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Design and Fabrication of a Universal Robotic Arm

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Abstract

In engineering and technological fields, especially in manufacturing industry, a large fraction of work is repetitive. Judicious application of automation is expected to make optimum utilization of machine and man power. Every industrialist in India cannot afford to transform his units from manual to semi-automatic or fully automatic ones, as automation is not less costly. The basic objective of this project is to develop a versatile and low cost robotic arm which can be utilized in industry, etc. for several applications such as welding, cutting with high accuracy, painting and lifting and gripping light and medium loads with as less as force required without damaging the object. This robotic arm is expected to be used for doing various types of work maintaining efficiency, economy and enhancing productivity.

1. Introduction

In this paper, steps for designing and fabricating a universal robotic arm are detailed such that any interested person can build up a robot according to his own need. The robot arm is such constructed that it becomes

- cost effective, light weight and safe,
- a combination of simple mechanisms, and
- versatile with all possible movements within its working range and can be used in multipurpose operations in industries.

2. Formulation of Kinematic Equations

The universal robotic arm considered for fabrication is planned to have 3 links with 4 degrees of freedom as shown in Fig.1.

Through forward kinematics, using given joint variables, end effector position and orientation $(x,y,z,\theta_1,\theta_2,\theta_3)$ would be evaluated.

Homogeneous[1] matrix T_0^n
-specifies the location of the i[th] coordinate frame w.r.t. the base coordinate system
-chain product of successive coordinate transformation matrices of T_{i-1}^i

$$T_0^n = T_0^1 . T_1^2 . T_2^3 . \;\ldots\ldots\ldots\; . T_{n-1}^n$$

$$= \begin{bmatrix} R_0^n & P_0^n \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} n & s & a & P_0^n \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \ldots\ldots \text{(i)}$$

$$A_i = R_{z,\theta_1} Trans_{z,2} R_{y,\theta_2} Trans_{z,11} R_{y,\theta_3} Trans_{x,15}$$

$$= \begin{bmatrix} \mathrm{Cos}\theta_1 & -\mathrm{sin}\theta_1 & 0 & 0 \\ \mathrm{sin}\theta_1 & \mathrm{Cos}\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 2 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} \mathrm{Cos}\theta_2 & 0 & \mathrm{Sin}\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ -\mathrm{Sin}\theta_2 & 0 & \mathrm{Cos}\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$. \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 11 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} \mathrm{Cos}\theta_3 & 0 & \mathrm{Sin}\theta_3 & 0 \\ 0 & 1 & 0 & 0 \\ -\mathrm{Sin}\theta_3 & 0 & \mathrm{Cos}\theta_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 & 15 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{vmatrix} \mathrm{Cos}\theta_1\mathrm{Cos}\theta_2\mathrm{Cos}\theta_3 - \mathrm{Cos}\theta_1\mathrm{Sin}\theta_2\mathrm{Sin}\theta_3 & -\mathrm{Sin}\theta_1 & \mathrm{Cos}\theta_1\mathrm{Sin}\theta_2\mathrm{Cos}\theta_3 + \mathrm{Cos}\theta_1\mathrm{Cos}\theta_2\mathrm{Sin}\theta_3 & 11\mathrm{Cos}\theta_1\mathrm{Sin}\theta_2 + 15\,(\mathrm{Cos}\theta_1\mathrm{Cos}\theta_2\mathrm{Cos}\theta_3 - \mathrm{Cos}\theta_1\mathrm{Sin}\theta_2\mathrm{Sin}\theta_3) \\ \mathrm{Sin}\theta_1\mathrm{Cos}\theta_2\mathrm{Cos}\theta_3 - \mathrm{Sin}\theta_1\mathrm{Sin}\theta_2\mathrm{Sin}\theta_3 & \mathrm{Cos}\theta_1 & \mathrm{Sin}\theta_1\mathrm{Sin}\theta_2\mathrm{Cos}\theta_3 + \mathrm{Sin}\theta_1\mathrm{Cos}\theta_2\mathrm{Sin}\theta_3 & 11\mathrm{Sin}\theta_1\mathrm{Sin}\theta_2 + 15\,(\mathrm{Sin}\theta_1\mathrm{Cos}\theta_2\mathrm{Cos}\theta_3 - \mathrm{Sin}\theta_1\mathrm{Sin}\theta_2\mathrm{Sin}\theta_3) \\ -\mathrm{Sin}\theta_2\mathrm{Cos}\theta_3 - \mathrm{Cos}\theta_2\mathrm{Sin}\theta_3 & 0 & \mathrm{Cos}\theta_2\mathrm{Cos}\theta_3 - \mathrm{Sin}\theta_2\mathrm{Sin}\theta_3 & 2 + 11\mathrm{Cos}\theta_2 + 15\,(-\mathrm{Sin}\theta_2\mathrm{Cos}\theta_3 - \mathrm{Cos}\theta_2\mathrm{Sin}\theta_3) \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$\ldots\ldots \text{(ii)}$$

