Robotic Arm Plotter (RAP)

Project Guide:
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***Abstract*—Robotic arm plotter (RAP) is capable of plotting a graph or an image. Its light weight and easy to install design, makes it a good replacement to the conventional Computerized Numerical Control (CNC) plotters. Our design enables the RAP to plot effectively in vertical as well as in horizontal alignment.**

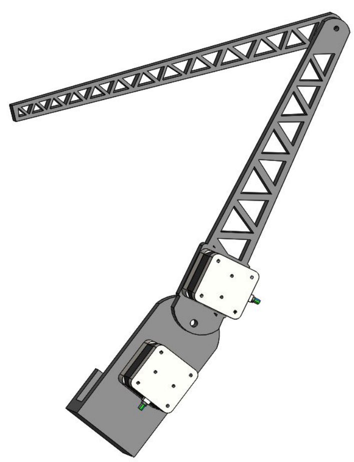


Fig. 1. RAP hardware model

I. INTRODUCTION

Unlike a conventional CNC plotter, Robotic Arm Plotter has a superior design which makes it a light, portable, carry anywhere printing device. In addition to this, RAP design would be a much cheaper one when compared to conventional printers or projectors. The idea of this device comes from a conventional CNC plotting machine, which uses a 2 -axis motion to plot images on its fixed surface. Conventional CNC design also doesn't allow it to plot on vertical surfaces, and the scalability factor is also absent. The device model is as shown in Fig. 1.

Prevalent methods to show complex diagrams in classrooms is done using projectors and screens. This setup is very expensive and usually out of reach for most schools in rural areas. In this premise comes one of the major applications of our device. .

II. LITERATURE REVIEW

Linyan Liu et al. (2014) presents a knowledge-centric process management framework for the CNC machine tool design and development (DD) with the integration of process and knowledge. Requirements for the framework are generated based primarily on the nature of the machine tool design practice. The proposed framework consists of process integration model, process simulation, process execution and knowledge objects management modules. The results of this study significantly contribute to efforts to achieve knowledge and process integration in CNC plotter [1].

The paper ”Development of a stereolithography (STL) slicing and G-code generation algorithm for an entry level 3-D printer” [2] deals with stereo-lithography (STL) slicing and G-code generation, which serves as a data front-end for an entry level three-dimensional (3-D) printer.

In order to develop a completely new design, some of the best existing today and the problems they faced were studied. The paper ”Design and Analysis Mini CNC Plotter Machine” [3] clearly laid out the principles and ideas they had used while designing their mini CNC plotter, and the drawbacks mentioned in this paper. Dr. J.B. Jayachandraiah et al (2014) provide the idea to develop the low cost Router system which is capable of 3 axis simultaneous interpolation [4].

III. HARDWARE

Basic block diagram of the model is given in Fig. 2. The hardware of Robotic Arm Plotter consists of the following.

Arms:
The arms cover the majority of the hardware. So, it is essential to reduce the weight and cost of the arms for an optimal design. In RAP 1.4, the parts were cut out of 2mm mild steel. Since this material is on the heavier side with a density of 7.85 g.cm^{-3}, a triangular framework structure is used to minimise the weight without compromising on the strength.

Two Independent Steppers:
In order to reach every single point on the surface where the device is expected to plot, two high precision steppers (Nema 17 Table.I) with 1.8 degree step angle are used. These steppers are controlled using A4988 drivers.

