DESIGN AND DEVELOPMENT OF A WEB-CONTROLLED 3RP ARTICULATED ROBOTIC ARM: A HANDS-ON LEARNING TOOL

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Abstract: The study and application of robotics are evolving rapidly, and the articulated robotic arm is a fundamental element of the study. This paper focuses on the design, development and control of a web application 3RP articulated robotic arm. This project aims to bridge the theoretical knowledge of robotics gained through classroom teaching with practical, hands-on experience. This enables students to understand some robotic concepts like degree of freedom, forward kinematics and inverse kinematics. The 3D design is done on Fusion 360. The 3D-designed parts are saved in stereolithography (STL) file format. These parts are then 3D-printed. The microcontroller implements kinematics calculations to give controls to the stepper and server motors. The web application is hosted locally on the microcontroller (Arduino + ESP 8266), and the board has Wi-Fi and hotspot enabled. As a result, users can connect to the hotspot generated by the microcontroller to access the web application hosted on it. The web application controls the robotic arm through the sending of commands, which are in the form of codes, to the microcontroller. The product design was tested and verified as being functional. The designed web application works well with the robotic arm and the arm was able to carry a load of 1.5 kg.

Keywords*:* 3D design, Arduino, ESP 8266, Forward Kinematics, Inverse Kinematics, Microcontroller, Robotic Arm.

Introduction

Robotics is an exciting and rapidly advancing field that encompasses the design, development, and application of intelligent machines capable of performing tasks autonomously or in collaboration with humans. A robot can be defined, according to The Robot Institute of America (1969), as a re-programmable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks (Mittal & Nagarath, 2003).

Robots are increasingly being integrated into working tasks to replace humans especially to perform repetitive tasks (Yusoffa *et al.,* 2012). The hand is a "differentiated" end-effector of the robotic arm that defines the purpose and the capacity of the arm (Moran, 2007). The fundamental components of robotics include mechanical systems, electrical and electronics design, control systems, artificial intelligence and machine learning, and human-machine interface. However, robotics is deemed abstract to those that are new to it. To enhance their understanding and engagement with robotics, it is essential to provide concrete examples and hands-on experiences that demonstrate the practical aspects of this field. The design and development of a 3RP (Three-Revolute-Prismatic) articulated robotic arm for educational illustration aims to bridge the gap between abstract concepts and real-world applications, serving as a tangible learning tool to facilitate students' comprehension and interest in robotics. Robotic arms are electro-mechanical systems whose function is similar to the human arm (Mittal *et al*., 2011), they find application in numerous fields like agriculture, medicine, and also in an educational environment (Roshnianfard & Nogushi, 2019; Sultan *et al.*, 2017; Jahnavi & Sivraj, 2017), and their application continually increases yearly (Suleiman *et al*., 2018).

This project focuses on the step-by-step exploration of the design and development process, intending to equip students with the necessary knowledge and skills to understand and create their robotic arm projects. It consists of a microcontroller which has timers, and other on-chip peripherals (Rafiquzaman, 1995), the microcontroller is the main component of the robot, helping the robot to perform logical operation and hence making decisions. It constantly communicates with the built web interface which serves as the brain (Aroca *et al*., 2012) and instructs the microcontroller. The robotic arm is also equipped with an end-effector which is a gripper. The gripper is capable of performing pick and place operations, it can handle objects with precision and efficiency (Vishakha & Andurkar, 2017). With this design and development of a 3RP-articulated robotic arm, the problems encountered by students are solved including; the gap between theory and practical, lack of hands-on experiences, disengagement due to passive learning through lectures and textbook, limited collaboration opportunities between different skills and fields and insufficient career readiness.

Some related research work has been carried out successfully some of which includes the following:

Shaibu et al., (2019) presents the design and development of Arduino controlled robotic arm with 5 degrees of freedom (5-DOF) designed for educational purposes. Servomotors were used to design this robotic arm Aluminum was selected to fabricate the components of the robotic arm. The torque exerted at each of the joints was calculated and a servo with the required torque rating was selected for each joint. The Arduino UNO R3 board was selected for the project and the Arduino IDE software was used for the control of the robotic arm. A Bluetooth module and an Android device were used to control each movement of the joint.

