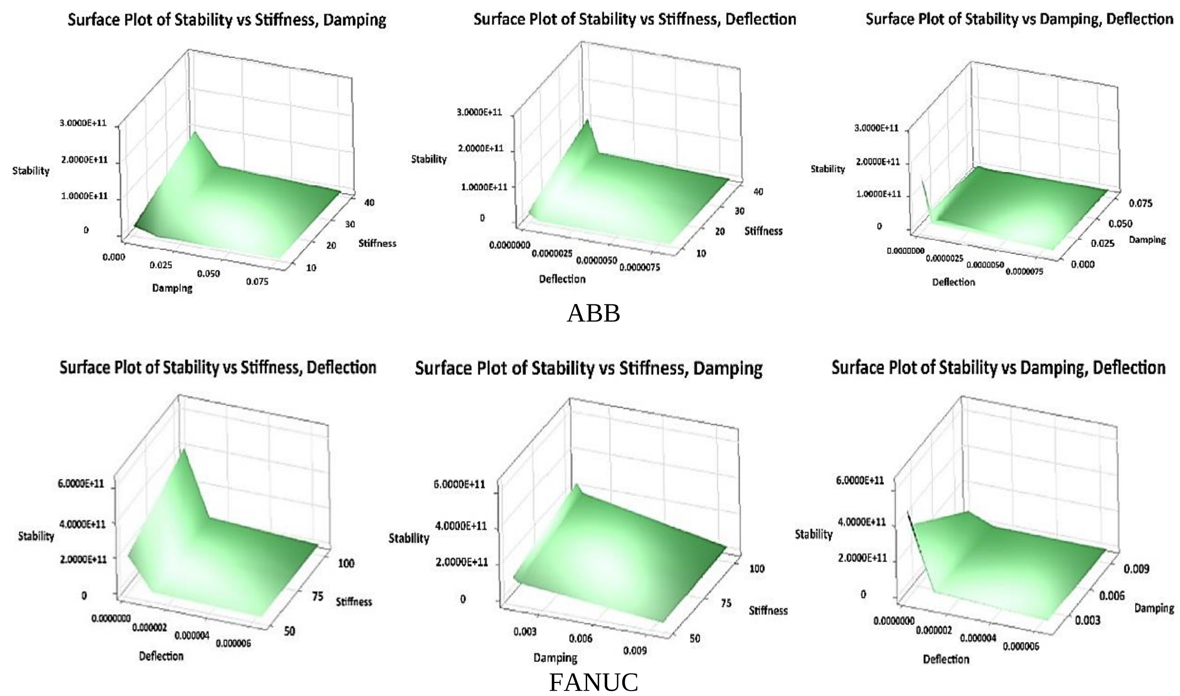

Figure 5. Surface plot of stability for the manipulators

By incorporating stiffness, deflection, and damping as input parameters, the surface plot of stability offers a comprehensive depiction of how these variables impact the performance of a robot manipulator. These can serve as a reference when developing manipulator systems that meet the specific requirements for stability, performance, and dependability.

In conclusion, our approach explores the impact of material parameters like stiffness, damping, and deflection on the stability of robot manipulators. Section 3 evaluates stability using both modified and conventional formulas for material properties, offering a detailed analysis of how various parameters impact overall stability. It emphasizes the importance of parameters like Young Modulus, mass, length, diameter, and payload in selecting suitable materials. Section 4 reveals that stiffness directly influences stability, unlike damping and deflection, which have an inverse relationship. The research uses a holistic approach, using the Taguchi method to design stability combinations and validates the approach using numerical values and simulation tools such as Minitab.

5. CONCLUSION

In this research work, a holistic approach is formulated to evaluate the stability level of an industrial robot manipulator using material-related parameters of stiffness, damping, and deflection. The Taguchi method is used to design probable combinations of stiffness, damping, and deflection as input and stability as output concerning the low, medium, and high. The combination of the output column of the Taguchi method is attributed to stability and is calculated using the proposed model of stability. Moreover, the approach is also checked by exploring different numerical values and the simulation tool. In both cases, it has been found that stability depends on stiffness, damping, and deflection, where stability is directly proportional to stiffness and inversely proportional to damping and deflection. The relation of stability with stiffness, deflection, and damping belongs to different values of the Young modulus of materials and models of robot manipulators. Stability about stiffness, damping, and deflection is essential to justifying the existing robot's working capacity and to designing and developing a new generation of robots. Besides, Young modulus, mass, length, diameter, and payload have a significant role in selecting the appropriate robot materials according to their applications in industry. The future presented stability method required further analysis using the Lyapunov stability analysis approach and its relation to the accuracy of the robot manipulator.

