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Design and Construction of a GSM-Controlled Pick and Place Robot

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

The modern manufacturing environment is dynamic and uncertain. In line with the global trend in manufacturing, this project is carried out to explore into the potentials of robots in manufacturing, service industry, and domestic use. The robot was designed and constructed to incorporate the use of mobile phones as control mechanism via dual-tone-multiple frequency (DTMF). Various components such as the Gripper, Gears, Chains, and Control system were designed with good factor of safety; with factors such as vibration, inertia concerns, availability, and reliability taken into consideration. MATLAB software was used extensively in the design, simulation and testing. The Root-locus, Disturbance response, and Polar plots of the control system transfer function were plotted using MATLAB. The results obtained showed good performance characteristics; such as stability of the control system, good damping characteristics, and excellent time response to step and impulse inputs.

Keywords: Design; construction; GSM-controlled; pick and place; robot.

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NOMENCLATURES

N_p = Number of teeth of the driving gear
N_g = Number of teeth of the driven gear
R_p = Rotational speed of the driving gear (rpm)
R_g = Rotational speed of the driven gear (rpm)
L = Length of chain (cm)
T_1 = No of teeth of the driving sprocket (teeth)
T_2 = No of teeth of the driven sprocket (teeth)
p = Pitch of chain (cm)
x = Centre-centre distance of chain (cm)
J = Rotor Inertia (Nms^2/rad)
b = Internal friction in motor (kg/ms)
L_a = Armature inductance (mH)
K_m = Motor constant (Nm/A)
R_a = Armature resistance (Ω)
K_b = Back EMF constant (Vs/rad)
P_m = Maximum power (W)
K = Gain
T_f = Transfer function
ω_n = Angular frequency of internal vibration of the control system (rad/s)
ζ = Damping ratio
D = Disturbance signal
$E(s)$ = Steady-state error
K_t = Feedback transfer function
ω_0 = Angular speed generated by the load disturbance (rad/s)

1. INTRODUCTION

The aftermath of the Second World War was rapid development in science and technology with significant inventions, such as: numerical control, microcontrollers and microprocessors, chip technology, and software development. The late 20th century manufacturing industry witnessed rapid use of computers, information and communication technology. There is no doubt that automation and computerization is the future of manufacturing. Various factors such as increasing labour cost, adverse influences from trade unions, international organizations and government policies, and grave consequences of industrial accidents, musculoskeletal disorders and other work-related diseases have caused a global shift from human-centered manufacturing to the era of robotics, artificial intelligence, and possibly, an unmanned factory.

Since 1961, when the first digital and programmable robot “Unimate” invented by George Devol, in 1954, was sold to General Motors where it was used to lift pieces of hot metal from die-casting machines; there has been pervasive use of robots in Automobile and Process industries because of its numerous advantages, such as: efficiency, reliability, labour savings, ease of control, improved safety and productivity. These technologies deal with automatic machines that can take the place of man in dangerous environment or manufacturing processes, or resemble humans in appearance, behavior, and/or cognition.

In recent times, Robots have replaced human in the assistance of performing those repetitive and dangerous tasks which humans prefer not to do or are unable to do due to the size limitations, or even those such as in outer space or at the bottom of the sea where human could not survive the extreme environments. Robots are designed to incorporate components such as mechanical elements (gears, springs, arm, gripper, base etc.), servomechanism, actuators, position feedback mechanism etc. Early designs made use of CNC, programmable and reprogrammable controllers, and the use of infra-red remote controllers. The use of GSM controllers were introduced due the obvious advantages, such as: global coverage, reliability, ease of control, and ability to effectuate control operation from any part of world. Talpur and Shaikh [1] designed a micro-controller based pick and place robot for a food manufacturing line; while Khakurel et al. [2] designed a robot for regulating the speed of DC motors using mobile phones. Even though the same methodology was adopted for this work, the complexity, degree of freedom and application defers from previous designs.

Unfortunately, the rapid advancement in field of robotics has not been explored in Nigeria. The manufacturing sector has witnessed a stunted growth, and notable decline in productivity because of the adverse effects of its political, economic, social and technological (PEST) environment; while multi-national organizations are decamping; small and medium-scale manufacturing factories are shutting down. Nigeria's inability to keep abreast with the rapid changing technologies, especially in robotics, has made manufacturing unattractive to investors. No doubt, the growth of the manufacturing industry in Japan is closely related to their technological advancement in the field of robotics and its applications to the various aspects of production. The introduction of robotics in manufacturing is a major step in revamping the Nigeria's manufacturing industry. Its wide range of applications in industrial, service sector and domestic uses makes it a sine-qua-non for a sustainable all-round development of the nation's economy.