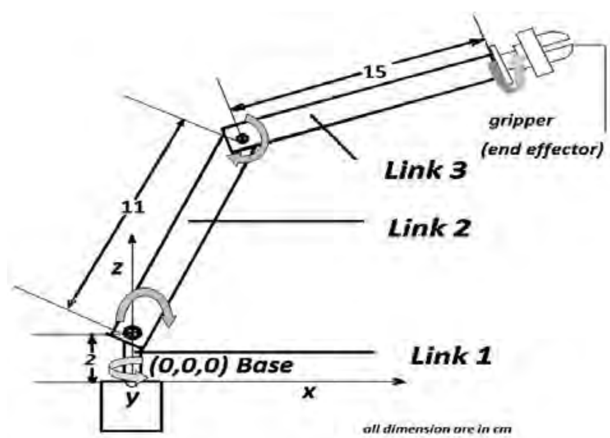

Figure 1. Sketch of Robot Arm with Dimensions

3. Gripping Mechanism with Exact Pressure

The formula W=2μF has been used to sense the exact pressure to be given by the gripper. The gripper is to be controlled by a servo motor and the gripping pressure will be increased up to an optimized value to be controlled by the microcontroller. By this, an egg can also be gripped by this gripper without being damaged.

This is possible when the object weight is sensed by the sensorbeforehand[2].

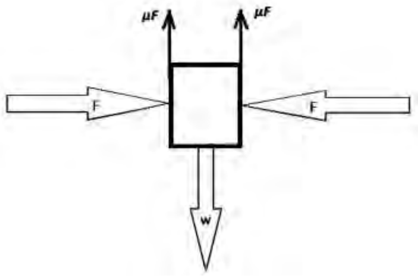

Figure 2. Free Body Diagram of the Object to be gripped

4. Design Approach

The basic design process starts with the matrix generation thus constitutes the motion of the servos and the links.

4.1. Positioning

Positioning means the method to move the end effector at its proper destination. The arm can do this easily by simply rotating its servos. After drawing the line diagram of the arm, it is easy to formulate the three governing equations to describe the locus of the end effector. Equations contain 6 variables, 3 of those are angular and rest three are in length units. As the length of links is constant, one can easily use the variables related to length as constants. So formulated are governing equations with the rest of the angular variables, and related matrices are generated[3,4].

When the matrix is formed, one can multiply them to find the matrix of the end effector which is dependent upon the movement of other links. The final 3x3 matrix can lead to get the final equation and solving it in Mathematica 9.0 one can easily get the angular values.

4.2. Gripping

Gripping is a part and parcel of robotic arm. To grip light and delicate objects one should not apply huge force to grip it, which may result in breaking or damaging the object. Moreover, to save energy one must grip the object with optimum force needed that is dependent upon the weight of the body and the co-efficient of friction between the gripper and the body to be gripped as per equation W=2μF.

