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Design and fabrication of a Microcontroller Operated PV Pipe Bending Machine

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Abstract: This paper discusses the design fabrication and performance analysis of microcontroller operated pipe bending machine. The objective of this paper is to create a machine that allows for precision bending of pipes used in various applications such as photovoltaic (PV) installations, ensuring reduced material cost and enhance precision.

Keywords— Microcontroller, PVC pipe bending, automation, design.

I. Introduction

In recent years there has been significant increase in global adoption of renewable energy technologies, particularly photovoltaic systems. As government and industries push towards more sustainable energy solutions, the demand for efficient and reliable infrastructure to support these installations has risen. One key aspect of PV installation is the construction of support structures, often requiring bend pipes or frames. This bent pipe is not only essential for mounting PV panels but also find application of plumbing systems, automobile exhaust frameworks and custom-built machinery components. The accuracy and precision of these bends are crucial for optimizing material usage and insuring the stability and durability of structure.

Traditionally, pipe bending has been performed manually using mechanical or hydraulic machines, but these methods come with several challenges. Manual bending techniques are time-consuming, labor-intensive, and prone to errors due to human involvement. Inconsistent bending angles and inaccurate shaping lead to material wastage, which increases overall costs and can compromise the quality of the installation. This issue is particularly important in industries like PV installation, where precision is paramount. The need for an automated solution has led to the development of various type of pipes bending machines. These machines not only improve accuracy but also reduced the amount of human intervention required, thereby increasing productivity and reducing labor costs. Automation in pipe bending is crucial for industries that require high-volume production with minimal variation in quality. By automating the process, manufacturers can ensure more consistent results, decrease production time, and lower operational costs

Several studies have explored the benefits of automating pipe bending processes. Kumar and Sing [1], examined the impact of automation on bending accuracy in the construction industry, showing that automated systems achieved significantly better precision, reducing the bending angle error to ±0.5°, compared to ±2° in manual systems. Rao, Singh, and Kumar [2] analyzed hydraulic systems for automated pipe bending in the automotive industry and demonstrated a 15% reduction in material wastage and significant cost savings through improved process efficiency. Y., Zhang, and Chen [3] studied microcontroller-based automation in pipe bending, highlighting the importance of real-time adjustments in bending parameters to handle different pipe materials and sizes. Their findings showed that integrating a microcontroller system improves the adaptability and accuracy of the bending process.

Other researchers, like Siddhartha, Gupta, and Sharma [4], focused on the productivity benefits of automation, showing a 30% increase in output and a 20% reduction in rework due to consistent and precise automation. Additionally, Davis, Wong, and Li [5] examined how automation improves material efficiency by minimizing waste and rejected parts, which is particularly important in high-demand industries like renewable energy.

The work of Johnson, Kumar, and Smith [6] explored material optimization in renewable energy, finding that automated systems not only reduce operational costs but also support the growing demand for renewable energy infrastructure. Al-Amin et al. [7]highlighted the importance of bend radius, pipe diameter, and thickness in manual pipe bending machines, showing that even though manual methods are cost-effective, they lack the precision needed for large-scale production. Khalifa, Sarker, and Islam [8]focused on pneumatic pipe and rod bending systems, emphasizing the advantages of pneumatic automation in achieving accurate [1] [2]bends at varying angles. The use of electronic sensors allows for precise control over bending operations, enhancing efficiency in both small-scale and industrial applications. Moreover, Ncube and Mushiri [10] explored the development of a PVC pipe-cutting machine, showing that automation significantly increases production rates while improving precision and reducing material waste. Hossain et al. [8] emphasized the impact of automated systems in large diameter pipe production, showing how the integration of finite element modelling and process optimization leads to improved bending quality and reduced defects.

Given these advantages it is clear that adopting automated pipe bending technology can offer substantial benefits across various industries, especially in the rapidly expanding PV installation sector. The challenges posed by manual methods, such as inconsistency in the bend, material wastage, increased labor costs can be mitigated by implementing and automated pipe bending machine. These project aims to develop and fabricate a microcontroller operated PVC pipe bending machine tailored for various applications. By integrating a microcontroller with a hydraulic bending mechanism, the machine we offer precise control over the bending process ensuring that the required angles are achieved with minimal error and increased productivity.

II. DIE MOLD: A KEY COMPONENT IN PIPE BENDING

Die molds are essential component in pipe bending machines, ensuring precise and consistent bending of pipe across various applications.

