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Algorithm-driven development of a simulation tool for industrial manipulator stability analysis

Shabnom Mustary[1], Mohammod Abul Kashem[1], Mohammad Asaduzzaman Chowdhury[2], Jia Uddin[3]
[1]Department of Computer and Software Engineering, Dhaka University of Engineering and Technology (DUET), Gazipur, Bangladesh
[2]Department of Mechanical Engineering, Dhaka University of Engineering and Technology (DUET), Gazipur, Bangladesh
[3]Department of AI and Big Data, Endicott College, Woosong University, Daejeon, Republic of Korea

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ABSTRACT

Industrial manipulators are essential to many manufacturing processes because they increase efficiency and productivity dramatically. However, maintaining operational safety and averting potential risks in industrial environments requires that these manipulators be stable. The development and implementation of an entirely algorithm-driven novel simulation tool intended to assess industrial manipulators' stability in-depth are presented in this research. The suggested tool combines sophisticated mathematical models with the material properties of the manipulator, such as deflection, stiffness, and damping. To analyses the dynamic behaviour of manipulators under various operating situations, a hypothetical simulation technique to assess the stability of robot manipulators combined with material properties is taken into consideration. The simulation tool offers vital insights into the stability characteristics of manipulators, allowing engineers and designers to enhance their performance and guarantee operational safety. The simulation tool's usefulness is showcased through case studies and comparative evaluations, emphasizing its capacity to improve the design and implementation of industrial manipulators in practical situations. In summary, this research enhances the field of industrial automation by offering a strong framework for assessing and upgrading the stability of manipulator systems. This, in turn, improves productivity and safety in industrial settings.

Corresponding Author:

Jia Uddin
Department of AI and Big Data, Endicott College, Woosong University
Daejeon, South Korea, Republic of Korea
Email: jia.uddin@wsu.ac.kr

1. INTRODUCTION

This study discusses a simulation tool for assessing industrial manipulator stability, highlighting its applications in manufacturing. It provides case examples and validation evaluations, highlighting its efficacy and dependability. The research aims to improve understanding of industrial manipulator stability, leading to increased productivity, decreased downtime, and safety. The tool also shows potential for future manipulator design. A considerable amount of research has evolved in response to this pressing requirement, delving into different methodologies, strategies, and instruments to assess and improve the stability of industrial manipulators [1], [2]. The review discusses the stability of manipulator systems, including mechanical design, control techniques, and dynamic stability criteria. It explores factors affecting stability, including structural dynamics, payload characteristics, and material parameters, and highlights scientific advancements in the field. In this section, different contemporary research papers has been reviewed to find out the research gap of respective research objects.

The mechanical stiffness of a manipulator is regarded as a prominent criterion for evaluating robot performance. The robot is utilized in several industrial sectors, including agriculture, healthcare, and various forms of small and large-scale production systems [3], [4]. The compliance of reducers and the elasticity of links contribute to the enhancement of the stiffness of industrial robots [5], [6]. Robot manipulator application tools are essential for robotics engineers, researchers, and practitioners. Developers may speed up development, improve robot performance, and enable automation and intelligent manipulation in new sectors and applications by using these tools [7], [8]. Several simulation tools use different modeling methodologies and algorithms to analyze industrial manipulator stability. These techniques range from simple kinematic simulations to dynamic assessments of inertia, friction, and external forces.

In the research paper [9], [10] dynamic modeling is incorporated into advanced simulation tools to capture the intricate interactions that occur between the manipulator and its surroundings. With the consideration of variables including inertia, friction, joint compliance, and outside disturbances, dynamic simulations provide more precise evaluations of stability. To effectively simulate real-world settings, these tools often use techniques like finite element analysis, multi-body dynamics, and control algorithms [11]–[13].