Writing Device Operator:
This is the most important and sophisticated piece of hardware, which is used to manoeuvre the writing device, which is currently modelled using a micro-Servo attached to

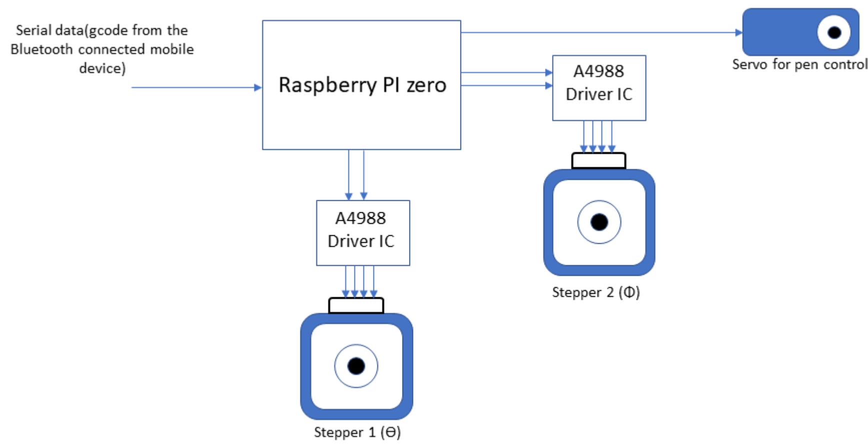
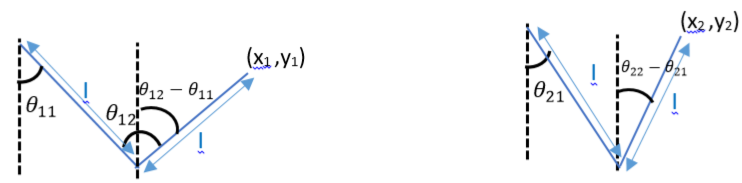


Fig. 2. Block Diagram of RAP hardware



$$x_1 = l\,\sin\theta_{11} + l\sin(\theta_{12} - \theta_{11})$$
$$y_1 = l\,cos\theta_{11} - l\,cos(\theta_{12} - \theta_{11})$$

$$x_2 = l\,\sin\theta_{21} + l\sin(\theta_{22} - \theta_{21})$$
$$y_2 = l\,cos\theta_{21} - l\,cos(\theta_{22} - \theta_{21})$$

Fig. 3. Conversion from the Cartesian system to two angle system

a cylindrical structure, holding the pen/chalk/marker.

Clamp:
It is a mild steel plate designed to hold on to the surface and keep the device stable. This part will also host our processor, the drivers and one of the high precision steppers. Basically, it houses almost all the device's electronics. It can be tightened to any board using two tightening screws provided at the back.

Processor:
Raspberry Pi Zero is used for processing the image as well as converting the Gcode obtained to motor commands which will then be sent to the motor driver IC A4988, through the GPIO pins of the Pi Zero. The connection to the proceesor is as shown in Fig.4.

Drivers:
A4988 drivers is used to manoeuvre the steppers. A4988 was chosen over others, like DRV8825 and L297 because of its superior current controlling characteristics and features such as adjustable current limiting, over-temperature protection, and five different micro-step resolutions (down to 1/16-step).

IV. SOFTWARES

A. *Android Studio*

A user-friendly android application is modelled with Android studio. It uses a mixture of JAVA and XML codes. Layouts are usually defined using XML, and can include GUI components such as buttons, text fields, and labels. Layouts only define the appearance of the app. What the app does and the logic used are based on Java code [5]. The User controls the device through an android application, in which the user have the following options (as shown in Fig.5)

INSERT IMAGE: On clicking the option, it gives two other options to select action:

- Select photo from gallery: It triggers a new intent ”ACTION_PICK” and opens a gallery, from which the photo can be selected accordingly.
- Capture photo from camera: It triggers the intent ”ACTION_IMAGE_CAPTURE” and opens camera.

INSERT TEXT: It is to type anything on the board. The text input is given to this and it converts it into image, so that all options have a standard png output.

