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Design and Construction of a Three-Axis Automated Drilling Mechanism with Depth Controllability

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ABSTRACT
To increase the quality and quantity of products current development in the industry has been towards computer-controlled manufacturing process. Manual manufacturing of such items as the wood workpiece or circuit board or metal sheets will have a big faulty case and uneven quality. This proposed drilling machine is designed to drill the holes automatically over a job according to the drilling depth and co-ordinate data programmed through a controller. The goal was to implement an automated drilling mechanism using the automation process for the workpiece movement. The concept of integrating sensor-based controlling with adaptive feedback control allowed the mechanism towards multiple drilling. The depth controllability function allowed drilling with variable depth for each drilling operation within the workpiece thickness. Exploring with CNC system provided control over functions and motions of the machine tool through coded alphanumeric data. Ultimately reducing human effort and time consumption while implementing better accuracy for the small-scale industry is what makes this paper through.

Keywords: Automated drilling, CNC, depth controllability, path planning, reducing human effort etc.

1. Introduction
Manual drilling is one of the important manufacturing operations where lots of error could happen. To mitigate this,an automatic process is presented here. The entire process falls under the subject of mechatronics & various fields of technologies must be included to full-fill the target. The integration of electronic engineering, mechanical engineering & control technology is forming a crucial part in this design. Especially the control circuit design plays a dominant role in this work. The automation operation is done with IDE (Integrated Development Environment). The main aim of the project lies in interfacing or in simple words, is to make a mechanical system work by making use of a personal computer of basic configuration. This project is carried on keeping in mind the needs of a small-scale industry, which need small sized components in a few numbers, which by other processes would cost more emphasizing the time required for manual operation. The only thing the operator needs to do is to input the coordinates of the drilling points allowing multiple drilling points (in both x,y-axis) with special depth controllability whereas some previous works emphasized on only 1 axis for workpiece movement thus ensuring the difference of the project [1].

2. Background theory
For the background theory, there are two main prospects presented here. They are drilling process and automation part.

2.1 Drilling
By definition, drilling is a cutting process that uses a drill bit to cut a hole of circular cross-section in solid materials. The drill bit is usually a rotary cutting tool, often multipoint. This forces the cutting edge of the drill bit against the workpiece, cutting off chips from the hole as it is drilled. So in simple words, the rotating edge of the drill exerts a large force on the workpiece and the hole is generated.

2.1.1 Drilling Machine Types
There are many types of drills. They can be classified according to many types. According to source power:
1. Manual Powered
2. Energy Powered (Electricity, compressed air, Internal combustion engine)

Some examples of manual powered drills are bow drill, eggbeater drill, Persian drill, gimlet drill. Whereas, pistol grip drills, magnetic drilling machine, rotary hammer drill, drill press are some common form of energy powered drill.

2.1.2. Drill bits
Drill bits are cutting tools used to remove material to create holes, almost always of circular cross-section. Drill bits come in many sizes and shape and can create different kinds of holes in many different materials. In order to create holes, drill bits are attached to a drill, which powers them to cut through the workpiece, typically by rotation.
Basic drill bit nomenclatures: [2]
Axis: Imaginary straight line that forms the center line of the drill.
Body: Portion of the bit extending from the end of the flutes to the outer corner of the cutting edge.
Drill Diameter: The diameter over the margins over the margins of the drill measured at the point.
Body diameter clearance: The portion of the land that has been cut away so it will not bind against the walls of the hole.

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Other important nomenclatures are flutes, back taper, drill margin,and margin width etc.

2.1.3. Drilling Process

Important drilling process nomenclatures are cutting speed, spindle speed, feed rate, depth of cut etc. [3]

2.2 Automation

The term automation, inspired by the earlier word automatic (coming from automaton), was not widely used before 1947 when Ford established an automation department. [4]

Automation or automatic control is the use of various control systems for operating equipment such as machinery, processes in factories, boilers,andheat-treating ovens, switching on telephone networks, steering,and stabilization of ships, aircraft,and other applications and vehicles with minimal or reduced human intervention. [5]

Now, when it comes to the automation process with machinery it requires a computer to control. This is the starting phase of Computer Numerical control or CNC.