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REFERENCES

[1] O. Kroemer, S. Niekum, and G. Konidaris, "A review of robot learning for manipulation: challenges, representations, and algorithms," *Journal of Machine Learning Research*, vol. 22, 2021.

[2] M. Javaid, A. Haleem, R. P. Singh, and R. Suman, "Substantial capabilities of robotics in enhancing industry 4.0 implementation," *Cognitive Robotics*, vol. 1, pp. 58–75, 2021, doi: 10.1016/j.cogr.2021.06.001.

[3] V. Satya Durga Manohar Sahu, P. Samal, and C. Kumar Panigrahi, "Modelling, and control techniques of robotic manipulators: a review," *Materials Today: Proceedings*, vol. 56, pp. 2758–2766, 2022, doi: 10.1016/j.matpr.2021.10.009.

[4] C. S. Tiwary *et al.*, "Five decades of research on the development of eutectic as engineering materials," *Progress in Materials Science*, vol. 123, Jan. 2022, doi: 10.1016/j.pmatsci.2021.100793.

[5] R. H. Taylor, "Medical robotics and computer-integrated interventional medicine," in *Medical Imaging 2012: Image-Guided Procedures, Robotic Interventions, and Modeling*, Feb. 2012, vol. 8316. doi: 10.1117/12.916500.

[6] A. Zacharaki, I. Kostavelis, A. Gasteratos, and I. Dokas, "Safety bounds in human robot interaction: a survey," *Safety Science*, vol. 127, Jul. 2020, doi: 10.1016/j.ssci.2020.104667.

[7] W. Zhao, A. Klimchik, A. Pashkevich, and D. Chablat, "Non-linear stiffness behavior of planar serial robotic manipulators," *Mechanism and Machine Theory*, vol. 172, Jun. 2022, doi: 10.1016/j.mechmachtheory.2022.104783.

[8] L. Liu, S. Leonhardt, C. Ngo, and B. J. E. Misgeld, "Impedance-controlled variable stiffness actuator for lower limb robot applications," *IEEE Transactions on Automation Science and Engineering*, vol. 17, no. 2, pp. 991–1004, Apr. 2020, doi: 10.1109/TASE.2019.2954769.

[9] S. Sierra, L. Arciniegas, F. Ballen-Moreno, D. Gomez-Vargas, M. Munera, and C. A. Cifuentes, "Adaptable robotic platform for gait rehabilitation and assistance: Design concepts and applications," in *SpringerBriefs in Applied Sciences and Technology*, Springer Singapore, 2020, pp. 67–93. doi: 10.1007/978-981-15-4732-4_5.

[10] H. Deng, L. Cheng, X. Liang, D. Hayduke, and A. C. To, "Topology optimization for energy dissipation design of lattice structures through snap-through behavior," *Computer Methods in Applied Mechanics and Engineering*, vol. 358, Jan. 2020, doi: 10.1016/j.cma.2019.112641.

[11] B. G. Cho, J. E. Lee, S. H. Hwang, J. H. Han, H. G. Chae, and Y. Bin Park, "Enhancement in mechanical properties of polyamide