This paper presents the design and construction of a GSM-controlled pick and place robot. The various components were considered and designed for efficient performance.

2. DESCRIPTION OF THE ROBOT

The main components of the robot include the arm, elbow, base, gripper, the controller circuit, and two 12V 6Ah batteries. The rotational movement of the gripper, arm, and elbow is achieved using three DC wiper motors attached to each component. An additional DC stepping motor attached at the interior top of the base control the 360º rotation of the elbow, arm and gripper components. Beneath the base have two DC wiper motors that provide motion to the two rear wheels via chain drive mechanism. These control the forward/backward motion and rotary motion of the base. Two castor wheels fitted at the front provides mobility to the base. The controller circuitry and the 12V DC are housed inside the metallic base. The main components of controller circuit are CM 8870 tone decoder, AT 89S52 microcontroller, electromagnetic relays, bridge rectifiers, and resistive and capacitive components. The batteries provide power to the controller circuit and drive the motors. Provision was made for charging the batteries using AC power source.

2.1 Design Considerations

In carrying out the design of the various components of the machine, we followed standard design procedures as outlined in standard machine design and control system texts as contained in works of Budynas and Nisbett [3], Khurmi and Gupta [4], Shigley and Mischke [5] and Dorf and Bishop [6].

2.1.1 The gear

A spur gear was used to decrease the speed of rotation in order to achieve gradual and smooth rotation of the elbow. Computations were carried out as follows:

$$\frac{N_g}{N_p} = \frac{R_p}{R_g} \quad (1)$$

The motor speed is 467 rpm, and the required speed is 160 rpm. Hence, the required transmission ratio is 3:1. Based on the availability, weight and space limitations, a 17 – 51 gear teeth arrangement with desired tooth profile was used in the construction.

2.1.2 Chain drive

The open-chain arrangement was used to transmit motion to the rear wheels. The design, primarily, involves the determination of the length of chain for a given diameter of the sprockets and centre-to-centre distance. Space and weight limitations were considered in determining the optimum diameters of the sprockets and centre-to-centre distance between the sprockets. The same speed is transmitted, hence the sprockets has equal diameters. The length of chain is calculated as follows;

$$L = \frac{p}{2}(T_1 + T_2) + 2x \quad (2)$$

$T_1 = T_2 = 15$ teeth; $p = 1.3$cm; $x = 11$cm. $L = 41.5cm$

2.1.3 Base

This houses the controller circuitry and two 12V 6Ah DC battery. The gripper-arm-elbow sub-assembly is fitted on the top of the base using nuts. It consists of a rectangular mild steel box with bored holes at strategic locations to accommodate bolt and nut fasteners for the removable top plate. The specification of the base is given thus:

Length = 40.8cm
Width = 31.0cm
Thickness = 1.5mm
Height = 19.0cm

2.1.4 Gripper specification

Due to the required "Pick and Place" function of the robot, an internal gripper was used based on the limitation of minimum distortion and scratching of the work, it was designed for a "Partial Capture Grip" using a V – type tooth profile. The specifications are as follows:

Structural Weight = 500g
Maximum weight of work-part = 800g
Gripping force = 30.66N
Tooth tip force = 8.34N
Gripper opening = 0 – 100mm
Maximum closing speed = 100 deg/sec
Elapsed time for full range motion = 0.9 sec
Maximum acceleration of the robotic arm = 2 m/s^2
Material = mild steel

Design factor = 1.5
Actuator = 12V DC wiper motor

2.1.5 Arm and elbow

The arm and elbow component consists of 15cm x 6cm x 4cm hollow rectangular metallic pipe with thickness of 2mm. The hollow pipe houses the rectangular-shaped component of the electric motors. The rotary motion of the arm and elbow are actuated by the electric motors attached to it.

2.1.6 Electric motor

The DC motor was used as the actuator for the various control movement. The DC motor was preferred to AC motor because of its feature such as: miniature structure, less design complexity and excellent response. The gripper and arm were directly connected to their respective motor; the elbow was connected via a system of gears; whereas, the two wheels were connected via chain mechanism. The specification of electric motors used is given in Table 1.

Table 1. Specifications of the DC motor

Parameter	Symbol	Value
Rotor inertia	J	$1\ Nms^2/rad$
Friction	b	$20\ kg/ms$
Armature inductance	L_a	$100\ mH$
Motor constant	K_m	$5\ Nm/A$
Armature resistance	R_a	$1\ \Omega$
Back EMF constant	K_b	$0.1\ Vs/rad$
Maximum power	P	$187\ W$

2.2 GSM Control via DTMF Signals

The GSM control is achieved using the DTMF signal system. DTMF refers to the system of representation, coding and decoding of audio signals generated by the superposition of two pure sinusoidal tones. This system is very commonly used for telephone signalling over the line in voice frequency band to the call switching centre. The DTMF data output are shown in Table 2.