As a result of the external forces acting on the end-effectors during machining, industrial robots are prone to static and dynamic deformations, also known as chatter vibrations, because of their comparatively low stiffness [14]. In the case of robots with variable stiffness require high stiffness for high performance, while low stiffness is necessary for safety. Their damping capability is their ability to release elastic strain energy during vibrations. High-damping materials should only be used in specific situations. Cantilever beam theory characterizes robot deflection, with numerical analysis focusing on the deflection of a cantilever beam [15]–[18]. Robot stability is assessed by taking into consideration the straight or non-straight layouts [19], [20]. The text discusses a method for computing critical force in serial planar manipulators, focusing on nonlinear phenomena like quasi-buckling. Depending on the stiffness of the arm and the force delivered, the end-point of a robot manipulator arm will deflect when a force is applied. The importance of simulation tools for industrial manipulator guaranteeing the safety [21], [22]. A comprehensive investigation has been taken into account to determine the necessity of algorithm-driven simulation tools and to understand the involvement of different parameters of robot manipulators. This investigation is shown in Table 1 using the attributes of various types of algorithm-driven simulation tools, used parameters of the algorithm, the output of the algorithm, consideration of the level of stability, and the developed or used database.

This study evaluates and stabilizes manipulator systems to improve industrial automation. It creates an algorithm-driven simulation tool to investigate manipulator dynamics under different operation situations. The tool combines mathematical models with stiffness, deflection, and damping. The tool is useful in assessing the manipulator’s level of stability, providing insights for optimizing performance and ensuring safety. It can also create robotics research datasets. It is expected that this research work can be applied to real-life problems, where robot stability is crucial. In this research work, we have reviewed different theoretical and review papers focusing on material parameters and also taken into account the related research papers addressing on algorithm-driven simulation tools. A comprehensive investigation has been also considered to identify the research gap by the predefined objectives of the research. An explicit analysis of material parameters, development of an algorithm-driven simulation tool using hypothesis rules, and verification of this tool by the collected data are considered in this research method.

The paper is structured as follows. The second section of the article describes the analysis of material parameters for stability. Section 3 presents the development of a simulation tool. Section 4 discusses the results and discussion. Lastly, the conclusions of this work are presented in section 5.

2. ANALYSIS OF MATERIAL PARAMETERS FOR STABILITY

This section analysed different material parameters such as deflection, stiffness, and damping, which are explored initially in the literature [9]. The goal of this research is to develop an algorithm-driven simulation tool that considers material parameters to determine the level of stability of the robot manipulator. These parameters have different multifaceted mathematical approaches. Therefore, a comprehensive analysis of these parameters is required to find insight into the interconnection of the stability of the robot manipulator. The evolution of material parameters is dependent on respective quantifiable issues (mass, length, shape, diameter of material, force of system, and young modulus of material). To find out these quantifiable issues, we have completed different case studies on ABB [23] and FANUC [24] series of manipulators. Figure 1 illustrates the selected robot manipulators model, in Figure 1(a) ABB and FANUC in Figure 1(b).

Deflection, stiffness, and average damping coefficient are three (03) key factors that are affected by the qualities of the material. The stability of a robot manipulator is determined by the complicated relationship that exists between these three parameters of the material.

Table 1. A comprehensive investigation of related work to justify the algorithm-driven simulation tools for the robot manipulator

Ref.	Types of algorithm-driven simulation tools	Used parameters of the algorithm	Output of the algorithm	Considered		Database	
				Stability	Level of stability	Developed	Used
[8]	Algorithm-driven simulation tools such as physics simulations	Physical properties of objects, environmental conditions, sensor inputs, and control strategies	Optimized control strategy	Yes	No	No	No
[25]	MATLAB, MSC.ADAMS	Kinematic and dynamic parameters	Optimized virtual prototype	Yes	No	No	No
[26]	Smoothly RRT (S-RRT) algorithm	Maximum curvature constraint, minimum path angle	Ensured efficient and safe navigation for the robotic manipulator	Yes	No	No	No
[27]	Dynamic movement primitives (DMPs) as a simulation tool	Task configuration similarity, skill coordinate frames, and abstractions in the data	Performing manipulation tasks	Yes	No	No	No
[28]	PyBullet and V-Rep for benchmarking simulated robotic manipulation	Metrics of Euclidean distance error, velocity max, average, and error	Set of metrics that assess the success of the simulation	Yes	No	Yes	No
[29]	Algorithm-driven simulation tool using a continuum manipulator	Euclidean distance error, and the young's modulus matrix (YMM)	Threshold values	Yes	No	No	No
[30]	Algorithm-driven simulation tools and machine learning	Physical properties, environmental conditions, and task-specific variables	A set of optimized robotic control strategies and actions	Yes	Yes	No	Yes
[31]	Virtual robot experimentation platform (V-REP), Gazebo, and MATLAB/Simulink	Physical properties, environmental conditions, sensor inputs, and task-specific variables such as the type of crops and field conditions	The output consists of performance metrics and data	Yes	No	No	Yes
[32]	Neural network-based algorithms	State variables, actuator signals, fault indicators	Severity of faults within the actuator systems of the robot manipulators	Yes	No	No	No
[33]	PID and fuzzy logic controllers	Position and velocity	Vibration control of a flexible manipulator system	Yes	No	No	No
[34]	Algorithm-driven simulation tools in robotics	Mechanical design parameters, control policy design parameters, and specifications of the system	Accelerate the engineering design cycle by reducing the time associated with the design process	Yes	Yes	No	No