4.3. Governing equation formation

After formulating the matrix of the movement of the end effector, the main task is to form the Governing Equation representing the locus of the end effector. Formation and solving of equation has been done in Mathematica 9.0. The governing equations are as follows :

$$11\cos\theta_1\sin\theta_2 + 15(\cos\theta_1\cos\theta_2\cos\theta_3 - \cos\theta_1\sin\theta_2\sin\theta_3)=X \quad \ldots\ldots \text{(iii)}$$

$$11\sin\theta_1\sin\theta_2 + 15(\cos\theta_2\cos\theta_3\sin\theta_1 - \sin\theta_1\sin\theta_2\sin\theta_3)=Y \quad \ldots\ldots \text{(iv)}$$

$$2 + 11\cos\theta_2 + 15(-\cos\theta_3\sin\theta_2 - \cos\theta_2\sin\theta_3)=Z \quad \ldots\ldots \text{(v)}$$

Where, X, Y, Z represents the co-ordinates of the desired position.

These 3 equations are used to solve the 3 variables, $\theta_1, \theta_2, \theta_3$ If co-ordinates of the final location are (5,5,15), then solving the equation in Mathematica9.0 one can get the following set of values in radian,

$$\theta_1=0.785,\ \theta_2=-0.712,\ \theta_3=0.395$$

Putting these values in the Arduino Interface one can get the desired movement.

5. Fabrication and Final Assembly

5.1. Base

At first, the base is made with a specific design such that all the links, motors and sensors are easily assembled as per the design, and the arm can easily rotate and reach all the positions within its working range.

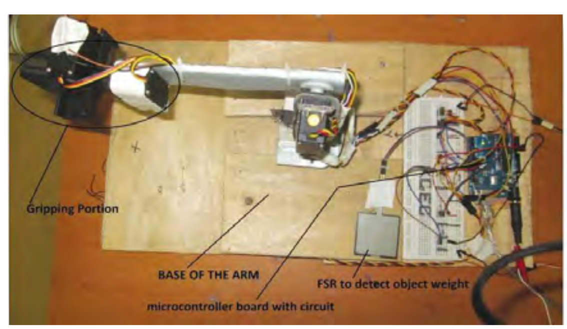

Figure 3. Base of the Arm

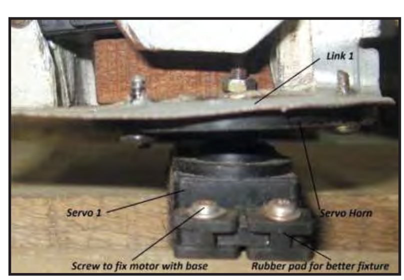

Figure 4. Image of joined Links

5.2. Links

Three aluminium (Al) plates duly bent suitably to make channel sections are used for constructing the links. Joints between the links are made revolute joints. These links carry the weight of motors, other links and loads to carry by the end effector. These links provide the working area which the robotic arm can reach up to [5].

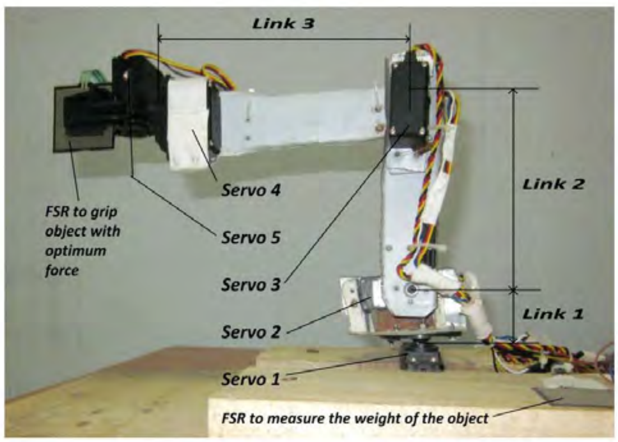

Figure 5. Links with Motors

Links are joined by simple screw joints and nut bolt joint with the servo horn. Servo1 is joined with base by simple screw joint.