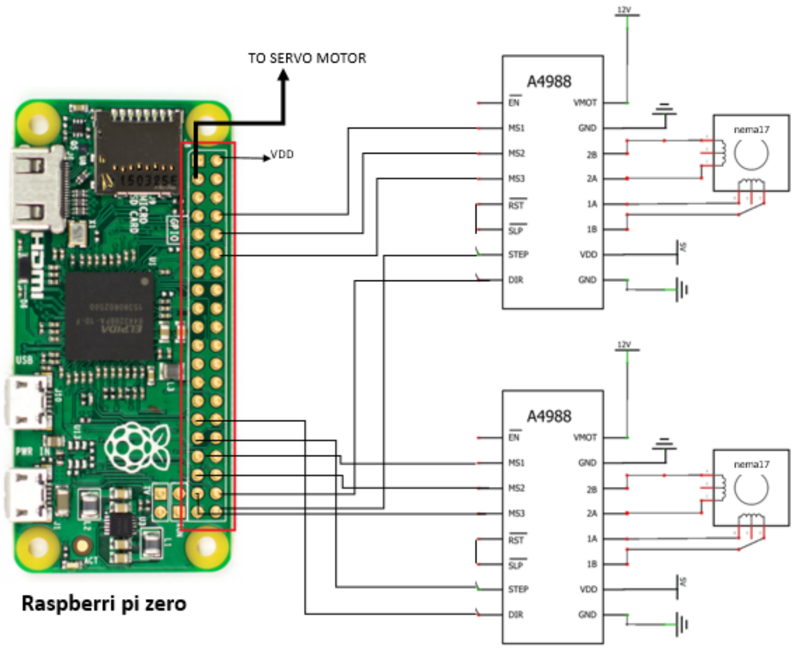


Fig. 4. Circuit diagram

DRAW: It opens a canvas to draw upon clicking "DRAW" icon in the screen. It opens a new activity named as "Canvas-Activity". It is implemented using the android library "DrawingView". This DrawingView is added to 'CanvasActivity'. The image of the drawing will be stored temporarily upon clicking 'PROCEED'.

PROCEED: The image fetched/captured/drew through this methods can be sent to the receiver by clicking on the "PROCEED" button. It triggers "ACTION_SEND" intent. And asks for different options to send.

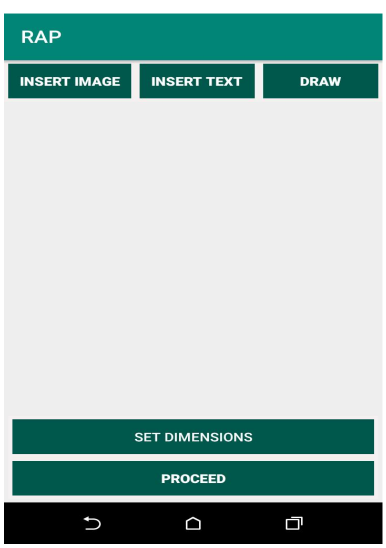


Fig. 5. Screenshot of Android Application

B. *Inkscape*

Inkscape is a free and open-source vector graphics editor. This software is used to process the image (converting to greyscale, detecting the boundaries etc.) and to finally convert it to Gcode for testing purposes.

C. *SolidWorks*

Solidworks is a CAD software mainly used for 3D modelling. It has several functionalities including an option to simulate strains and tear with changes in material properties etc. Solidworks was used to conceptualise the plotter and test the effectiveness of different design configurations. For instance different ways were tried to move the second part of the plotter arm, like keeping the stepper motor on the first arm in order to reduce the stress on the frame etc. It was also used to come up with a modular design which was found to be impractical upon further contemplation, because of monetary constraints [6].

For the last design iteration, Solidworks is used to figure out the material mass and the centre of mass.

V. Conversion from Cartesian to angular system

The Gcode interpreters in python usually gives Cartesian coordinates as output. But here, it has to be changed to angular system inorder to move the stepper motor appropriately as modelled as in Fig. 3.

$$x = sin(\theta_1) + sin(\theta_2 - \theta_1)$$
$$y = cos(\theta_1) - cos(\theta_2 - \theta_1)$$

From these 2 equations,

$$\theta_1 = 2\arctan(\frac{2x \pm \sqrt{(4-(x^2+y^2)).(x^2+y^2)}}{x^2+y^2+2y})$$

$$\theta_2 = \pm 2\arctan(\sqrt{\frac{-(x^2+y^2)}{x^2+y^2-4}})$$

These are used to find the angle to be rotated for the first and second motors respectively, for plotting.