For this project we have used pipes with three different diameters. 1 inch, 1.5 inch and 0.5 inch, for each pipe either different die mold is provided which is very costly or attachment is provided for a single die which reduces cost in large amount. So, we have used the latter option, in which interchangeable inserts are provided. The base die remains same, and you only swap the inserts to match the required diameter.

The die material must be strong and durable to resist wear during the bending process; hence the material used for die is mild steel or EN-8. After the die is machined, it is hardened to sustain the load and stress during the process of bending.

III. PROBLEM IDENTIFICATION AND OBJECTIVES

In many industries, the bending of PV pipes is a critical yet challenging process, often performed manually using heat and physical force. This traditional method suffers from several drawbacks:

- Lack of precision: Achieving the exact bending angle repeatedly is difficult, leading to errors and waste.
- Labor intensive: The manual process is physically demanding and time-consuming.
- Inconsistent result: Manual operations often result in varied quality, especially for complex or repeated bends.
- Risk of material damage: Excessive heat or improper force can weaken or break the pipes.

The objective of this paper is:

1. To design and fabricate a microcontroller-operated machine for the efficient and accurate bending of PV pipes.
2. To ensure repeatability and precision in bending operations.
3. To simplify the process, reducing operator fatigue and manual labor.
4. To develop a user-friendly interface that allows operators to input desired bending angles and parameters.

IV. METHODOLOGY

The methodology follows a structured approach to design, development, testing, and evaluation of the microcontroller-operated pipe bending machine.

1. Problem analysis: A thorough examination of the existing manual pipe bending methods was conducted, identifying the key limitations such as labor intensity, lack of precision, and material wastage.
2. Literature review: Studies on automated pipe bending systems, such as those conducted by Siddhartha et al. [4], Rao et al. [1], and Chen et al. [3], were reviewed to gather insights into the current advancements and possible improvements in the field of pipe bending automation.
3. Design development: Using solid works and other CAD tools, the machine was modelled with a focus on modularity, wase of maintenance, and optimal use of materials. The design was iterated based on stress analysis and simulation results to ensure reliability under operational conditions.
4. Material selection: Material for the machine’s component, including high- strength steel for the framework and hydraulic systems, were selected based on their durability and ability to withstand operational stresses.
5. Microcontroller programming: The machine’s hydraulic system was integrated with a microcontroller, which automates the bending process. The microcontroller was programmed to control bending angles, pressure levels, and timing, ensuring consistent results with minimal human intervention.
6. Prototyping and testing: A prototype of the machine was fabricated and subjected to extensive testing to validate the design. The bending angle, material integrity and operational efficiency were evaluated. Adjustments were made based on test results to enhance performance.
7. Final fabrication: After successful testing, the final version of the machine was assembled and prepared for field testing in a simulated industrial environment.

V. STEPS INVOLVED IN PROCESS OF BENDING

The pipe bending process involves several key steps to ensure that, pipes are bent to the correct dimensions and angle. Understanding these steps is crucial to designing the machine that automates the bending process efficiently and precisely.

1. **Cutting the pipe:** The process begins by cutting the pipe to the required length. This is done to ensure that the pipe fits into the bending machine properly, avoiding excess material that could interfere with the bending process.
2. **Positioning the pipe:** The pipe is then placed into the mold or bending die, which holds the pipe securely during the entire process of bending. Proper alignment is crucial to ensure a consistent bent thought the length of the pipe.
3. **Applying pressure:** The bending force is applied using hydraulic cylinders. The hydraulics system generates the pressure, which then transferred to the pipe by the means of die. Which further will take the shape of mold.
4. **Monitoring the bent:** During the bending process the angle and pressure are carefully monitor by the microcontroller to insure proper operation. Sensors detect the angle of the bend and adjust the pressure accordingly to maintain consistency.
5. **Releasing the pipe:** After the desired bend angle is achieved the pressure is released and the bend pipe is removed from the machine. The pipe is then inspected to ensure that it needs the specified dimensions and quality standards.

   These steps are designed to minimize human error and material wastage, ensuring that each bent is consistent and meets industrial standards.

VI. DESIGN AND MODELLING

The design and modelling of the Microcontroller Operated PVC Pipe Bending Machine are critical to ensuring that the machine operates efficiently and meets the required specifications. This section outlines the key design elements, modelling techniques, and software used to create the machine's components.