CM8870 is a DTMF receiver incorporating switched-capacitor filter technology and an advanced digital counting/ averaging algorithm for period measurement. CM8870 provides full DTMF receiver capability by integrating both the band split filter and digital decoder functions into a single 18-pin DIP, SOIC, or 20-pin PLC package. CM8870 decoder uses digital counting techniques for the detection and decoding of all 16 DTMF tone pairs into a 4 - bit code which is interpreted by the micro-controller to effectuate appropriate actuator control movement.

Table 2. The DTMF data output

Lower group frequency (Hz)	Higher group frequency (Hz)	Digit	Q5	Q4	Q3	Q2	Q1
697	1209	1	H	L	L	L	H
697	1336	2	H	L	L	H	L
697	1477	3	H	L	L	H	H
770	1209	4	H	L	H	L	L
770	1336	5	H	L	H	L	H
770	1477	6	H	L	H	H	L
852	1209	7	H	L	H	H	H
852	1336	8	H	L	L	L	L
852	1477	9	H	H	L	L	H
941	1209	0	H	H	L	H	L
941	1336	*	H	H	L	H	H
941	1477	#	H	H	H	L	L

Robot Control: The keypad control and the various control movement is shown in Table 3.

Table 3. The mobile phone keys and their control movements

Phone key	Control movement
1	Robot move forward
2	Robot move backward
3	Elbow rotate clockwise
4	Elbow rotate anti-clockwise
5	Elbow move forward (left)
6	Elbow move backward (right)
7	Arm rotate anticlockwise
8	Arm rotate clockwise
9	Gripper open
0	Gripper close
*	Robot rotates anticlockwise
#	Robot rotate clockwise

2.2.1 Control system design

Control system design entails the determination of configuration, specification and identification of the key parameters of a proposed system required to satisfy a given need.

The goal of the control system is to achieve desired movement of the base, arm, and gripper using a mobile phone. It is desired that the movement of the base, the angular movement of the arm and gripper should be controlled using the numerical keys of the mobile phone. Good response and damping characteristics with short settling time is anticipated.

As designers, the first attempt to configure a system that will result in the desired control performance was done, as shown in Fig. 1.

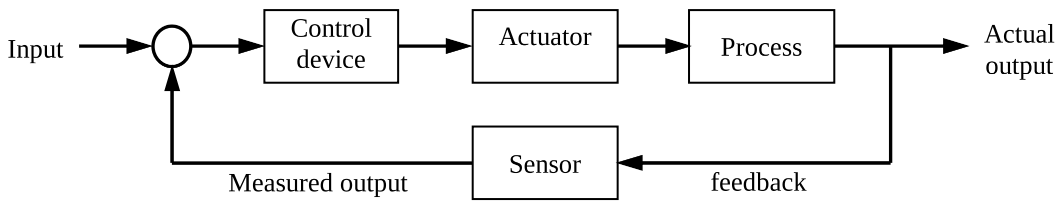

Fig. 1. Proposed system configuration

The next phase of the design process is to select the actuator. A wiper DC motor is used for the gripper, arm and elbow, while a stepping motor is used for the base. An ATMEL tone decoder and a micro-controller circuit are used as the controller. The function of the tone decoder is to convert the input signal to binary form which can be used by the micro-controller to effectuate the control of the robot. The final step in the design process is the adjustment of the parameters of the system in order to achieve the desired performance.

2.2.2 Transfer function

Having taken the motor specification into account, the overall transfer function of the control system is given as;

$$\boldsymbol{T_f(s)} = \frac{\mathbf{5K}}{\boldsymbol{s(0.1s^2+3s+20.5)}} \quad (3)$$

2.2.3 Internal vibration of the control system

Vibration occurs in electric motors during operation due to its rotating parts. The frequency and damping ratio is obtained from the denominator of its transfer function. The open-loop transfer function is given as;

$$q\ (s) = s(0.1s^2 + 3s + 20.5) = s\ (s^2 + \ 2\zeta\omega_n s + \ \omega_n^2) \quad (4)$$

Thus, we obtain: $\omega_n = 14.318\ rad/s;\ \ \zeta = 1.048$

The system is slightly over-damped; hence, all anticipated vibrations are damped effectively.