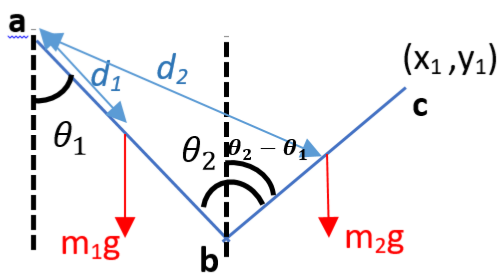


Fig. 6. Mathematical model of the device.

VI. Mathematical Model of Device

To understand what torques need to be generated by the actuators at the joints to produce a desired force at the tip of writing device and to rotate the arms, a general model of the robotic arm was analyzed.

In the Fig.6, **'ab'** represents the model of the first arm and **'bc'** represents the model of the second arm of the device.

To make the arms move, the applied torque should be greater than the torque due to its weight and friction.

Let the mass of the first arm, second arm and second motor (which is placed above first arm) be m_1, m_2, and M respectively.

To find the torque, the distance from the centre of mass from the axis is also needed. Let that distance be d_1, d_2, and D from the center of mass of the first, second arm and second motor respectively, to the axis of rotation (clamp). Then the equation for applied torque becomes,

$\tau >$ component of m_1g in perpendicular to first arm.d_1+ component of m_2g in perpendicular to first arm.d_2+component of Mg in perpendicular to first arm.D
From the fig.6,

$$\tau > (m_1g.d_1 + M.D).sin(\theta_1) + m_2g.sin(\theta_2 - \theta_1).d_2$$

So the torque specification required for the motor can be found by calculating the maximum possible torque. It can be safe to assume that the actuators in the arm will be subjected to the highest torque when the arm is stretched horizontally, i.e, when both the arms are horizontal to the writing board. Thus, the required torque is,

$$\tau > max((m_1.d_1 + M.D)g.sin(\theta_1) + m_2g.sin(\theta_2 - \theta_1).d_2)$$

$$\tau > m_1g.d_{1max} + M.D_{max} + m_2g.d_{2max}$$

In these cases, impact of friction on torque is completely ignored. But if the coefficient of friction (μ) or normal reaction (N) is significant, this term also need to be considered.

$$Torque_{friction} = \mu \cdot N \times distance$$

The above equations only deal with the case, where the arms are being held horizontally (not in motion). This is not necessarily the "worst case" scenario. For the arm to move from a rest position, an acceleration is required. To solve for this added torque, it is known that the sum of torques acting at a pivot point is equal to the moment of inertia (I) multiplied by the angular acceleration (α).

$$\tau = I\alpha$$

Where I is moment of inertia and α is angular acceleration. Now, taking the worst-case, i.e, arms are in horizontal position, the torque will be,

$$\tau_{max} = (I_{twoarms} + I_{secondmotor})\alpha$$

Assuming arm as a perfect plate and motor as a cube, and equal weights for both arms, the moment of inertia about one end is,

$$I_{arms} = \frac{2 \cdot m \times (a^2 + b^2)}{12}$$

where a and b are length and breadth of the arm respectively. For cube (motor), the moment of inertia about the centre through the centre of two sides is,

$$I_{arms} = \frac{m \times (d^2)}{6}$$

where d is the length of a side of the cube.