(a) (b)

Figure 1. Model of (a) ABB and (b) FANUC manipulators

2.1. Deflection, stiffness, and damping

This study examines mechanical behaviors and geometrical structures in Figure 2, focusing on the deflection characteristics of a cantilever beam, the geometric configuration of an open-end cylindrical tube, and the amplitude reduction factor for different materials, providing insights into their damping properties and dynamic response. Deflection is crucial for industrial manipulator stability, impacting accuracy, payload capacity, dynamic behavior, and performance. The cantilever beam loaded at end mechanism is considered for connection with simulation tools. Figure 2(a) shows the deflection of a cantilever beam, where moment of inertia can be detect about neutral bending axis. Moreover it is also observe that the deflection is interconnected with the stiffness of material or spring constant of material. The formulas used for material parameters of deflection [35] is expressed as (1):

$$Deflection = \partial_{max} = \frac{PL^3}{3EI}\ ; K = \frac{P}{\partial_{max}} \tag{1}$$

where, P is force, L is length of robot link, E is young modulus, I is moment of inertia, and K is spring constant.

This study investigates stiffness in cylindrical manipulators using young's modulus as a case study. Stiffness is correlated with the modulus of elasticity and moment of inertia, with the angular frequency being closely related to natural frequency and the elastic constant. Figure 2(b) shows the involvement of the inner radius and outer radius of the cylindrical shape of the manipulator, which is incorporated with a moment of inertia. It has been also analysed that young modules of materials and the moment of inertia correlate with different material shapes. A consequence evolution of stiffness for different applications has been established differently. To interconnect the parameter of stiffness with the simulation tool, the following formula for the material parameter of stiffness [36] is used as (2):

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

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

Recent research links damping coefficient to stiffness and amplitude reduction factor. Damping stabilizes manipulator motion, releasing energy and minimizing oscillations. Inadequate damping can cause instability, while excessive damping hinders response and energy consumption. The amplitude reduction factor is directly linked to a material's capacity to dissipate vibrational energy, with steel having a higher capacity than copper and copper having a higher capacity than aluminum. Figure 2(c) shows the amplitude reduction factor for different materials (steel, copper, and aluminum). The simulation tool enables engineers to assess the damping characteristics of the manipulator system and fine-tune damping coefficients for stable and efficient performance in different operating situations. To interconnect the parameter of damping with the simulation tool, the following [9] for material parameter of damping is used as (3):

$$Damping\ Cooficient = C_{avg} = \frac{\xi}{n};\ \xi = \frac{\delta}{C_c};\ C_c = \sqrt{4mS_{stiff}};\ ln\left(\frac{x_1}{x_2}\right) = \frac{2\pi\delta m}{\sqrt{1-\delta^2}} \tag{3}$$