2.2.1 Computer Numerical Control (CNC)

Computer numerical control is the automation of machine tools by means of computers executing pre-programmed sequences of machine control commands. This is in contrast to machines that are manually controlled by hand wheels or levers, or mechanically automated by cams alone. [6]

The applications of CNC include both for machine tools as well as non-machine tool areas.

The benefits of CNC are high accuracy in manufacturing, short production time, greater manufacturing flexibility, simple fixture, contour machining, reduced human error. Though negligible CNC has also some drawbacks which include cost, maintenance, and the requirement of the skilled part programmer.

2.2.1.1 Elements of CNC

i. Part program
ii. Machine control unit (MCU)
iii. Machine tool

i. Part Program: The part program is a detailed set of commands to be followed by the machine tool. Each command specifies a position in the Cartesian coordinate system (x,y,z) or motion (workpiece travel or cutting tool travel), machining parameters and control functions.

ii. Machine Control Unit: The machine control unit (MCU) is a microcomputer that stores the program and executes the commands into actions by machine tools. It consists of two main units:

a. Data Processing Unit (DPU)
b. Control Loops Unit (CLU)

The DPU software includes control system software, calculations algorithms, translation software that covers the part program into a usable format for the MCU. The DPU processes the data and provides it to the CLU. The CLU operates the drives attached to the machine leadscrews and receives feedback signals.

iii. Machine tool: The machine tool could be one of the following: lathe, drilling, milling, laser, plasma etc. Its motion has to be controlled.

2.2.1.2 Principles of CNC

i. Point to point system:

The point-to-point system is those that move the tool or the workpiece from one point to another and then the tool performs the required task.

ii. Continuous path cutting:

These systems provide continuous path such that the tool can perform while the axes are moving, enabling the system to generate angular surfaces, two-dimensional curves or three-dimensional contours. Example: - an automated milling machine.

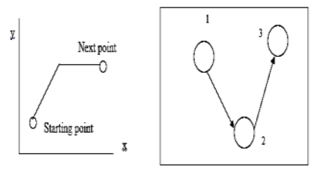

Fig.1 Point to point cutting system

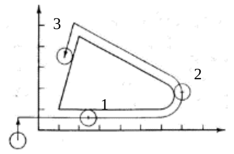

Fig.2 Continuous path cutting

As shown in Fig. 1 the operational points are 1,2 & 3. But the path between 1-2 or 2-3 does not have any machining operation in point to point cutting system. On the other hand, in Fig.3 between cutting point 1 and 3 in point 2 there is a curved feature that has to be done while moving the cutting tool from 1 to 3 and this is called continuous path cutting.

iii. Incremental & Absolute system:

In incremental mode, the distance is measured from one point to the next. In the absolutesystem, all the moving commands are referred from a reference point (zero points or origin)

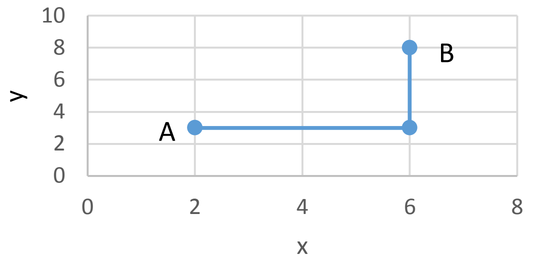

Fig.3 Incremental and absolute system

To go to point A (2, 3) to B (6, 8), in incremental, the move is specified by x=4, y=5 giving the distance of point B in respect of point A.