66-carbon fiber composites containing graphene oxide-carbon nanotube hybrid nanofillers synthesized through in situ interfacial polymerization," *Composites Part A: Applied Science and Manufacturing*, vol. 135, Aug. 2020, doi: 10.1016/j.compositesa.2020.105938.
[12] Y. Cho, H. M. Do, and J. Cheong, "Screw based kinematic calibration method for robot manipulators with joint compliance using circular point analysis," *Robotics and Computer-Integrated Manufacturing*, vol. 60, pp. 63–76, Dec. 2019, doi: 10.1016/j.rcim.2018.08.001.
[13] M. Bottin, S. Cocuzza, N. Comand, and A. Doria, "Modeling and identification of an industrial robot with a selective modal approach," *Applied Sciences*, vol. 10, no. 13, Jul. 2020, doi: 10.3390/app10134619.
[14] A. Verl, A. Valente, S. Melkote, C. Brecher, E. Ozturk, and L. T. Tunc, "Robots in machining," *CIRP Annals*, vol. 68, no. 2, pp. 799–822, 2019, doi: 10.1016/j.cirp.2019.05.009.
[15] M. Sharifzadeh, "Model driven design optimization and gait selection of compliant foldable robots," Arizona State University, 2021. [Online]. Available: https://www.proquest.com/openview/94b0c3811a532c80d53041ceab529753
[16] M. Leco, "A multi-step learning approach for in-process monitoring of depth-of-cuts in robotic countersinking operations," Ph.D. dissertation, Faculty of Engineering, University of Sheffield, 2020.
[17] Y. Ding and U. Thomas, "Improving safety and accuracy of impedance controlled robot manipulators with proximity perception and proactive impact reactions," in *Proceedings - IEEE International Conference on Robotics and Automation*, May 2021, vol. 2021-May, pp. 3816–3821. doi: 10.1109/ICRA48506.2021.9561025.
[18] S. Q. An, H. L. Zou, Z. C. Deng, and D. Y. Guo, "Damping effect of particle-jamming structure for soft actuators with 3D-printed particles," *Smart Materials and Structures*, vol. 29, no. 9, Aug. 2020, doi: 10.1088/1361-665X/ab9f47.
[19] M. A. Khozeimeh, R. Fotouhi, and R. Moazed, "Static and vibration analyses of a composite CFRP robot manipulator," *Journal of Composites Science*, vol. 6, no. 7, p. 196, Jul. 2022, doi: 10.3390/jcs6070196.
[20] W. Wang, Q. Guo, Z. Yang, Y. Jiang, and J. Xu, "A state-of-the-art review on robotic milling of complex parts with high efficiency and precision," *Robotics and Computer-Integrated Manufacturing*, vol. 79, Feb. 2022, doi: 10.1016/j.rcim.2022.102436.
[21] S. B. Niku, *Introduction to robotics: analysis, control, applications*, 3rd ed. Hoboken: John Wiley & Sons, 2020.
[22] D. Singhal and V. Narayanamurthy, "Large and small deflection analysis of a cantilever beam," *Journal of The Institution of Engineers (India): Series A*, vol. 100, no. 1, pp. 83–96, Nov. 2019, doi: 10.1007/s40030-018-0342-3.
[23] T. S. Fanse, "A numerical analysis of a micro-scale piezoelectric cantilever beam: The effect of dimension parameters on the eigen frequency," *International Journal of Engineering Science Invention (IJESI)*, vol. 10, no. 9, pp. 35–40, Sep. 2021, doi: 10.35629/6734-1009013540.
[24] W. Zhao, Y. Zhang, and N. Wang, "Soft robotics: research, challenges, and prospects," *Journal of Robotics and Mechatronics*, vol. 33, no. 1, pp. 45–68, Feb. 2021, doi: 10.20965/jrm.2021.p0045.
[25] P. Xu *et al.*, "Stiffness modeling of an industrial robot with a gravity compensator considering link weights," *Mechanism and Machine Theory*, vol. 161, Jul. 2021, doi: 10.1016/j.mechmachtheory.2021.104331.
[26] Y. Yang, Y. Qi, P. Pan, Y. Zhao, S. Zhong, and Y. Yang, "Oscillation suppression in a particle robotic arm by stiffness and damping regulation," *Mechatronics*, vol. 85, Aug. 2022, doi: 10.1016/j.mechatronics.2022.102819.
[27] N. Van Quyen, B. T. H. Linh, D. Q. Tuan, N. T. Thanh, and N. H. Quang, "Dynamic stability control and calculating inverse dynamics of a single-link flexible manipulator," *International Journal of Mechanical Engineering and Robotics Research*, vol. 12, no. 4, pp. 200–209, 2023, doi: 10.18178/ijmerr.12.4.200-209.