2.2.4 Disturbance signals in the control system

Applying the Mason's signal-flow gain formula as follows, the steady-state error due to the disturbance signal was obtained by utilizing the final-value theorem, thus:

$$E(s) = \lim_{s\to o}(s\omega(s)) \ = \frac{1}{b+\left(\frac{K_m}{R_a}\right)(K_t K + K_b)}\ D \quad (5)$$

When the amplifier gain is sufficiently high, we have

$$E(s) \simeq \frac{-R_a}{K_a K_m K_t} D \quad (6)$$

2.2.5 Construction process

Fabrication was carried out at Chibuike mechanical workshop, Nekede, Nigeria; while the assembly operation was done at the mechanical workshop of Faculty of Engineering, Nnamdi Azikiwe University, Awka, Nigeria. Fig. 2 shows the exploded view of the robot. The base, top plate, bottom plate and castor plates were fabricated from a 1.5mm thick mild steel. The two 12V battery and the controller circuitry were enclosed by the base. The arm and elbow were fabricated from standard hollow pipe to house the rectangular-shaped components of the electric motor. Fig. 3 shows the assembled pick and place robot.

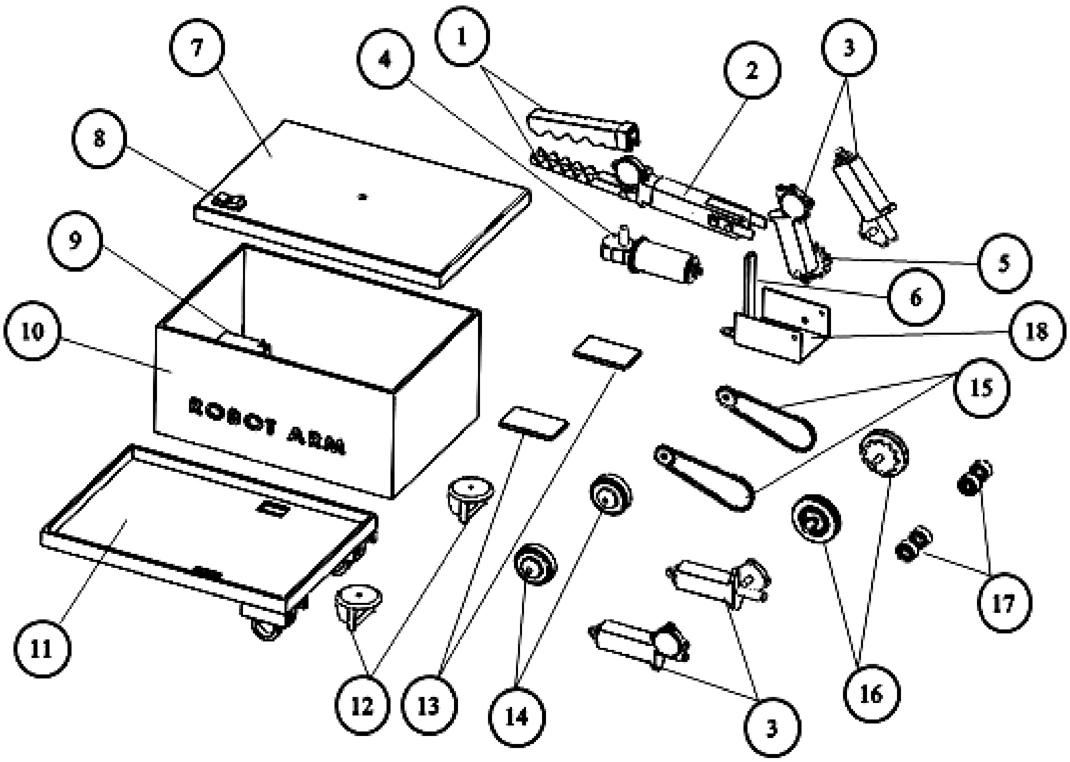

Fig. 2 Exploded view of the robot

1- Gripper, 2- Arm, 3- DC Wiper motors, 4- Stepping motor, 5- Gear, 6- Datum bar, 7- Top plate, 8- On/Off button, 9- 12V battery, 10- base, 11- Bottom plate, 12- Castor fittings, 13- Castor plates, 14- Castors, 15- Chains, 16- Wheel, 17- Nuts, 18- Elbow support plate.