Susmitsingh *et al.,* (2022) designed a smartphone-controlled robotic arm. In this project, Six (6) servo motors were used, the robotic arm could move in different directions and could hold or release things with its gripper. For the proper control of the arm, the Arduino UNO controller was used. A smartphone application that will be linked to the Arduino UNO microcontroller via Bluetooth module was used to control the movements of the servomotors which were responsible for the movement of the robotic arms.

Hussein *et al.,* (2022) presented the design and implementation of a robotic arm. The project is controlled through a mobile app and it has 6 degrees of freedom (6-DOF). The design controlled by the Arduino platform receives orders from the user's mobile application through Bluetooth. The arm is made up of five rotary joints and an end effector, where rotary motion is provided by the servomotor. The Arduino has been programmed to provide rotation to each corresponding servo motor to the sliders in the designed mobile application for usage from a distance.

Ashraf *et al.,* (2011) presented the design and development of a competitive low-cost robot arm with four degrees of freedom. The project was designed with cost in mind, the robotic arm is designed for performing simple tasks such as lightweight material handling. Also, Vo *et al* (2021) presented a paper which is concerned with the design, fabrication and control of a 3-DOF robot arm implementing stepper motors. The robotic arm design uses three parallelogram mechanisms for the positioning of the end effector. Yagna *et al*., (2019) presented a paper which focuses on the design and development of a 5-DOF robotic arm manipulator by using a Cortex ARM M3 LPC1768 Microcontroller including an ultrasonic sensor and a digital controller using a computer system. The robotic arm can move freely having 5 Degrees of Freedom (DoF) with a Servo motor situated at each joint. A robotic Arm can position the link that is required at a particular angle. By using a rotary-encoder the feedback of the angle can be measured. This research work aims at using robotic arms in manufacturing industries to reduce human errors and to produce efficient materials. A distinct approach is used to control the robotic arm, this involves building a web application using HTML, CSS and JavaScript. The web application is hosted locally on the microcontroller which serves as an access point to connected devices, this provides cost-effective and a more flexible interface for controlling the robotic arm.

This project aimed at make the teaching and studying of the robotics easier by developing an interactive web app that can be used to control and the robotic arm. The web controlled robotic arm will serves as a training tool, which is presently limited in supply for students and teachers in the field of robotics.

Materials and Method

The materials used in constructing the robotic arm is as follows:

3D Materials: PLA material with 10 per cent in-fill is used for 3D printing, the PLA material is used because it is a biodegradable polymer which possesses good strength and biodegradable properties which is highly needed in the production of 3D components (Aravind *et al.,* 2018). The arm's structural framework is constructed primarily of lightweight but durable materials. This material provides strength and rigidity while minimizing weight which is essential for achieving efficient movement and operation.

Mechanical components: This system incorporates a variety of joint mechanisms to enable movement and articulation, encompassing revolute joints for rotational motion and prismatic joints for linear motion. Each joint is designed to deliver smooth and precise movement within the arm's operational range, this can be achieved by utilizing the appropriate mechanical components. Some of the mechanical elements used in this project includes:

Smooth Rod-Shafts: These rod-shafts are needed for the assembling of the robotic arm, they join the base to the main arm of the robot, and they give this robotic arm a definite shape. It is characterized by a uniform and even surface along its length devoid of any threading or grooves.

Thrust Ball Bearings: Thrust ball bearings (Figure 1) are designed to accommodate axial loads, they form a portion of the parts needed for the assembling of the robotic arm. These bearings consist of two washers and a set of balls or rollers positioned between them. Its purpose is to enable smooth rotation and minimize friction when axial loads are exerted thereby facilitating effective force transmission throughout the robotic arm.

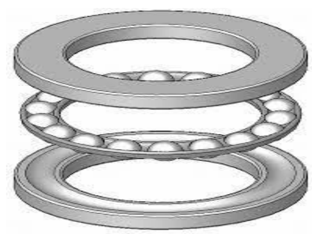

Figure 1: Thrust Ball Bearing (Jadeja & Pandya, 2019)

Lead Screw: This is used to transform rotary movement into linear movement and vice versa, the lead screw is used in this robotic arm to convert the rotary movement of the stepper motor into linear movement, it forms the linear movement and the prismatic joint of the robotic arm, it also allows the end effector to perform linear motion. It comprises a threaded screw and a nut that meshes with the threads.