5.3. Motors

In the present work, servo motors are used. Three servo motors, servo1, servo2, servo3 are employed for smooth rotation, servo4 is used for alignment purpose and servo5 is utilised for gripping purpose. Two types of servo motors are used in this work. Their specifications are as follows :

Figure 6. Servo HS-311

Specifications of Hitec Servo[6] HS-311 are :

3 pole type motor, Nylon bearing

Operating Voltage :	4.8 - 6.0 Volts
Torque at 4.8V :	42 oz/in (3.0 kg/cm)
Torque at 6.0V :	51 oz/in (3.7 kg/cm)
Dimensions :	1.57 x 0.78 x 1.43 in (39.88 x 19.81 x 36.32 mm)
Weight :	1.51 oz (42.81 gm)

Having light weight, low cost, fulfilling the torque required are the reasons for selecting this standard economy servo.

Specifications of Hitec Servo[7] HS 645MG that is also used in this work are given below :

Metal Gear Dual Ball Bearings

Torque at 4.8V:	107 oz - in (8 kg-cm)
Torque at 6.0V:	133 oz - in (10 kg-cm)
Dimensions:	1.59 x 0.77 x 1.48 in. (40.39 x 19.56 x 37.59 mm)
Weight :	1.94 oz (55 gm)

The reason behind selecting this servo is that it fulfils the torque needed within affordable price and rotates with angular precision too.

Figure 7. Servo HS-645MG

5.4. Micro Controller

In this present work, a microcontroller is chosen for the embedded application, in contrast to a microprocessor used in personal computers or other general purpose applications. The specification of the microcontroller used is given below :

Figure 8. Arduino Microcontroller

Arduino[8] Uno R3 :

Microcontroller	atmega328
Operating Voltage	5V
Input Voltage	7-12V
Digital I/O Pins	14
Clock Speed	16 Mhz

Purpose of selecting this microcontroller is that it is quite user friendly, having an open source license, and also has wide variety of applications.

5.5. Sensors

In this work, FSR (force sensitive resistor)[9] type sensor is used. A force-sensing resistor is a material whose resistance changes when a force or pressure is applied. The force sensitive resistor (FSR) used has the following specification :

Overall length : 3.5"
Overall width : 1.75"
Sensing area : 1.75 x 1.5"
Range 10gm - 500 gm.

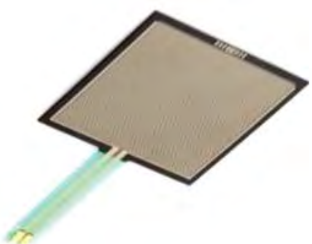

Figure 9. FSR

This is a resistor and when more force is applied on it, resistance increases and the value can be mapped in between 0 to 1023.

5.6. Gripper

In this work, used gripper detail is given below :

Capacity : up to 200gm
Openings : 3.5cm
Servo Controlled : 2

Figure10. Gripper

5.7. Assembly

First the base is constructed. When the base is ready, other parts can be fitted on it. A servo motor (servo1) is attached with base in upward direction (z axis). Link1 joins servo1 and servo2. Servo2 rotates around y axis. Link2 starts from the point of servo2 and end at the servo3. Similarly servo3 rotates around z axis and it holds link3. At the end of link3 there is another motor (servo4) which can rotate the gripper. The joints are temporary for easy dismantling to transfer to the work place. Gripper is the last and main holding part which is able to grip objects with certain dimensions. A 10K rotary potentiometer is used for rotating servo4 in a desired angle for gripping an inclined object.

The pressure sensor has two parts. One is attached on the base and measures the weight and calculates how much force is required to hold and carry, and another is attached with the gripper. The microcontroller and breadboard are fixed with base with screw joints. These parts are joined in such an array that it never hampers or creates obstruction on rotating paths.