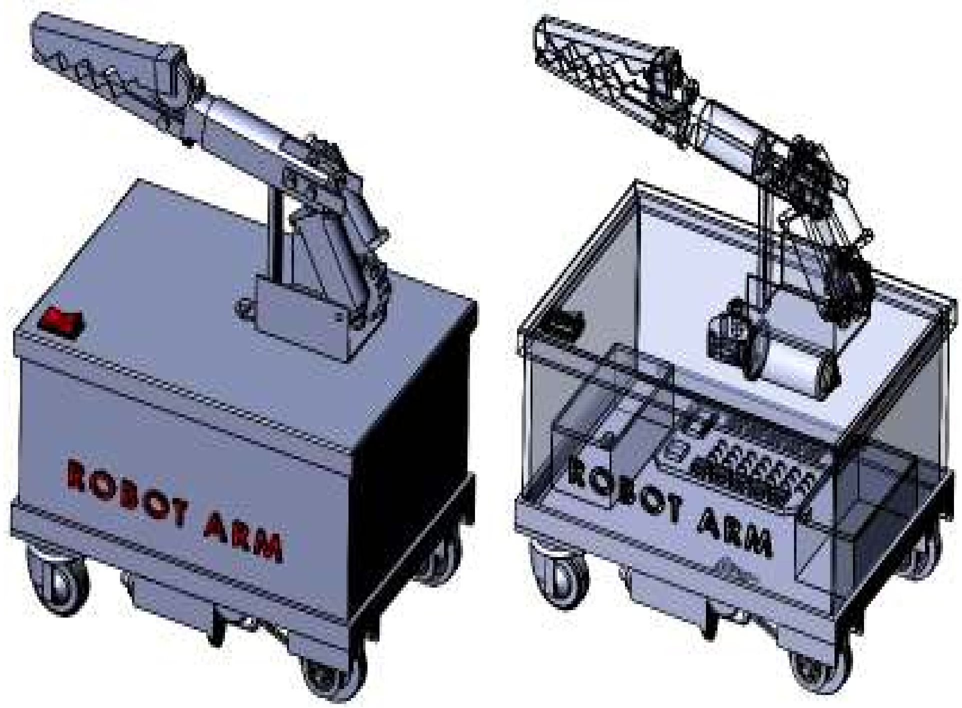

Fig. 3. The pick and place robot

3. RESULTS AND DISCUSSION

The MATLAB software was extensively used to plot and simulate the response characteristics of the control system. The following results were obtained were;

3.1 Disturbance Signal

Fig. 4 shows the plot of the closed-loop step response to a disturbance signal. The error in angular speed attains a steady-state at t = 0.5 sec. The steady-state value of ω_0 is;
$\omega_0(\infty) = \omega_0(0.5) = -0.1961$ rad/s

Therefore the steady-state error for the closed loop is;

E(s) = 0.1961 rad/s

The steady-state error obtained from the closed-loop control system is within design range.

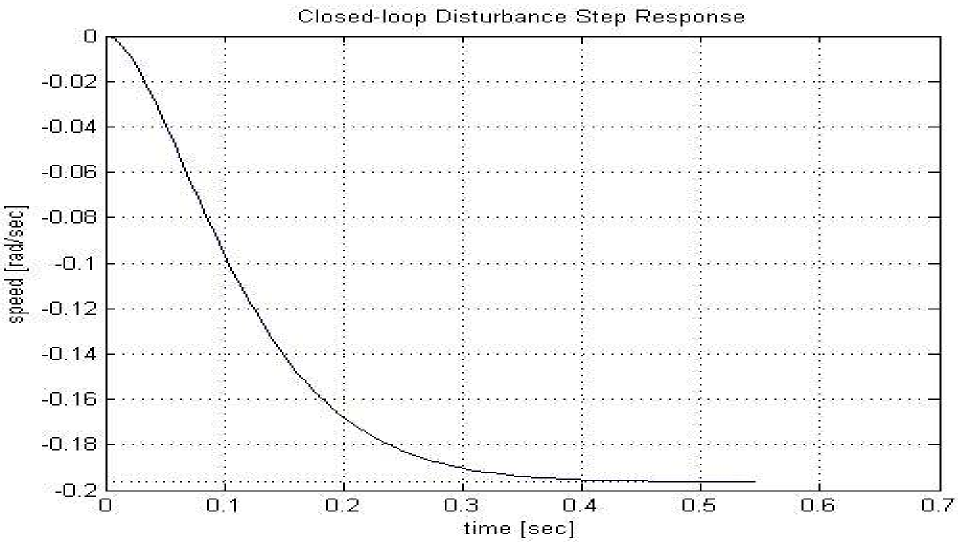

Fig. 4. Closed-loop disturbance step response

3.2 Percentage Overshoot and Settling Time

Fig. 5 shows the plot of the percent overshoot and settling time of the feedback control system. These parameters were used to investigate the effect of the gain of the microcontroller on the control system. Decreasing the gain, decreases the percent overshoot and settling time. At a maximum gain K = 20, the percent overshoot is 13% and settling time = 1.6secs. This implies that, for any given input, the system will produce the desired output in less than 2 seconds. This system response is desirable; any further attempt to optimize cannot be justified for the purpose for which the robotic system is intended.