Whereas in absolute positioning the move is specified by x=6, y=8 which is calculated from a reference point (0,0) though the cutting tool moving from point A.

iv. Open loop and closed loop control system:

The open-loop control means that there is no feedback and uses stepping motors for driving the lead screw. A stepping motor is a device whose output shaft rotates through a fixed angle in response to an input pulse.

2.2.2 Hardware for automation

In automation, process hardware plays a vital role. So it needs to fulfill some requirements, such as powerful flexible products, built-in redundancy, the point of measurement, secure, redundant data reading, energy management solutions, and secure data recording. And also, another important criterion is to have embedded technologies to meet requirements.

2.2.3 Software for Automation

The software is the second most important part required for automation. In this thesis work for automation as a software suite IDE was used. An integrated development environment (IDE) is a software application that provides comprehensive facilities to computer programmers for software development. An IDE normally consists of a source code editor, build automation tools and a debugger. Most modern IDEs have intelligent code completion. Some IDEs, such as NetBeans and Eclipse, contain a compiler, interpreter, or both; others, such as SharpDevelop and Lazarus, do not.
IDEis designed to maximize programmer productivity by providing tight-knit components with similar user interfaces. IDEs present a single program in which all development is done. This program typically provides many features for authoring, modifying, compiling, deploying and debugging software. This contrasts with software development using unrelated tools, such as vi, GCC or make.
Some IDEs are dedicated to a specific programming language, allowing a feature set that most closely matches the programming paradigms of the language. However, there are many multiple-language IDEs.

3. Design & Automation requirements

Design:
The basic principle for the construction is based on the disc cutting tool position and workpiece movement based on drilling coordinate. Workpiece movement will be carried out by the following two systems:
i. Point to point positioning system
ii. Incremental system

3.1 Components

Table 1 shows the basic components that are required.

Table 1 Required components

Constructional components	Hardboard
	Wooden structure
	Light but strong rope
	Screws
	Pulley(Material: Nylon shaft)
Electrical components	DC gear motor
	Arduino Mega 2560
	Motor driver
	Breadboard
	Distance measurement sensor
	Jumper wire
	Power supply

3.2 Conceptual View

This is the basic conceptual 3-D view of the construction project.

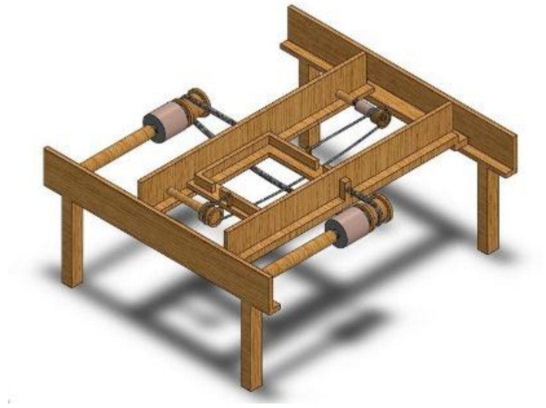

Fig.4 Workpiece controlling portion

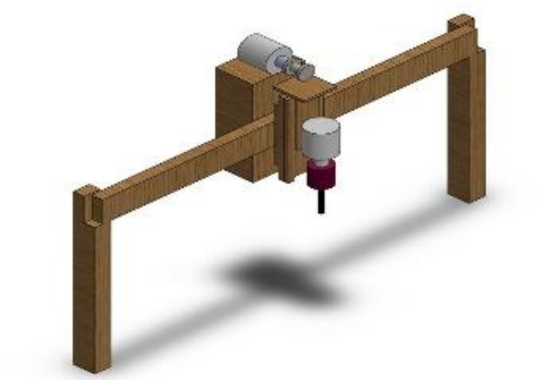

Fig.5 Drill bit holder

Fig. 4 shows the basic structure of the whole setup. It is made of wood and hardboard. There are in total 4 motors in this setup dividing by 2 for x and y-direction. The hardboard structure holds the workpiece and its movement in controlled by motors. Then this whole part consisting of hardboard, workpiece, motors moves by rest of the two motors.
Fig. 5 shows the drill bit holder which rests upon the setup of Fig.1. It consists of two motor, one for depth control and another for drill chuck.