5.8. Circuits

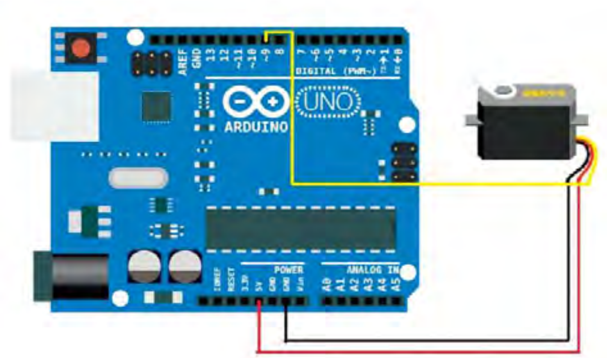

Figure 11. Servos connection with Arduino

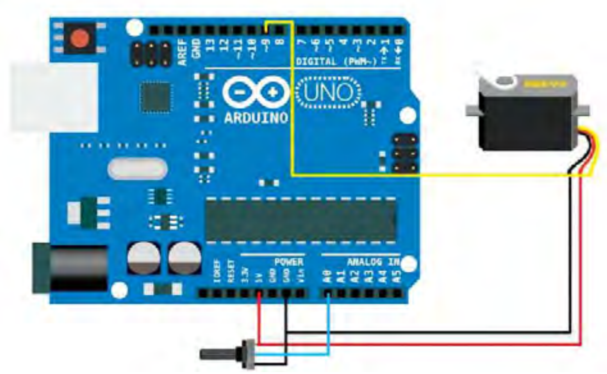

Figure 12. Servo4 and Potentiometer connection with Arduino

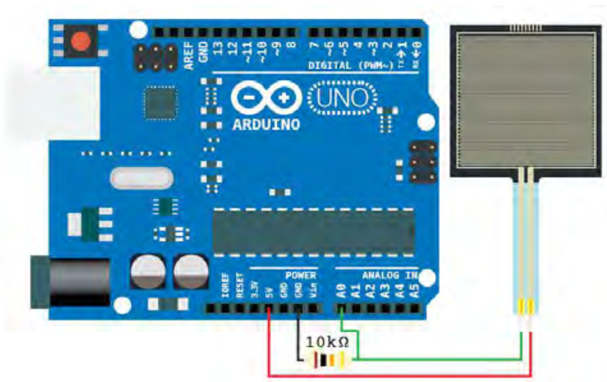

Figure 13. FSR connection[10] with Arduino

After getting all the mechanical part assembled the next step is to ensure that all the circuits are properly connected and insulated. Here all the circuit has been made by both side male header jumper wire. The four servos (servo1, servo2, servo3, servo5) are completely operated by the microcontroller after processing the digital signals from the user and the servo 4 is operated directly from user analogue signals (10K Rotary Potentiometer Signals). All the standard servos have 3 ports with standard colour code: GND (Black), +5V (Red), Signal (Yellow). In the fig.12 the connected potentiometer is completely operated by the user to select a desired angle of the tilted object. Next to all servos two FSRs have to connect with their desired analogue port of the Arduino UNO microcontroller. In this FSR two ports are present one is connected in +5V and other is connected in GND through a 10K? resistor in series. After connecting this circuit one signal is required from this FSR. So a wire is connected directly from FSR GND port to the A0 analogue pin in the board. According to this programme servo mappings are tabulated below.

Name of Servos	*Connected Arduino Digital Pin No.*
Servo 1	11
Servo 2	10
Servo 3	9
Servo Grip (Servo 5)	5
Servo Grip Rotor (Servo 4)	6

One can install the Arduino software to pc, which is available on www.arduino.cc. And using an USB cable, one can easily transfer the written programme to the Arduino board for operating the arm successfully. A sample programme is given in the appendix.

5.9. Test Results

The robotic arm has been tested after fabrication. It has been tested with different set of coordinates corresponding to the different angular rotations of each servo for its positional accuracy.

To grip a light and delicate object, it has been tested with mobile phones, flexible plastic tubes and thermocol block with concentrated load. In each test of gripping, taking the value of frictional coefficient with the gripping surface and the object surface is a vital issue. The gripper's surface has rubber pad for easy gripping. Frictional coefficient value between surfaces of rubber and mobile glass is 0.6, between rubber and plastic tube is 0.7, and between rubber and thermocol is 0.65. With these friction coefficient values, gripping forces have been calculated, and it has been found to work satisfactorily. For performing a specific task accurately, positioning and selecting the value of frictional co-efficient is to be made properly.