Radial Ball Bearing: A radial ball bearing, shown in Figure 2, is a type of precision bearing designed for reducing frictional force caused by radial loads. It comprises of inner and outer rings housing a series of balls or rollers between them. This element enables smooth rotation by minimizing friction between the rings.

Figure 2: Radial Ball Bearing (Jadeja & Pandya, 2019)

Electrical and Electronics Components

Stepper Motor –NEMA 17: A stepper motor as shown in Figure 3, is an electric motor whose shaft is capable of rotating by performing steps, that is, it moves depending on the number of specified degrees. It splits a complete rotation into several steps which is performed according to the control given to it. It converts electrical power into mechanical power.

Figure 3: NEMA-17 Stepper Motor (Owoeye *et al.*, 2023)

MG996R Servo Motor: Figure 4 shows a servo motor, this is a brushless DC motor that moves parts of a machine with high efficiency and great precision. It is equipped with positional feedback which allows the end effector to be moved to a particular angle, position, and velocity that a regular motor cannot do, the servo motor is applied in this robotic arm for precision positioning of the end effector. Figure 5 shows the diagram of a MG996R Servo Motor.

Figure 4: MG996R Servo Motor (Owoeye *et al.*, 2023)

Arduino + ESP8266 WIFI Development board: This board is a clone of the Arduino UNO microcontroller (Taufiq *et al.*, 2019). A microcontroller has a microprocessor as one of its main components (Gunther Gridling *et al.*, 2012). It uses the ESP8266 microcontroller as its WIFI module, the Arduino UNO can be used alone so as the ESP8266, the ESP8266 module is a low-power processor, open source and supports LUA programming language firmware developed for ESP8266 Wi-Fi chips (Yogendra, 2019). This hybrid board is suitable for the project due to its Wi-Fi compatibility and availability of the number of pins required.

Software Design

The web application was developed with HTML, CSS and JavaScript. Calculations of forward and inverse kinematics are implemented using JavaScript, human users can give control to the robotic arm by interacting with this app. It is hosted locally on the microcontroller. The movement of the motors is implemented through Arduino codes. When the required angles and directions are received from the app, through the program uploaded to the microcontroller, the motors perform the required movement to carry out its pick-and-place operation. Figure 5 shows the designed controller that is used for controlling the 3RP robotic arm.

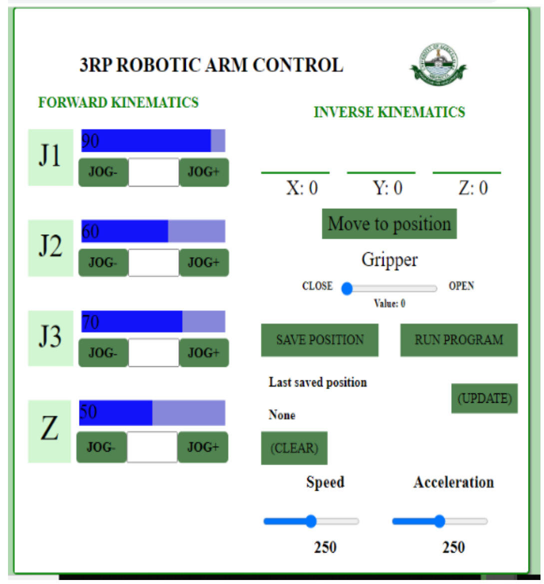

Figure 5: The web application for the robotic arm (3RP Robotic Arm Control)

Figure 6 depicts the circuit diagram of the system (3RP robotic arm), in shows the various components used including the motors and the microcontroller. The system's block diagram which represent the functional view of the system, it also illustrates how the different elements of the system are interconnected is shown in Figure 7, while Figure 8 shows the system's flow chart which constitute the processes, inputs and outputs of the physical model of the system.