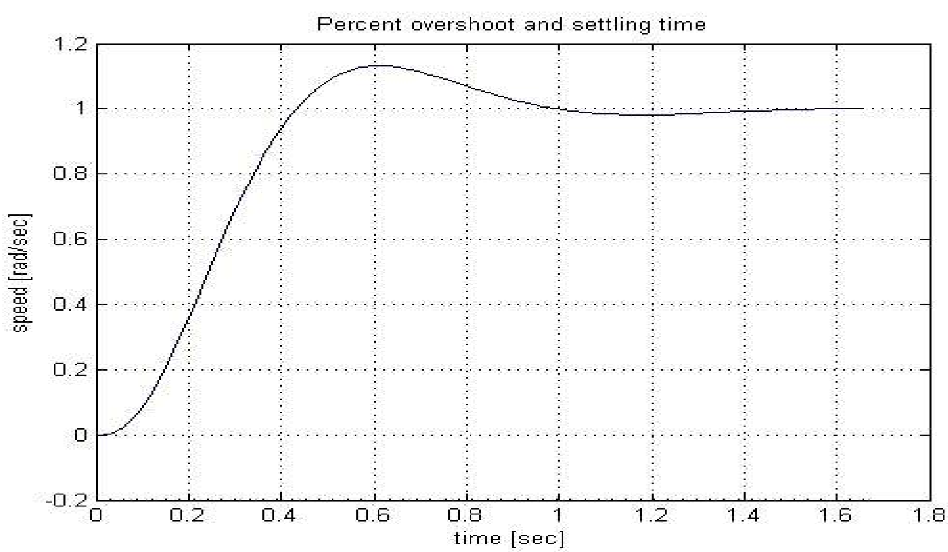

Fig. 5. Percent overshoot and settling time

3.3 Internal Vibration in the Control System

The damping characteristic of the control system is shown in Fig. 6. From the characteristic equation, the damping ratio ρ =1.0476; hence, the control system is slightly over-damped; no sinusoidal oscillation will occur in the control system.

At a natural frequency of 14.318 rad/s and a phase angle φ = π/4 rad, the anticipated vibration is successfully damped in $0.5 sec$. Consequently, the control system has good damping characteristics.

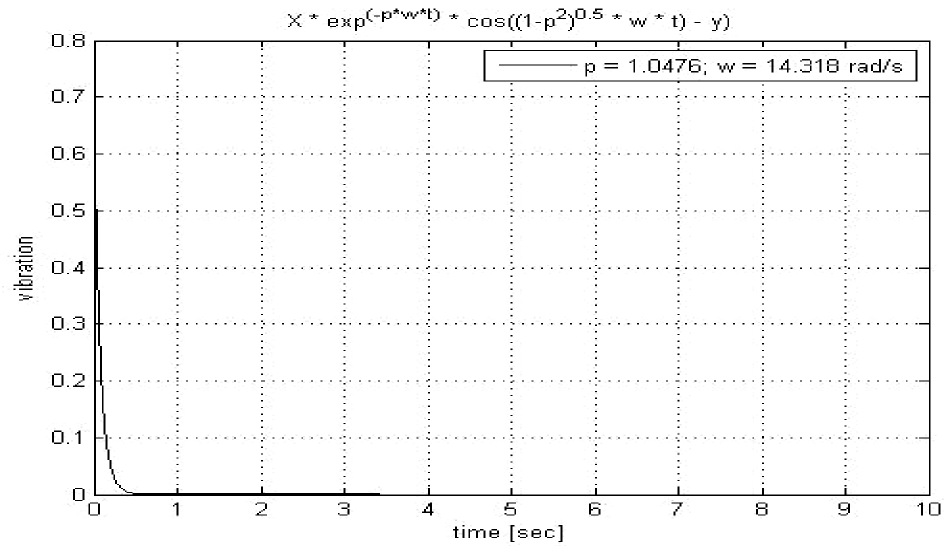

Fig. 6. Vibration and damping characteristics of the control system

3.4 Stability of the Control System

The stability of the control system is determined by finding the roots of the characteristic equation of the transfer function. The roots of the characteristic equation are: 0, -10.5279, -19.4721. Since the roots have non-positive real parts; therefore, the control system is stable.