VII. Calculations

Model	NEMA 17
Weight (gm)	375
Dimensions (mm) LxWxH	42x42x48
Holding torque (KgCm)	5.6

TABLE I
SPECIFICATIONS OF THE MOTOR USED

The motor used in all models designed are NEMA 17 and the specifications as given in the table. I. Let 'M' denotes mass of the motor and 'D' denotes the distance from the axis of rotation (clamp) to the centre of mass of the motor. From the table. I

$$M = 350g$$

A. RAP 1.1

It was modelled with wooden arms and second motor placed at the end of the first arms as shown in Fig. 7. The model was an utter failure since the torque calculations were not made properly.

$$Mass\ of\ each\ arm = m_1 = m_2 = 28g$$

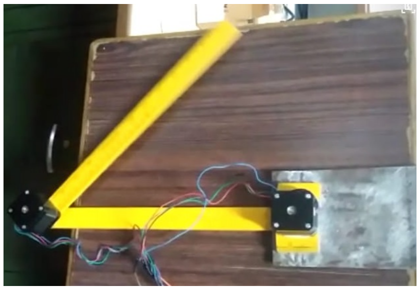


Fig. 7. RAP version 1.1

$$Length\ of\ each\ arm = l_1 = l_2 = 40cm$$

Centre of mass of both arms are at the centre of arm, i.e, at $\frac{l_1}{2} = \frac{l_2}{2}$ for first arm and second arm respectively. Since the motor is placed at the end of the first arm,

$$D = l_1 = 40cm$$

When the arms are kept horizontally and assuming the mass of the arms are uniform in nature,

$$d_{1max} = \frac{l_1}{2} = 20\ cm$$

$$d_{2max} = l_1 + \frac{l_2}{2} = 60\ cm$$

$$Torque\ required, \tau = D \cdot M + d_{1max} \cdot m_1 + d_{2max} \cdot m_2$$

$$= 17240\ g.cm\ = 17.24\ kgcm$$

But the motor could only provide a torque of 5.6 kgcm (From table. I).

B. RAP 1.2

It was also modelled with wooden arms, but the motor was placed at a 8.5cm distant from axis on the first arm and a belt was fixed from that motor to control the second motor, so that the torque due to the motor will reduce significantly.

$$l_1 = l_2 = 40cm$$

$$m_1 = m_2 = 28g$$

$$D = 8.5cm$$

Assuming the mass of the arms are uniform in nature,

$$d_{1max} = \frac{l_1}{2} = 20cm$$

$$d_{2max} = l_1 + \frac{l_2}{2} = 60cm$$

$$Torque\ required, \tau = D \cdot M + d_{1max} \cdot m_1 + d_{2max} \cdot m_2$$

$$= 5427.5\ g.cm\ = 5.4275\ kgcm$$

Even though the calculated torque was less than the maximum torque of motor,i.e, 5.6 kgcm, first arm was very very slow and was not able to reach even 15° from the resting position. It was because in the calculations, the role of friction was not considered.

Coefficient of friction(μ) between wood and cast iron is 0.59 approximately.

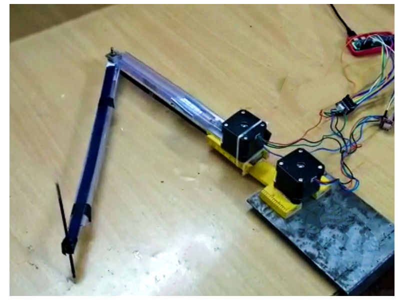


Fig. 8. RAP version 1.3.

C. RAP 1.3

This was a quick modification of RAP 1.2 (as shown in Fig. 8), $1/3^{rd}$ of the first arm was wooden and the other part with hollow polycarbonate tubes, which is much lighter than wood. For stiffness of second arm, a cast iron rod was also integrated with the polycarbonate tube. Also, the length of the arms were reduced to 30 cm.