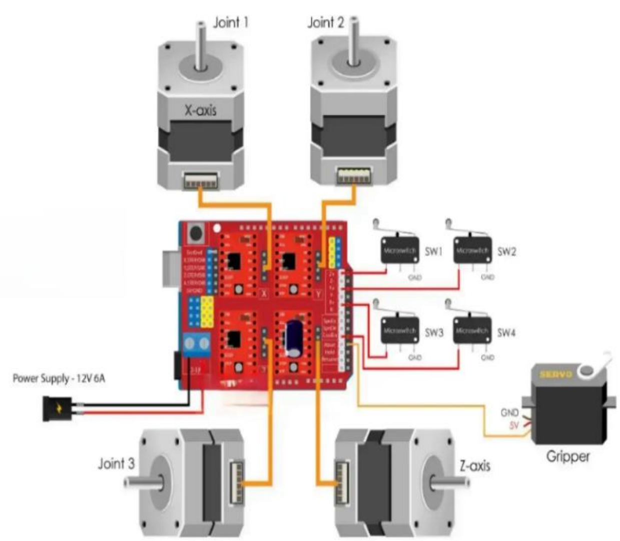

Figure 6: Circuit Design

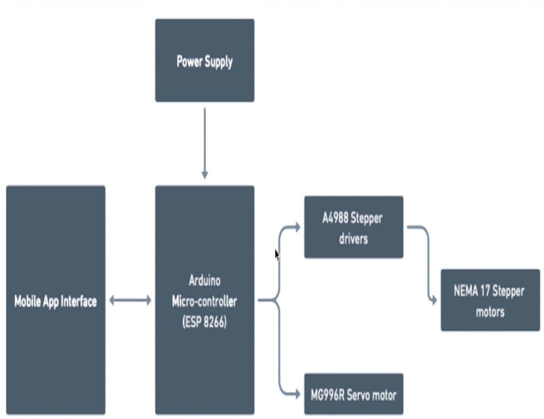

Figure 7: Main System Block Diagram.

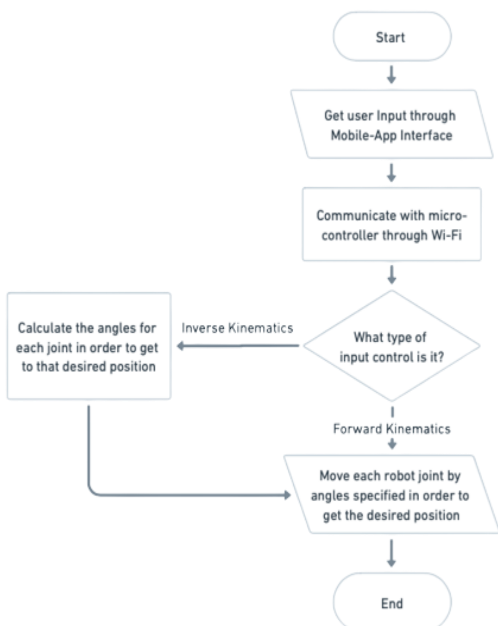

Figure 8: System Flowchart

Design Calculation

Forward Kinematics

D-H Parameters: D-H parameters stand for Denavit-Hartenberg notations (Denavit & Hertenberg, 1995; Craig, 2004; Edris & Shao, 2013) which are four parameters used for attaching reference frames to the link of a manipulator. It is a convention used in robotics for selecting reference frames (Kesaba & Choudhury, 2022). Table 1 shows the D-H parameter of the 3RP robotic arm.