3.3 Assumptions

For the construction following assumptions were taken:
Workpiece material cork sheet
Workpiece thickness= 1.5 inches or 3.3 cm
Workpiece dimension = 23*22 cm
Workpiece cutting area = 18*18 cm
Standard safety factor for motor selection = 10%
Linear velocity of workpiece movement v = 4cm/s
The workpiece material was chosen cork sheet because of its availability and scope of the easy drilling operation. All dimensions were taken in account of

keeping the whole setup in the feasible and compact state. For the convenient operation on the woodsurface, the workpiece movement velocity ‘v’ was chosen by trial and error method. The concerned factors for this were surface roughness of wood, state,and integrity of connecting ropes, the visible vibration of the setup etc.
According to the Cartesian coordinate for positioning the middle point of the workpiece was considered origin. So, the cutting area is now divided into four quadrants. According to this now the workpiece has to be free to move at least 9cm in all four directions (positive and negative x, y).

3.4 Torque and specification selection

For x-axis movement
Now the setup for x-axis mass m_x= 0.61 kg
Workpiece mass m_w= 0.003 kg
So, total weight required to move by x-axis motor w_x= (0.61 + 0.003) * 9.8 N
= 6.0074 N
In the vertical direction, the normal force must be equal and opposite of the weight. As the motor will rotate in zero acceleration so,
Force required to overcome static friction (f_s) and kinetic friction ($f_{k);}$
$f_s= \mu_s * w_x$
= 0.3 * 6.0074 N = 1.802 N

$f_{k=} \mu_k * w_x$
= 0.2 * 6.0074 N = 1.2014 N
Where, for movement of wood on wood
Static friction co-efficient μ_s= 0.3
Kinetic friction co-efficient μ_k= 0.3
When the distance of the workpiece from the motor (9 cm) will be maximum torque required will be maximum.
So, the maximum torque required
= (1.802 * 0.09) Nm
= 0.1622 Nm
(Considering static force for its higher value)
Now x-axis motor torque, pulley diameter and the linear speed of the motor can be calculated fromthe following equation

$$T_x=\frac{I*V*E*60}{N*2\pi}$$

Where,
T_x = Motor torque = 0.1622 * 1.1 = 0.18 Nm (Considering 10 % safety factor)
I = Rated Current = 0.6A
V= Supply voltage = 12V
E= Motor efficiency = 10%
N= Motor rpm
So, N = 38 rpm
And, from the equation

$$N=\frac{60*v}{\pi*D}$$

So, pulley diameter Dx = (60 * 4) / ($\pi * 38$) = 2 cm

For y axis movement
Now the setup for y axis mass m_y = 1.235 kg
W_y = 1.235 * 9.8 = 12.103 N
As previous,
$f_s= \mu_s * w_y$= 0.3 * 12.103 = 3.6309 N
$f_{k=} \mu_k * w_y$ = 0.2 * 12.103 = 2.4206 N
So, mtheaximum torque required would be
= (3.6309* 0.09) Nm
= 0.3267 Nm
So, T_y = 0.3267 * 1.1 = 0.36 Nm
Holding the same values for I, V and E as previous the equation $T_x=\frac{I*V*E*60}{N*2\pi}$, provides
N = 19 rpm
For same linear velocity v,we get,
Pulley diameter D_y = 4 cm

For z axis movement
This is the setup for z axis movement which will be controlled by dc motor. The drill motor with drill chuck will be set as shown
As the work piece is just a model made of cork sheet drilling thrust force requirement can be neglected as the gravitational force will take care of it.
Now, the total mass of the drilling equipment with other necessary parts that the motor has to lift in the z-direction is m_z = 700 gm = 0.7 kg
So, w_z = 0.7 * 9.8 = 6.86 N which is in the very close vicinity of the dead weight for x-axis motor.
So, same configuration motor can be used here.