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

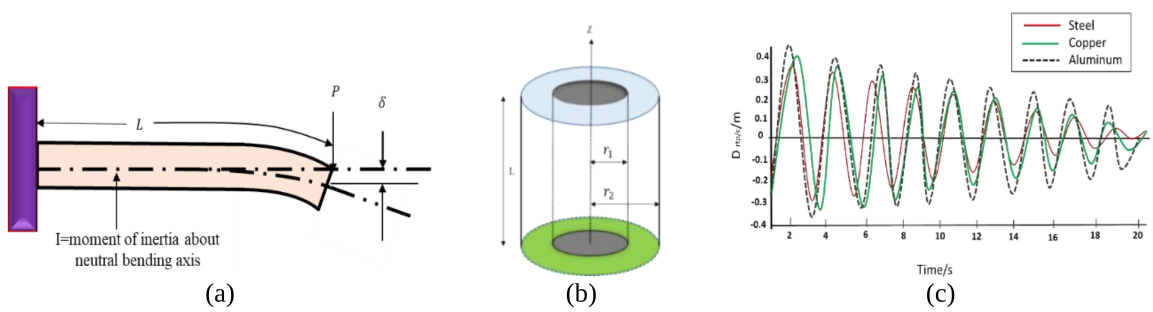


Figure 2. Focusing on (a) the deflection characteristics of a cantilever beam, (b) the geometric configuration of an open-end cylindrical tube, and (c) the amplitude reduction factor for different materials

The case study of manipulators reveals that the stability of robot manipulators is linked to material parameters like stiffness, damping, and deflection. Stiffness increases stability, while deflection and damping decrease it. The stability hypothesis can be validated using a simulation tool and different numerical values of measurable issues.

3. DEVELOPMENT OF ALGORITHM-DRIVEN SIMULATION TOOL

In the field of robotics, maintaining the performance and stability of robot manipulators is critical to their efficient use in a variety of applications. The material qualities that determine their construction, in particular elements like deflection, stiffness, and damping, influence their behaviour. Creating simulation tools specifically designed to evaluate these factors has become a vital undertaking, enabling thorough evaluations to optimize robot manipulator designs. In this context, developing a simulation tool that utilizes a new algorithm is seen as a symbol of innovation. This tool provides a methodical way to evaluate and improve the stability of robot manipulators.

In the process of this investigation, we thoroughly examined the fundamental principles that form the foundation of the suggested algorithm, thereby clarifying its effectiveness in simulating the intricate dynamics of robot manipulators. This algorithm's entire lifecycle will be elucidated, commencing with its theoretical conception and culminating in its practical implementation. Furthermore, an analysis of its performance in comparison to established benchmarks and real-world scenarios will be conducted to validate its efficacy as a fundamental tool utilized by robotics engineers. The proposed algorithms for the development of simulation are divided into the following:

Algorithm 1 can be applied to insert the input value including different query values to create a user-defined database and the output value of all possible queries. The pseudo-code of this algorithm is shown in Algorithm 1.

Algorithm 1. User define database
```
Input: Robot Type R
Output: Return parameters value
Step1: Query from the database based on R
Step2: Store query value on min, medium and max for Stiffness, Deflection, and Damping
Step3: Return all possible query value
```

Algorithm 2 can be applied to find the different level of stability as output, which is calculated from the numerical values of deflection, stiffness, and damping as input. The pseudo code of this algorithm is shown in Algorithm 2.

Algorithm 2. Check stability level
```
Input: DeflectionValue de, stiffnessValue st, and dampingValue da
Output: Return integer stability value such as 0, 1 or 2
Step1: Initial User Define Database All value and store in new variable to min, medium and
max Stiffness s, Deflection D, and Damping d
Step2: ans=0
Step3: Calculation stability value of based on relation of material parameters and store in
ans
Step4: Return ans value
```

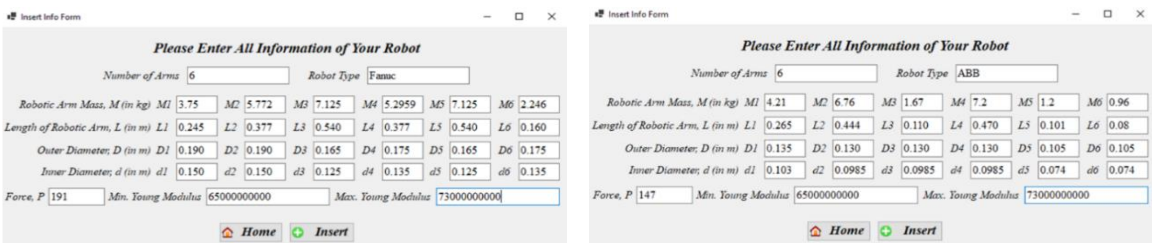
Algorithm 3 can be applied to determine the status of stability using material parameters, where input value considered from different factors of the robot manipulator (mass, length, diameter, force, and young modulus of respective materials). The material parameter of deflection, stiffness, and damping are derivate from (1) to (3). The pseudo-code of this algorithm is shown in Algorithm 3.