Table 1: D-H Parameter

	α_i	a_i	d_i	θ_i
0-1	0	0	0	θ_1
1-2	0	0	d_2	0
2-3	0	l_3	0	θ_3
3-4	180°	l_4	0	θ_4

d_i is calculated based on the height of the end effector. α_i represents the angular movement along the Z-axis, while θ_i denotes the angular movement about the X-axis. Similarly, a_i corresponds to the linear movement along the Z-axis, and d_i represents the linear movement along the X-axis.

$$^{0}T_1=\begin{bmatrix} cos\theta_1 & -sin\theta_1 & 0 & 0 \\ sin\theta_1 & cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{1}T_2=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{2}T_3=\begin{bmatrix} cos\theta_3 & -sin\theta_3 & 0 & l_3 \\ sin\theta_3 & cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{3}T_4=\begin{bmatrix} cos\theta_4 & -sin\theta_4 & 0 & l_4 \\ -sin\theta_4 & -cos\theta_4 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{0}T_4=\begin{bmatrix} \cos(\theta_1+\theta_3+\theta_4) & -\sin(\theta_1+\theta_3+\theta_4) & 0 & l_3cos\theta_1+l_4cos(\theta_1+\theta_3) \\ -\sin(\theta_1+\theta_3+\theta_4) & -\cos(\theta_1+\theta_3+\theta_4) & 0 & l_3sin\theta_1+l_4\sin(\theta_1+\theta_3) \\ 0 & 0 & -1 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$P_x = l_3cos\theta_1 + l_4cos(\theta_1+\theta_3)$,
$P_y = l_3sin\theta_1 + l_4\sin(\theta_1+\theta_3)$,
$P_z = d_2$
P_x, P_y and P_z represents the position along the x, y and z axis respectively.

Inverse Kinematics

<u>Calculation of θ3:</u>

$X = l_3cos\theta_1 + l_4cos(\theta_1 + \theta_3)$
$X = l_3cos\theta_1 + l_4cos\theta_1cos\theta_3 + l_4sin\theta_1sin\theta_3$
$Y = l_3sin\theta_1 + l_4sin(\theta_1 + \theta_3)$
$Y = l_3sin\theta_1 + l_4cos\theta_1sin\theta_3 + l_4sin\theta_1cos\theta_3$
$cos\theta_3 = \frac{(X^2+Y^2-l_3{}^2-l_4{}^2)}{2l_3l_4}$
$\theta_3 = cos^{-1}\left[\frac{X^2+Y^2-l_3{}^2-l_4{}^2}{2l_3l_4}\right]$

<u>Calculation of θ1:</u>

Here, $\theta_1 = \beta - \alpha$
$\tan\alpha = \frac{cos\theta_2 sin\theta_2}{cos\theta_2 cos\theta_2+4}$
$\tan\beta = \frac{y}{x}$
We know that,

tan (A-B) = $\left(\frac{tanA-tanB}{1+tanAtanB}\right)$ ➔ tan θ_1 = tan ($\beta-\alpha$)

$\theta_1 = \tan^{-1}\left\{\frac{y(l_3+l_4cos\theta_3)-(xl_4sin\theta_3)}{x(l_3+l_4cos\theta_3)+(yl_4sin\theta_3)}\right\}$

Torque Calculation:

Arm 1:

Total weight of arm 1 = 5.69

Length of arm 1 = (2049.629/10x1000) = 0.2m

Therefore, the torque that should be produced by the stepper motor = 5.69 x 0.2 = 1.138Nm.

Arm 2:

Total weight of arm 2 = 3.34N

Length 0f arm 2 = 2229.839/10X1000 = 0.22m.

Therefore, the torque that should be produced by the stepper motor used to control arm 2 =

3.34 x 0.22 = 0.735Nm

For the minimization of price and additional load to the robot, the NEMA 17 stepper motor is used and a counter torque system is built to account for the remaining torque.

NOTE: A scale of 1:10 is used; hence all measurements are divided by 10. The density of the material used for the 3D printing (PLA) [density = 1.24g/cm^3 = 0.00124g/mm^3].

Results and Discussion

The entire system underwent rigorous integration and testing to evaluate the attainment of its intended objectives within real-life conditions. In this model, a web application was integrated into the system, facilitating communication with diverse components, including the Arduino. The system, meticulously arranged on a printed circuit board (PCB), was then securely housed within a fabricated casing constructed from lightweight plastic material.

Performance Test

The system was initially linked to an AC power source, and subsequently transformed into a DC voltage source. Upon activation of the power supply, the entire system powered up quickly and without any errors. Before assessing the system as a whole, each stepper motor for each joint underwent individual testing to ensure its functionality.