3.5 Root-Locus Plot

Fig. 7 shows the root-locus plot of the characteristic equation of the system transfer function. The root-locus plot is used to investigate the behaviour of the root with respect to the gain from the microcontroller. The break-away point on the real axis is -4.5, while the cross-over point on the imaginary axis is 14.3i.

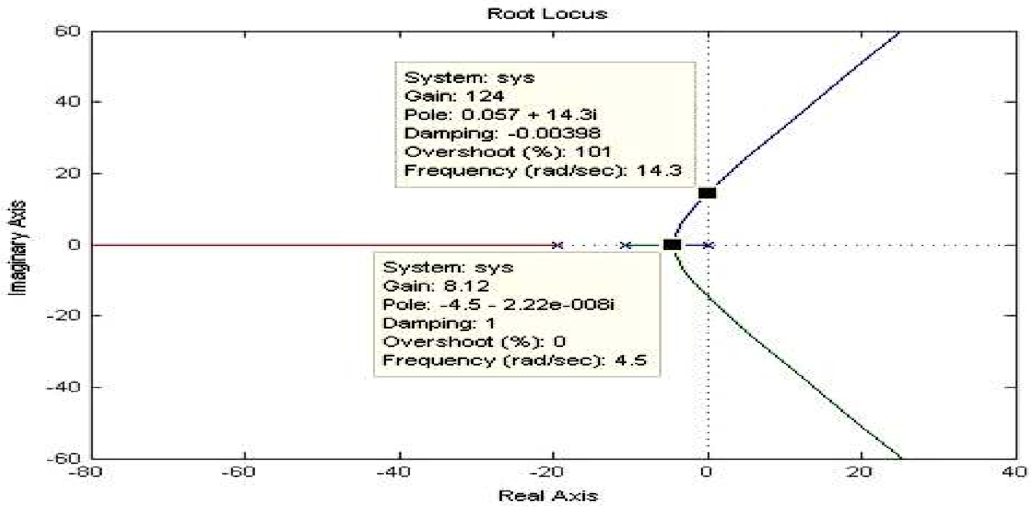

Fig 7. Root locus plot

3.6 System Response to Step and Impulse Input

Fig. 8 shows the plot of the displacement of the robotic system to step and impulse input. From the Step input system response, the displacement vector attains a steady state value at 0.7 rad-rev. From the Impulse input system response; at angular speed of 1 rad/s, the displacement vector per unit rev attains its magnitude at 0.1 rad-rev, while the effect of the impulse dies away at 0.6 rad-rev. These system responses satisfy the desired functional requirements.

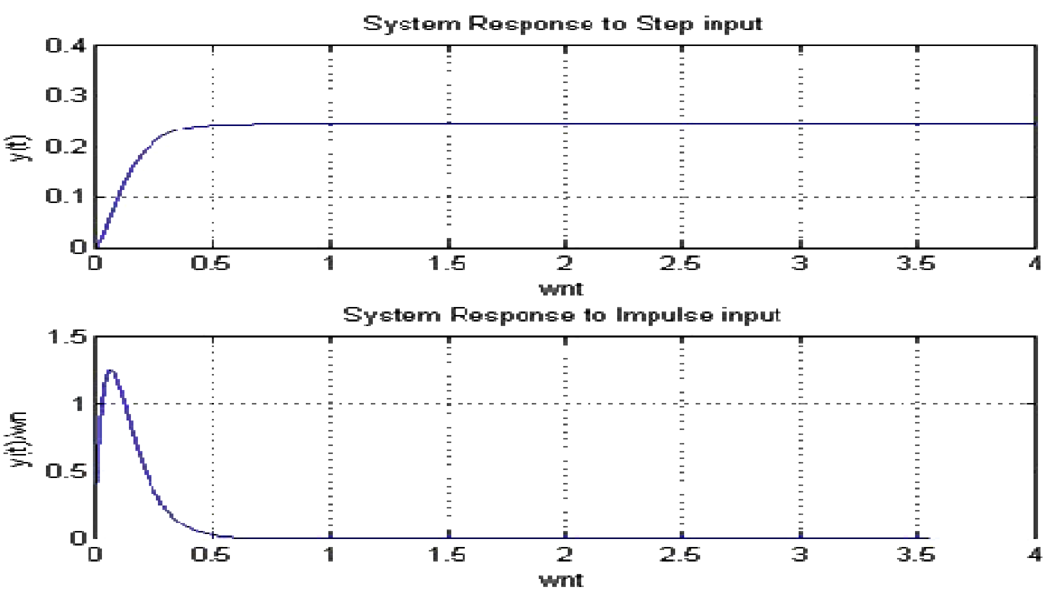

Fig. 8. System response to step and impulse input

3.7 Nyquist Plot

The Nyquist plot is used to investigate the stability of the control system in the frequency domain. For a system to be stable, its Nyquist plot must not encircle point $(-1{,}0)$. From Fig. 9, since the number of encirclements of the (-1, 0) point is zero, the control system is stable.