Algorithm 3. Derivation process of stability using material parameters
```
Input: mass, length, outerDiameter oD, innerDiameter iD, force, minYoungModulus
mYM, maxYoungModulus mYM, Number of input n
Output: Return stability message
Step1: Deflection, stiffness, and damping calculation
deflection= [], stiffness= [], damping= []
minSpringConstant = (force / deflectionMax[n])
dampingCoefficient = Math.Sqrt((8.967) / ((4 * PI * PI * mass * mass) + (8.967)))
while n not equal to zero do
areaMomentOfInertia = (π / 64.0) * ((4* oD) - (4 * iD))
deflectionTemp = (force * (3 * length)) / (3 * mYM * areaMomentOfInertia)
deflection.insert([deflectionTemp])
momentOfInertia = (1 / 8.0) * mass * ((2 * oD) + (2 * iD))
stiffnessTemp = (Math.Sqrt(minSpringConstant / mass)) * momentOfInertia
```

```
stiffness.insert([stiffnessTemp])
minCriticalDampingCoefficient = Math.Sqrt(4 * mass * stiffness)
dampingTemp = dampingCoefficient / minCriticalDampingCoefficient
damping.insert([dampingTemp])
end while
deflection.sort(), stiffness.sort(), and damping.sort() sort by ascending order
minDeflection = deflection[0], minStiffness = stiffness[0], minDamping = damp-ing[0]
mediumDeflection = (deflection[0] + deflection[n-1]) / 2.0
mediumStiffness = (stiffness[0] + stiffness[n-1]) / 2.0
mediumDamping = (damping[0] + damping[n-1]) / 2.0
maxDeflection = deflection[n-1], maxStiffness = stiffness[n-1], maxDamping =
damping[n-1]
Step2: Calculation stability value
finalStiffness = [minStiffness, mediumStiffness, maxStiffness]
finalDeflection = [minDeflection, mediumDeflection, maxDeflection]
finalDamping = [minDamping, mediumDamping, maxDamping]
countLow = 0, countMedium = 0, countHigh = 0
for i, j, k less than 3 do
status = CheckStability(finalStiffness[i],finalDeflection[j],finalDamping[k])
if status equal to 0 then
countLow = countLow + 1
else if status equal to 1 then
countMedium = countMedium + 1
else if status equal to 2 then
countHigh = countHigh + 1
end if
i=i+1, j=j+1, k=k+1
end for
Step3: Return Math. Max (countLow, countMedium, countHigh)3
```

These simulation algorithms or methods can be used by computer programs to imitate the behaviour of real-world systems or processes. This algorithm can generate data that reflects the possible outcomes of different actions or events, based on certain assumptions and rules. An experimental activities has been completed for the proposed algorithm where, the front-end of this algorithm is written in C#, and the back end is written in SQL. In the process of developing an architecture for the database, the attributes of the database are taken into consideration by the given specifications, as well as their related classification and target value requirements.

The simulator can be used to ascertain the stability classifications of robot manipulators for commercially accessible robots. The simulator consists of two panels: one designated for the Admin and the other for the User. The respective numerical values of ABB and FANUC have been computed using the proposed and updated formula, and the real value is inserted into the simulation interface shows in Figure 3. The interface of input values for FANUC shows in Figures 3(a) and 3(b) shows the interface of input values for ABB.These figures demonstrate how to input various numerical values for the respective factors of material parameters. After entering the information, the backend database will be created. The simulator can modify and remove existing data, which can then be utilized for additional study of different data sets. The overall output and different dimensions of numerical values are discussed in the next section.