1. Base and support structure: The base is the foundation element of the machine, providing the stability and support to the other component. The base is made up of the high strength material (Cast Iron) capable of bearing various forces.
2. Upper and support plates: The upper and support plates are integral part of the machine structures providing support for the bending die. The assembly is held together using studs, nuts and various fasteners, maintaining the alignment of bending mechanism.
3. Design diagrams: Below shows the design diagram which shows the machine and its component.

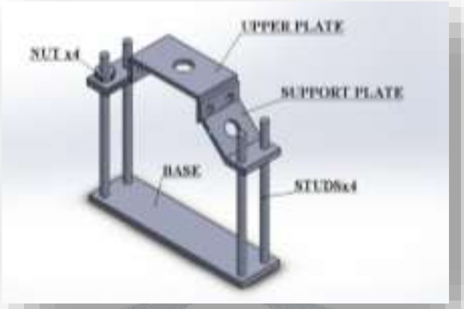

Figure 1: Assembly of PV pipe Bending machine

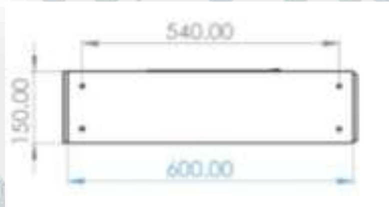

Figure 2: Bottom vie of machine with dimensions

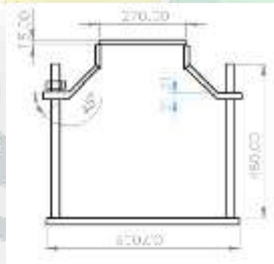

Figure 3: Front view of machine with dimensions

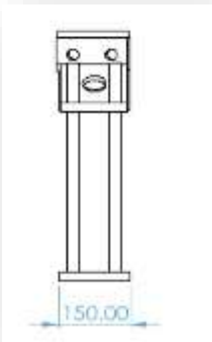

Figure 4:Side view of machine with dimensions

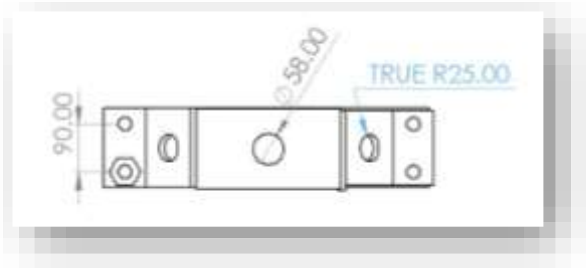

Figure 5: Top view of machine with dimensions

The design and fabrication of the pipe bending machine involves various components working in synchronization. The images below show the actual assembly of the microcontroller operated PV pipe bending machine, highlighting the key parts.

1. Hydraulic cylinders: Positioned at each arm these are responsible for the bending operation, applying the necessary force to the bend to the plastic pipe accurately.
2. Structural frame: The machine frame supports the hydraulic system and the mechanical components, ensuring that the bending process is stable and precise.
3. Guiding mechanism: These helps guide the pipe during the bending process ensuring the uniform bends.

Specifications of hydraulic cylinder:
Total three cylinder is used in this project, of specification listed below-
This cylinder will be used to press the male part of Mold or to press the die.

Parameter	Specification
Bore diameter	50mm
Rod diameter	25mm
Stroke length	300mm
Operating pressure	$359.8\times 10^3\ Pa$
Force capacity	Up to 20kN
Mounting type	Flange mounting
Material	High-strength alloy steel

Two separate cylinders will be used for expanding the diameter of pipe, of specification listed below-

Parameter	Specification
Bore diameter	50mm
Rod diameter	25mm
Stroke length	200-150mm
Operating pressure	$150\times 10^3 Pa$
Force capacity	Up to 10kN
Mounting type	Flange mounted
Material	High-strength alloy steel

VII. NOMENCLATURE

1. Bending moment calculation
    - *M:* Bending moment (Nm)
    - *P:* Applied load (N)
    - *L:* length of pipe segment (m)
2. Moment of inertia calculation
    - *I:* Moment of inertia (m^4)
    - *D:* Outer diameter of the pipe (m)
    - *d:* Inner diameter of the pipe (m)
3. Stress calculation
    - σ: Stress introduced in the material (Pa or MPa)
    - *M:* Bending moment (Nm)
    - *c:* Distance from the neutral axis to the outer fiber of the pipe (m)
4. Hydraulic pressure calculation
    - *P:* Hydraulic pressure (Pa or MPa)
    - *F:* Force exerted by the hydraulic system (N)
    - *A:* Area of the hydraulic cylinder (m)
    - *Dc:* Diameter of hydraulic cylinder (m)
    - *rc:* Radius of the hydraulic cylinder (m)
5. Temperature effects on PVC
    - *SF:* Safety factor
    - *T:* Temperature (°C)
    - σt: Stress at temperature (T)