[28] A. Bartfai, A. Barrios, and Z. Dombovari, "Stability analysis of a one degree of freedom robot model with sampled digital acceleration feedback controller in turning and milling," *Journal of Computational and Nonlinear Dynamics*, vol. 18, no. 8, May 2023, doi: 10.1115/1.4062229.
[29] J. Fabian, F. Garcia-Cardenas, R. Canahuire, and O. E. Ramos, "Sensorless impedance control for the UR5 robot," Oct. 2020. doi: 10.1109/ICCAD49821.2020.9260525.
[30] C. da Costa e Silva, S. F. Maassen, P. M. Pimenta, and J. Schröder, "A simple finite element for the geometrically exact analysis of Bernoulli–Euler rods," *Computational Mechanics*, vol. 65, no. 4, pp. 905–923, Dec. 2020, doi: 10.1007/s00466-019-01800-5.
[31] P. de Mattos Pimenta, S. Maassen, C. da Costa e Silva, and J. Schröder, "A fully nonlinear beam model of Bernoulli–Euler type," in *CISM International Centre for Mechanical Sciences, Courses and Lectures*, vol. 597, Springer International Publishing, 2020, pp. 127–151. doi: 10.1007/978-3-030-33520-5_5.
[32] E. Franco and A. Garriga-Casanovas, "Energy-shaping control of soft continuum manipulators with in-plane disturbances," *International Journal of Robotics Research*, vol. 40, no. 1, pp. 236–255, Mar. 2021, doi: 10.1177/0278364920907679.
[33] P. Kumar and B. Pratiher, "Modal characterization with nonlinear behaviors of a two-link flexible manipulator," *Archive of Applied Mechanics*, vol. 89, no. 7, pp. 1201–1220, Mar. 2019, doi: 10.1007/s00419-018-1472-9.
[34] N. Mishra and S. P. Singh, "Hybrid vibration control of a two-link flexible manipulator," *SN Applied Sciences*, vol. 1, no. 7, Jun. 2019, doi: 10.1007/s42452-019-0691-1.
[35] J. Huang and J. Ji, "Vibration control of coupled Duffing oscillators in flexible single-link manipulators," *JVC/Journal of Vibration and Control*, vol. 27, no. 17–18, pp. 2058–2068, Sep. 2021, doi: 10.1177/1077546320952598.
[36] B. Yuan *et al.*, "Experimental study and analysis of the wheel's stiffness characteristics for China's Mars exploration rovers," in *2019 IEEE 4th International Conference on Advanced Robotics and Mechatronics (ICARM)*, Jul. 2019, pp. 331–335. doi: 10.1109/ICARM.2019.8833714.
[37] H. Celikag, N. D. Sims, and E. Ozturk, "Cartesian stiffness optimization for serial arm robots," *Procedia CIRP*, vol. 77, pp. 566–569, 2018, doi: 10.1016/j.procir.2018.08.222.
[38] K. Yang, W. Yang, G. Cheng, and B. Lu, "A new methodology for joint stiffness identification of heavy duty industrial robots with the counterbalancing system," *Robotics and Computer-Integrated Manufacturing*, vol. 53, pp. 58–71, Oct. 2018, doi: 10.1016/j.rcim.2018.03.001.
[39] ABB Robotics, "Product Specification CRB 15000." ABB Robotics, Zurich, 2022.
[40] "CRX-10iA," *Fanuc*, Accessed: Aug. 13, 2024. [Online]. Available: https://www.fanuc.eu/es/en/robots/robot-filter-page/collaborative-robots/crx-10ia
[41] S. Mustary, M. A. Kashem, M. A. Chowdhury, and J. Uddin, "Model and fuzzy controller design approaches for stability of modern robot manipulators," *Computers*, vol. 12, no. 10, Sep. 2023, doi: 10.3390/computers12100190.
[42] S. Mustary, M. A. Kashem, M. A. Chowdhury, and M. M. Rana, "Mathematical model and evaluation of dynamic stability of industrial robot manipulator: Universal robot," *Systems and Soft Computing*, vol. 6, Dec. 2024, doi: 10.1016/j.sasc.2023.200071.
[43] K. J. Wadi, J. M. Yadeem, S. Mustafa khazaal, L. S. Al-Ansari, and H. J. Abdulsamad, "Static deflection calculation for axially FG cantilever beam under uniformly distributed and transverse tip loads," *Results in Engineering*, vol. 14, Jun. 2022, doi: 10.1016/j.rineng.2022.100395.

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