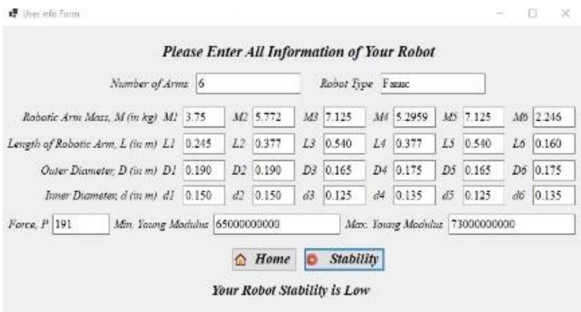
(a) (b)

Figure 3. Inserted real value for (a) FANUC and (b) ABB

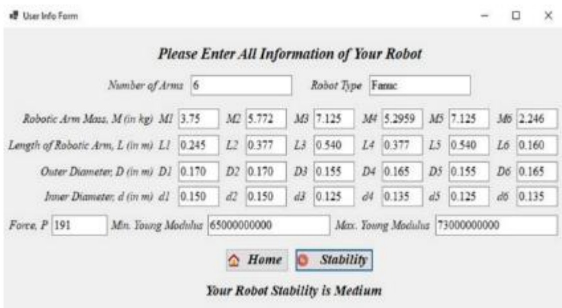
4. RESULTS AND DISCUSSION

This study examines the stability of industrial manipulators using a simulation tool. Factors like algorithm, manipulator stability, and material properties like deflection, stiffness, and damping are analyzed. Manipulator geometry, material properties, and applied forces influence deflection patterns. Furthermore, the examination of how the stiffness of materials affects the stability of a manipulator yielded enlightening discoveries. Manipulators made from materials with increased stiffness showed decreased deflection and enhanced resistance to structural deformation, which can be further investigated using (1) and (2). Moreover, the damping characteristics have been identified as a crucial component that influences the dynamic behaviour. The logarithmic decrement, which can be obtained from the amplitude reduction factor of industrial manipulators as described in (3), plays a key role in this analysis. The correlation between the stiffness of materials and the stability of a manipulator highlights the need of choosing suitable materials during the design stage to improve overall performance and dependability.

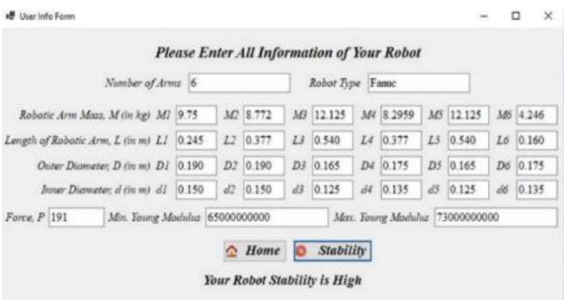
The simulation tool utilized a novel algorithm as its backend and various interfaces were designed to input the necessary variables. This technique facilitated precise forecasting and assessment of manipulator stability across a wide range of operating situations. The simulation program enabled a thorough evaluation of manipulator stability using different performance indicators. The findings indicated that the stability levels were affected by variables such as the bulk of the payload, velocity, and the intricacy of the trajectory. The stability of manipulators was found to be influenced by diverse operating conditions, emphasizing the need to take dynamic aspects into account when designing manipulators and developing control systems. This is crucial to maintain the safe and dependable functioning of manipulators in industrial settings. Figure 4 shows the screenshot of the output result for the FANUC manipulator's stability level as in Figure 4(a) low, Figure 4(b) medium, and Figure 4(c) high.



(a)



(b)