6. Bending angle correction
   - *Θ:* Angle of bending (radians or degree)
   - *Δθ:* Spring back angle (radian or degree)
7. Force required for bending
   - *F:* Force required for bending (N)
   - *M:* Bending moment (Nm)
   - *r:* Bending radius (m)
8. Energy required for bending
   - *E:* Energy required for bending (J)
   - *Θ:* Angle of bend (radian)
9. Spring back angle calculation
   - *Δθ*: Spring back angle (radian)
   - *E:* Modulus of elasticity (Pa)
   - *σ:* Yield strength (Pa)
   - *θ:* Angle of bend (radian or degree)

VIII. DESIGN CALCULATIONS

1. Bending moment calculations
   The bending moment (*M*) applied to the pipe during bending can be calculated using the formula:
   $M = \frac{P \cdot L}{4}$
   Example calculation: Assuming an applied load of P= 1060N and pipe segment length of L=150mm:
   $M = \frac{706.4 \times 0.15}{4} = 26.49\ Nm$
2. Moment of inertia calculations
   The moment of inertia (*I*) for hollow circular section can be calculated as:
   $\frac{\pi}{64} \times (D^4 - d^4)$
   Example calculation: Foe a PVC pipe with:
   - Outer diameter, *D*= 25mm = 0.25m
   - Inner diameter, *d*= 20mm = 0.20m

Calculating *I:*

$I = \frac{\pi}{64}((0.025)^4 - (0.020)^4)$

$I = \frac{\pi}{64} \times 0.00000023 \approx 1.131 \times 10^{-8} m^4$

3. Stress calculation:
   The stress (σ) include in the material due to bending can be calculated using:
   $$\sigma = \frac{M \cdot c}{I}$$
   Assuming:
   The outer radius $c = \frac{D}{2} = 0.025m$
   Substituting values:
   $$\sigma = \frac{26.49 \times 0.025}{1.131 \times 10^{-8}}$$
   $\sigma = 29.27 \times 10^6\ P_a\ or$
   $\sigma = 29.27\ MP_a$
   "The stress is below yield strength of PVC, hence the design is safe"
4. Hydraulic pressure calculation
   The hydraulic pressure required to achieve the necessary bending force can be calculated using:
   $$P = \frac{F}{A}$$
   Example calculation: Assuming:
   - Force *F* = 706.4 N
   - Diameter of hydraulic cylinder *Dc* = 0.05m
   - Radius $r_C = \frac{D_C}{2} = 0.025m$

   Calculating area, *A*:
   $A = \pi r_c^2 = \pi \times (0.025)^2$
   $A = 1.9635 \times 10^{-3} m^2$
   Calculating hydraulic pressure *P:*
   $$P = \frac{706.4}{1 \cdot 9635 \times 10^{-3}} \approx 359.8 \times 10^3 Pa\ or\ 0.359\ MPa$$
5. Temperature effects on PVC
   Yield strength variation: The yield strength of PVC decreases with increasing temperature [9]. For example, at room temperature (~20°C), yield strength can be about 60MPa but can drop to 40MPa at elevated temperatures (e.g., 60°C)
6. Bending angle correction

- When bending pipes, the angle of bending is crucial. The machine should account for **spring back**, which can cause the pipe to revert slightly after bending. Therefore, slightly over-bending the pipe may be necessary.

7. Force required for bending
The force required for bending can also be expressed as:
$$F = \frac{M}{r}$$
Assuming the bend radius of r = 0.025m
$$F = \frac{26.49}{0.025} = 1059.6\ N$$
8. Energy required for bending
The energy required to bend the pipe can be calculated as:
$$E = M\theta$$
Were, θ is angle bend in radians (e.g., for 90° bend, $\theta = \frac{\pi}{2}$)
$$E = 26.49\frac{\pi}{2} \approx 41.62J$$

IX. RESULT AND DISCUSSION

➢ Results

- Bending accuracy: The machine achieved an accuracy rate of ±3 degree in bending angles, significantly surpassing the typical manual method.