$$l_1 = l_2 = 30cm$$

Length of wooden part in 1^{st} arm, $l_{wooden} = 10\ cm$
Length of hollow polycarbonate part in 1^{st} arm,

$$l_{hollow} = 20\ cm$$

Mass of wooden part in 1^{st} arm, $m_{wooden} = 7\ g$
Mass of hollow polycarbonate part in 1^{st} arm,

$$m_{hollow} = 8\ g$$

$$m_1 = m_{wooden} + m_{hollow} = 15\ g$$

$$m_2 = 29g$$

$$D = 8.5cm$$

$$d_{1max} = \frac{m_{wooden} \times \frac{l_{wooden}}{2} + m_{hollow} \times [\frac{l_{hollow}}{2} + l_{wooden}]}{m_{wooden} + m_{hollow}}$$

$$= 13.8235\ cm$$

Assuming the mass of the second arm are uniform in nature,

$$d_{2max} = l_1 + \frac{l_2}{2} = 45cm$$

$$Torque\ required, \tau = D \cdot M + d_{1max} \cdot m_1 + d_{2max} \cdot m_2$$

$$= 4699.8525g.cm\ = 4.7kgcm$$

This model worked properly, but it was not rigid.

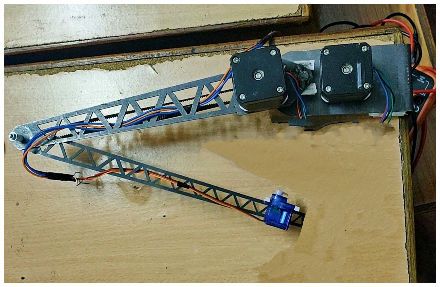


Fig. 9. RAP version 1.4

	First arm	Second arm
Volume (cm^3)	11.508	74.14
Centre of Mass (cm)	12.05	13.12
Mass calculated (g)	90.344	48.204

TABLE II
SPECIFICATIONS OF ARMS

D. RAP 1.4

Currently working with RAP 1.4 model, which is designed with mild steel. Here, the length of the arms are set to 28 cm and the second motor is placed at 4 cm from the axis of rotation 9.

$$D = 4cm$$

The density of mild steel is 7.85 gcm^{-3}.

From the results obtained from Solid works, which is given in the table. II.

$$d_{1max} = 12.05cm$$

$$d_{2max} = l_1 + 13.12 = 41.12cm$$

The torque calculated using these results is,

$$Torque, \tau = 4570\ kgcm$$

VIII. CURRENT STATUS

The following points emphasize the work that has been successfully completed.

- Designed and finalized the most optimal structure for device using Solid works software.
- Constructed a beta model capable of plotting simple 2D images.
- Studied basics of Android studio and implemented an android application •To take an image from device folders •To capture image by using camera •In-app drawing facility •To transfer the image to the raspberry pi 0 for controlling the plotter.
- Converted the gcode to motor instructions and testing and improving accuracy.
- Developed an algorithm to convert gcode to two variable angles system and implemented in python2.7.

IX. CHALLENGES FACED AND OUR APPROACH

Initially, nodeMCU was chosen as the controller. But, there were no JAVA script libraries that would convert images to Gcode. Thus, the entire conversion is done on the plotter itself, making it a completely independent unit. In order to achieve that objective Raspberry pi zero was chosen as replacement for NodeMCU because of its superior processing capacity.

When we shifted from nodeMCU from Raspberry Pi Zero, we had to basically rewrite the entire code base, as the nodeMCU works with arduino IDE and the coding was mostly in C, where the libraries are more specific and readily available. Converting the entire system to python 2.7 was a very difficult and time consuming task. Since the libraries used in python are way more general and are not actually written for real time devices with extensive hardware support like our Plotter, we had to put in lot of original code work there. At the time of implementation, we can say with conviction that this is one of the first plotters working on ARM based processors like Raspberry Pi.

Another major challenge was properly designing the parts, we had to go for 4 design iterations to come up with the final design.

X. WORK PLAN

1) **Optimising the algorithm**: Optimising the algorithm for selecting the shortest method to achieve a continuous curve.
2) **Updating the app**: Updating the RAP app to incorporate all the planned input options like direct image from device, draw live on screen, etc.
3) **Implementing splining**: Implementing the splining function which will join the input points to form a continuous curve hence enable the plot function in the app.
4) **Enabling multiple writing devices**: Modifying the 6th part such that the hardware will be able to support multiple writing devices.

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