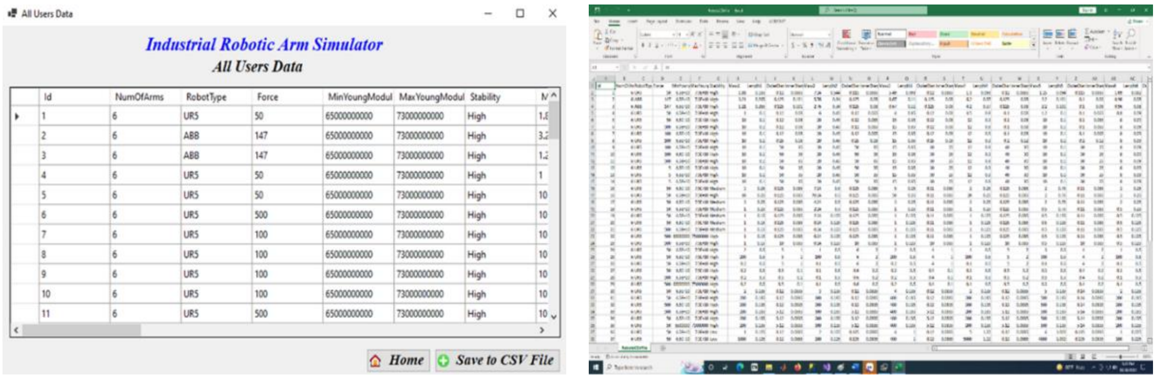


(c)

Figure 4. Screenshot of interface for the output result as (a) low, (b) medium, and (c) high

The manipulator's mass of arm, length of arm, and inner diameter-outer diameter are monitored and assessed as effective factors for determining the varying levels of stability. The simulation tool also provides various processed data that is saved in the cloud. Figure 5 shows the screenshot of the interface of saved data, in Figure 5(a) user data and Figure 5(b) sample database.

The results of our study emphasise the crucial significance of the characteristics of materials, the design of algorithms, and the operational factors in affecting the stability of industrial manipulators. Engineers can utilize the developed simulation tool to obtain significant insights into the behaviour of manipulators and make well-informed design choices to enhance stability and performance. By using sophisticated algorithms and simulation approaches, the tool's ability to make accurate predictions is improved. This allows for more streamlined iterations in manipulator design and decreases the necessity for expensive experimental testing.



(a) (b)

Figure 5. Screenshot of the interface of (a) user data and (b) of database

5. CONCLUSION

Our research conclusively shows that the created algorithm-driven simulation tool is highly effective in assessing the stability of industrial manipulators. The tool offers useful insights for optimizing manipulator performance and guaranteeing safe and reliable operation in industrial settings by taking into consideration variables like as material features, algorithm design, and operating conditions. Additionally, the developed tool can be used to build a specific dataset in the relevant area for additional research as needed. This work enhances the progress of robotics technology and simplifies the development of more resilient and effective industrial automation systems. However, it is crucial to acknowledge the constraints of simulation-based methodologies, which encompass simplifications in modelling assumptions and uncertainty in real-world operating settings. Future research should prioritize the improvement of simulation approaches, the verification of results through experimental testing, and the expansion of the simulation tool's usefulness to a broader range of manipulator configurations and situations.

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BIOGRAPHIES OF AUTHORS

Shabnom Mustary is currently a Ph.D. candidate at Dhaka University of Engineering and Technology at the Department of Computer Science and Engineering. Her research area includes robotics, artificial intelligence, and machine learning. She can be contacted at email: shobnom93717@gmail.com.

Prof. Dr. Mohammod Abul Kashem is a Professor at the Department of Computer Science and Engineering (CSE), Dhaka University of Engineering and Technology (DUET). His research interest are national relevance domain with contemporary technology (artificial intelligence (AI), machine learning (ML), Industry 4.0, cyber-physical systems, and the internet of things (IoT). He can be contacted at email: drkashemll@duet.ac.bd.

Prof. Dr. Mohammad Asaduzzaman Chowdhury is a Professor of mechanical engineering at Dhaka University of Engineering and Technology (DUET), Gazipur, Bangladesh. His research interests are advanced materials, nanotechnology, advanced thermodynamics, energy storage materials, engineering tribology, surface engineering, coating technology, and biomedical engineering. He can be contacted at email: asad@duet.ac.bd.

Dr. Jia Uddin is as a Professor, Department of AI and Big Data, Endicott College, Woosong University, Daejeon, South Korea. He received Ph.D. in computer engineering from University of Ulsan, South Korea. He was a visiting faculty at School of Computing, Staffordshire University, United Kingdom. He is an Associate Professor (now on leave), Department of Computer Science and Engineering, Brac University, Dhaka, Bangladesh. His research interests are industrial fault diagnosis, machine learning/deep learning based prediction, and detection using multimedia signals. He can be contacted at email: jia.uddin@wsu.ac.kr.