Trail	Measured diameter (inches)	Target Angle	Error Degrees
1	1	90°	3
2	1	90°	2
3	1	90°	-2
4	1	90°	3
5	1.5	90°	2
6	1.5	90°	-1
7	1.5	90°	2
8	1.5	90°	-3
9	0.5	90°	3
10	0.5	90°	3
11	0.5	90°	2
12	0.5	90°	-1
13	1	90°	2
14	1	90°	-1
15	1	90°	2
16	1.5	90°	-3
17	1.5	90°	2
18	0.5	90°	1
19	0.5	90°	-1
20	0.5	90°	2

- Operational Efficiency: The automated process reduced the average bending time per pipe from 15 minutes to approximately 5 minutes, demonstrating a substantial improvement in productivity.
- Material integrity: Post-bending, inspection showed no significant deformation or structural weakness in the pipes, conforming that the machine maintains the integrity of the material throughout the bending process.

➢ Discussion

- Interpretation and accuracy of bending: The achieved accuracy of ±3 degree indicates the effectiveness of the automated system in achieving precise bends. This precision is essential in the application where alignment is critical, such as photovoltaic installations.
- Implication of PV installation: The increased operational efficiency observed in this study implies potential cost savings for projects involving PV installations. Faster bending cycles can lead to quicker projects completions and lower labor costs, making the machine a valuable asset for the renewable energy sector.
- Limitations: Despite these successes, the result indicates that variation in material properties could impact bending accuracy. Future research should address these variables through controlled testing to ensure the machine's reliability across different types of PVC
- Conclusion: The findings suggest that implementing this microcontroller-operated machine can greatly improve efficiency and precision in pipe bending for PV installations. The reduced bending time and enhanced accuracy demonstrate the machine's potential to revolutionize standard practice in the industry.

- Before and after images of pipe:

Figure 6: Bent PVC pipe if dia. 1.5" before and after process

Figure 7: Bent PVC of dia. 1.5" before and after process

Figure 8: Bent PVC pipe of dia. 1" before and after process

X. CONCLUSION

The design and fabrication of microcontroller operated PVC pipe bending machine represent a significant advancement in the field of pipe bending technology, especially for applications in various fields such as automobile, PV installments. By automating the bending process, the machine has demonstrated enhanced precision increased operational efficiency and a reduction in material wastage.

The successful implementation of microcontroller system has minimized human intervention and error providing a more reliable and user-friendly solution for industrial application. Future work may involve exploring additional features, such as integrating advance sensors for real time feedback and further optimization of bending parameters. Overall, this project lays the groundwork for more effective practices in the various industrial sectors.

XI. LIMITATIONS

While the project has achieved its objectives, several limitations were encountered:

- Material Properties: The bending performance is highly dependent on the specific grade of PVC used. Variability in material properties can affect results.
- Environmental Conditions: Changes in temperature and humidity can affect the performance of PVC during bending.
- Complex Geometries: The machine may struggle with more complex bending geometries that exceed its design capabilities.

XII. FUTURE WORK

Future enhancements could include:

- Exploring the use of additional material for improving versatility.
- Implementing real time monitoring and feedback systems to further enhanced precision.
- Investigating the automation of pipe cutting and positioning to streamline the entire process.

XIII. PRACTICAL APPLICATION

The microcontroller-operated pipe bending machine has potential applications in various fields beyond photovoltaic installations, including:

- Plumbing: efficiently bending pipes for residential and commercial plumbing systems.
- Construction: Creating custom pipe structures for building framework and supports.
- Automotive: Bending piping for exhaust systems and custom car parts.

XIV. ECONOMICS ANALYSIS

A brief analysis indicates that the microcontroller operated machine could reduce labor cost by to 50% compared to traditional manual methods. Additionally, the reduction in material wastage could lead to significant cost savings over time.

XV. VALIDATION AND TESTING METHODS

testing was conducted by applying varying loads and measuring the resulting bent angles. Multiple trials where perform to access the machine’s reliability and consistence under different operating conditions.

XVI. COMPARISON TO EXISTING TECHNOLOGIES

Compared to traditional manual bending methods, the microcontroller-operated machine offers:

- Increased precision and repeatability
- Enhanced operational efficiency with reduced labor requirements
- Flexibility in handing varying pipe sizes and materials.

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