3.5 Automation Components
Arduino Mega 2560

Table 2 Specification of Arduino Mega

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (limit)	6-20V
Flash Memory	256 KB
SRAM	8 KB
Clock Speed	16 MHz

Motor driver
L298N series motor driver
It’s an integrated monolithic circuit in a 15-lead Multiwatt and PowerSO20 package.
Ultrasonic sensor
A HC-SR04 Ultrasonic sonar sensor was selected. Ultrasonic ranging module HC - SR04 provides 2cm - 400cm non-contact measurement function, the ranging accuracy can reach to 3mm. The Module automatically sends eight 40 kHz and detect whether there is a pulse signal back

$$\text{Distance}=\frac{\text{velocity of sound(340 m/s)}*\text{time took}}{2}$$

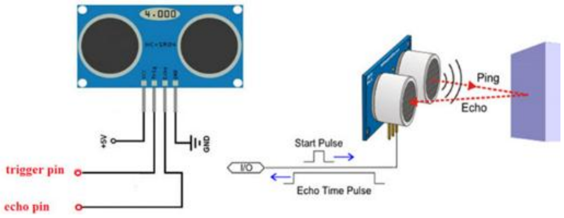

Fig.6 Operation of Ultrasonic sensor

3.6 Circuit diagram

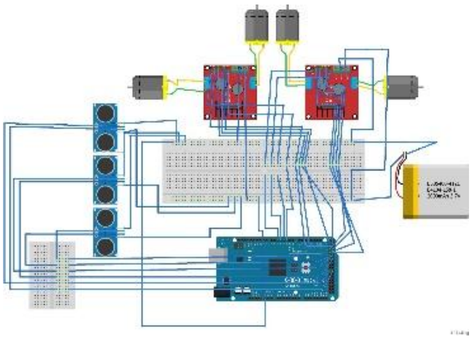

Fig.7 Circuit diagram

3.7 Part program or coding

For the operation, the whole code is written in IDE environment which is compatible with Arduino applications.

4. Working principle

One of the basic objectives of this work is to maintain simplicity in action. So, to perform a whole drilling operation the operator has to enter the following parameters:

1. Number of holes to be made
2. Each hole co-ordinate
3. Each holes depth (if variable)

The whole setup could be set on anywhere including upon something or just in the floor as the whole setup has its own support stand. Then after connecting the power source and computer, the program will be launched. The entry screen will appear now and after giving the entries and hitting start option the operation will start.

To carry out the whole operation, at first, the basic position will be obtained by entering the neutral position (0,0). Then for the first hole, the x-axis movement controller motor will start to rotate until the x coordinate of the first hole is right under the drill bit. Then the y-axis movement controller motor will start rotating similarly until the y coordinate of the first hole is positioned under the drill bit. In both case with Ultrasonic sonar sensor continuously variable distance will be measured at the 10-millisecond difference. After getting the desired value from the sensor motor will stop rotating.

After competition of rectilinear positioning, the drill bit will start to descend with drill bit rotates. When the desired depth will be reached then both descend controlling motor and drill motor will be stopped. Then the controlling motor will start ascending the drill motor (while drilling motor is rotating in opposite direction) and both of these two motors will be turned off when drill bit gets to its previous position.

5. Result and performance test

5.1 Result

Different observations are made for the performance test:

Table 3 Collected data

Observation 1:

No. of holes	Co-ordinate (in mm)	Depth (mm)	Drilled co-ordinate	Positioning Error (%) X	Positioning Error (%) Y	Drilled depth (mm)	Drilling depth Error %
3	30,60	33	30,62	0	3	33	0
	50,-40	15	48,-43	4	7.5	17	13
	-60,30	25	-60,31	0	3.3	28	12

Observation 2:

3	20,-10	25	22,-9	10	10	25	0
	30,-40	33	26,-41	13	2	33	13
	-15,40	33	-14,40	6	0	31	6.06