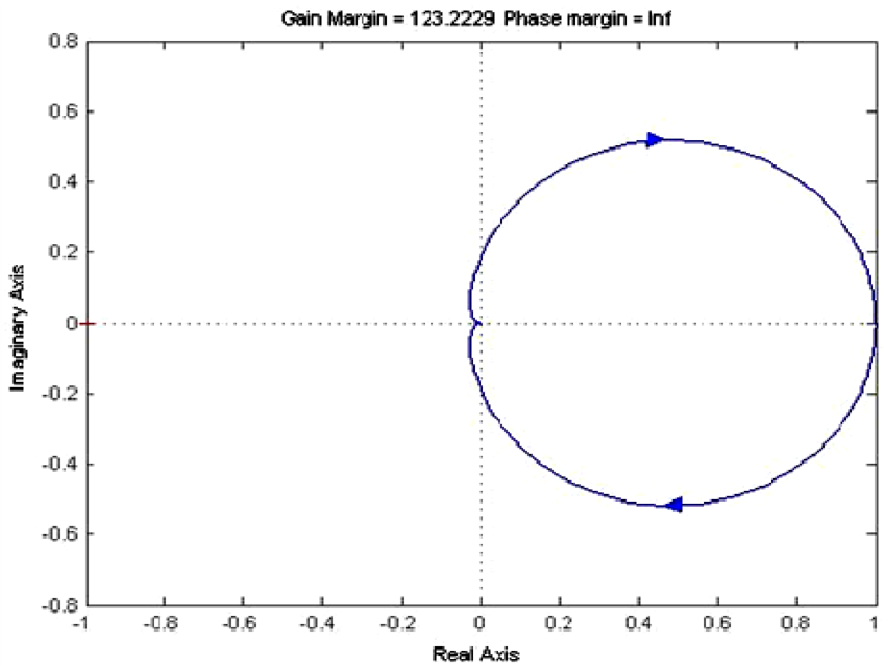

Fig. 9. Nyquist plot of the frequency response

4. ROBOT TESTING/ PERFORMANCE

4.1 Base Movement

The robot achieved a steady linear movement in both forward and backward directions with an average speed of 45m/min and a time response of 0.5s. The robot achieved a maximum of 22 complete rotations per minute in both clockwise and anti-clockwise directions with good dexterity.

4.2 Arm Movement

This showed slight concern as the added weight of the arm and gripper motors affected the movement of the arm. The arm rotated faster while moving towards gravity than when moving against it; hence, affecting its ease of control, as caution was observed when the arm was moving towards gravity.

4.3 Gripper Movement

The gripper has a maximum opening of approximately 100^o. Its opening, as well as closing movement was achieved in one second. However, it was observed that the manufacturing of the gripper tooth-profile was not carried out according to design due to constraints of available manufacturing processes and technical expertise. Consequently, significant distortion of the metallic work-part used in its testing was observed.

4.4 Elbow Movement

Since a stepper motor was used, the rotation movement of the elbow about the base was in steps with a step angle 9º in both clockwise and anticlockwise directions. Continuous rotation could have been achieved if an appropriate servo motor had been used. The elbow movement in forward and reverse rotation was smooth and stable, with the elbow completing its maximum dexterity in each direction in a fraction of a second.

During the testing, it was observed that the robot could carry a maximum of 550g while maintaining satisfactory movements as opposed to the anticipated 800g, based on the design. Generally, there was not much significant deviation between the desired and actual performance of the robot.

5. CONCLUSION

This work has demonstrated the ability to control the motion of a robotic system using DTMF tones. With the current wide range of coverage of GSM networks globally and the high level of compatibility of all service providers, this project would have a wide field of applications for industrial and domestic usage. The simplicity in the design and availability of the materials used in the design makes it practicable. Its good response characteristics make it suitable for operations that require high accuracy, precision, predictability, repeatability, and reliability. Moreover, the total cost of building, testing and installing such systems is small, compared to its benefits. Its real-life applications will be cheap and economically viable.

It is recommended that further research should be made to incorporate sensor technology, better design of the control system with good feedback and compensation circuits, use of composite materials to minimize inertia problems and optimize speed of response, direct user interface for easy programming and reprogramming, use of artificial intelligence, fuzzy logic and chip technology.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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