6. Conclusion

The fabricated Universal Robotic Arm worked properly. However, scope for betterment of the product does exist and further modification of the arm is possible for increasing strength, accuracy, capability and flexibility. Using proper tools, one can add to precision during fabrication, which will result in a better design. Reducing vibration by using different materials may lead to better accuracy. Degrees of freedom can be increased by using more servos thus increasing its flexibility. Force Sensitive Resistor (FSR) is the sensor that is a basic need of the project. Using more capable sensors means more capability of the arm. Programme development is needed to fit a situation. This robotic arm can be adapted for various industrial applications if it is fabricated suitably for the specific tasks.

Acknowledgement

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Appendix

```
#include <Servo.h>                  //includes the servo functions in this program
// Object for 3 arm servo
ServoservoOne;                      //servoOne is Servo Motor
ServoservoTwo;                      //servoTwo is Servo Motor
ServoservoThree;                    //servoThree is Servo Motor
// Object for force generating servo
Servo servoGrip;                    //servoGrip is Servo Motor (Servo 5)
Servo servoGripRoto;                //servoGripRoto is Servo Motor (Servo 4)
intfsrOne = 0;                      //the analog reading from the FSR resistor set to 0
intfsrTwo = 0;                      //the analog reading from the FSR resistor set to 0
int fsr1 = 0;
int fsr2 = 0;
floatpos = 0;                       //initailize position for all four servo
float rad = 0;                      //initalizeposition  for radian value input
intpotpin = 0;                      //value of potentiometer for ServoGripRoto
void setup()
{
servoOne.attach(11);                //servoOne is attached in port 11
servoTwo.attach(10);                //servoTwo is attached in port 10
servoThree.attach(9);               //servoThree is attached in port 9
servoGrip.attach(5);                //servo for grip is attached in port 5
//servoGripRoto.attach(6);          //servo for gripper rotation  is attached in port 6
Serial.begin(9600);                 //begin the serial port with 9600 baud
}
void loop()
{
// Rotation of servoOne
{
pos=180*7*(rad)/22;                 //put the desired angular value in radian
pos=map( pos, -90 , 90 , 0 , 180 ) ;
servoOne.write(pos);
}
// Rotation of servoTwo
{
pos= 180*7*(rad)/22;                //put the desired angular value in radian
pos=map( pos, -90 , 90 , 0 , 180 ) ;
servoTwo.write(pos);
}
// Rotation of servoThree
{
pos= 180*7*(rad)/22;                //put the desired angular value in radian
```

```
pos=map( pos, 90 , -90 , 0 , 180 ) ;
servoThree.write(pos);
}
// rotate the gripper
{
pos = analogRead(A2);              // reads the value of the potentiometer (0 to 1023)
pos = map(pos, 0, 1023, 0, 180);   // scale it to use it with the servo (value between 0 and 180)
servoGripRoto.write(pos);          // sets the servo position according to the scaled value
delay(10);                         //delay 10 ms
}
// Analog reading from two FSRs'
fsrTwo= analogRead(A1);            //reads the fsrTwo value in A1 port
while(fsrTwo>=20)
{
servoGrip.write(0);
fsr2=fsrTwo;
break;
}
Serial.print("A1 = ");             //prints 'A1='
Serial.println(fsr2);              //prints the fsr2 value
 //Grip the_object
 //servoGrip.write(0);
for(pos = 0; pos<= 120; pos += .25)
{
fsrOne= analogRead(A0);            //reads the fsrOne value
fsrOne= 1.2*(fsrOne);              //taking μ=.6 tally the w=2μR eq.
if(fsrOne<fsr2)
{
servoGrip.write(pos);
delay(20);                         //delay 20 ms
}
}
Serial.print("A0 = ");
Serial.println(fsrOne);
Serial.print("1.2 * A0 = ");
Serial.println(fsr1);
Serial.println("...........");
delay(1);                          //delay 1 ms
}
```

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