Observation 3:

2	-10,-10	33	-10,-13	0	30	33	0
	25,50	33	27,53	8	6	30	10

5.2 Error analysis:

From the above data:

An average error along x-axis movement

$$E_x = \frac{0+4+0+10+13+6+0+8}{8} = 5.125\%$$

Similarly, $E_y = 7.725\%$ & $E_z = 6.75\%$

The error analysis can be better shown with some graphical representation

Table 4 Error representation in graphical form

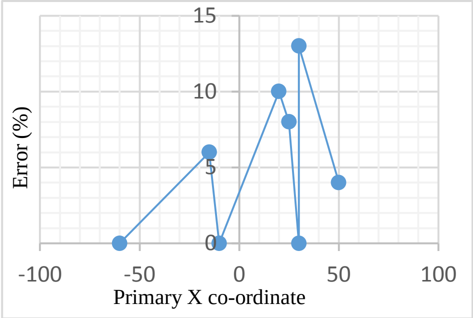

Fig.8 Error along x-axis movement

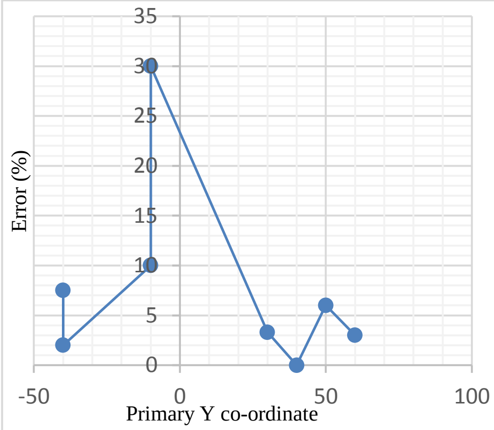

Fig.9 Error along y-axis movement

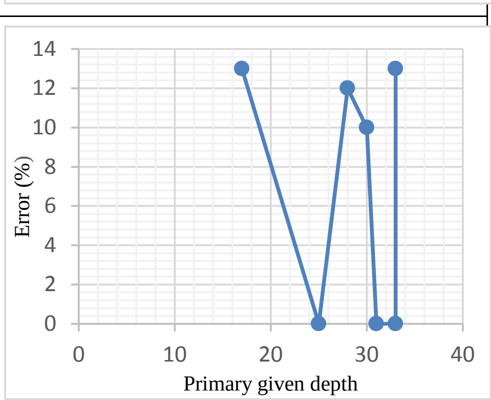

Fig.10 An error along z-axis movement

Fig.8 shows error along the x-axis is more when the position ison the positive side. It is basically due to some primary error in coinciding with the workpiece holder and workpiece mid-point.

Fig.9shows error along the y-axis movement is maximum around small values in the negative quadrant. Which is mainly due to the extra rope arrangement in this section.

Fig.10 shows around 6% error in average for almost all drill depth including full depth. It could be due to some technical problems of an ultrasonic sensor for this operation. And vibration in here also causes a lot of error.

6. Conclusion

The constructed automated drilling mechanism is a fine example of showing accuracy in drilling and fine controlling of motors for positioning. The purpose of implementing this project is to avoid the use of a CNC machine and robotic arms. The construction took almost BDT 6000 to finish the project which is not a great deal for personal or industrial level keeping in mind that it's wooden structure and error accepting. The usefulness of such type is to provide lost cost manufacturing process to the small-scale industries. Errors that might occur in manual drilling are totally eliminated with the 3-axis precise control of the drill head movements. So, drill bit positioning on a pad or breaking of tools is no more a problem. It can also be used in teaching institutes where actually the design and manufacturing system of CNC are taught to them.

NOMENCLATURE

f_S: Static frictional force
f_k: Kinetic frictional force
T: Torque
μ_s:Static friction coefficient
μ_k : Kinetic friction coefficient

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