Testing of the Stepper Motors

The microcontrollers assume control over the stepper motors. To conduct comprehensive motor tests, several critical prerequisites were met. This includes the provision of an ample power supply, the configuration of motor control software on the microcontroller, and the presence of a functional control interface to dispatch precise commands to the stepper motors.

Each stepper motor underwent individual testing to ascertain its precise functionality. This entailed subjecting each motor to a series of fundamental movements, meticulously validating their responsiveness.

To safeguard against motor damage, strict adherence to the specified voltage and current operating limits for each motor was ensured.

Testing of Each Joints

Before testing, every joint was carefully positioned to its designated home position, serving as a fundamental reference point. Methodically, each joint underwent individual testing, with a systematic approach:

- Gradual commands directed each joint to traverse its complete range of motion, ensuring unhindered access to maximum and minimum angles, free from physical obstructions.
- Precision was paramount during the assessment, verifying each joint's capability to execute movements with pinpoint accuracy.
- To gauge repeatability and accuracy, the joints were repetitively instructed to reach specific angles, consistently returning to those designated positions.

This meticulous process confirmed the robustness and reliability of the joints within the robotic arm and also delineated the precise work envelope of the robotic arm.

Testing of the Web Application Interface

The web application interface is effortlessly accessible through the internet, providing seamless communication with the microcontroller equipped with a WiFi module. Within this user-friendly interface**:**

- Users can define, store, and execute specific positions and angles for each joint within the robotic arm.
- The interface facilitates essential functions, including setting the arm to its home position, executing both forward and reverse kinematics calculations, and controlling the gripper to open or close as needed.
- This intuitive interface empowers users to effortlessly configure and orchestrate the robotic arm's actions, enhancing its versatility and usability.

Overall System Testing

After successful integration, a performance evaluation of the robotic arm was conducted. The test involved a pick-and-place operation, with each joint set to its home position. A load was introduced for the arm to lift and transport to a specified location, as defined within the web application. Remarkably, the robotic arm executed this task flawlessly, showcasing its capability to lift and precisely relocate the load.

Figure 9 shows the assembly in the stage of the robotic arm, while Figure 10 shows the final design of the robotic arm

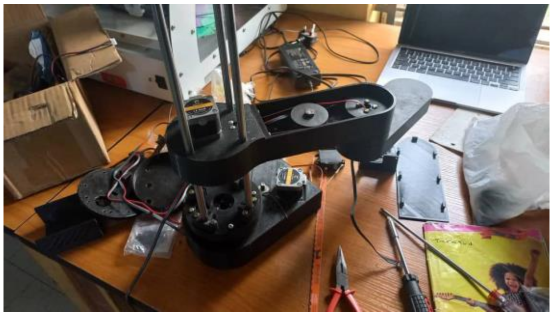

Figure 9 :Assembling of the robotic arm

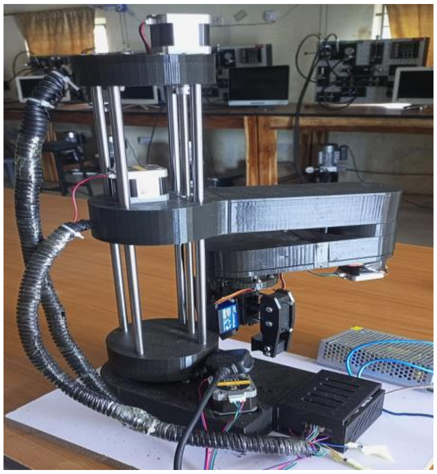

Figure 10: Exact designs

Conclusion

The web controlled robotic arm was designed to meet the set out objectives, the web interface was made to be interactive and easy to use for both students and lecturer, this will go a long in reducing the stress of teaching and learning some concepts of robotics engineering like work envelop of a robot, inverse and forward kinematics. The mobile app developed serves as an HMI which helps users to interact with the robot. The main purpose of this project is for educational purposes. However, it is not limited to the learning environment. It can also be utilized in the field of automation and robotics.

The performance of the robotic arm can be briefly summarized as follows:

- Average tracking error: 3 mm
- Payload capacity: 1.5 kg

Response time: 1s

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