UDC 681
DOI: 10.15587/1729-4061.2020.202184

DESIGN AND DEVELOPMENT OF HIGH-ACCURACY MACHINE FOR WIRE BENDING

The use of a bending machine acquired a high level of importance as a consequence of increasing the level of the industry. This paper aims to develop a more accurate and precise bending machine. The proposed bending machine has achieved brilliant output products, in which three main manufacturing parameters have been examined for the production of an equilateral triangle, which are flange length, bending angle and bending radius. The main point depends on the proposed algorithm, which has been developed based on separating the process, in which the central controller is responsible mainly for controlling the sub-controller, where the sub-controllers are programmed using PID to control the entire mechanisms of feeding and bending separately and ensure that the outcomes of these mechanisms are compatible with the input data from the central controller. Ten different dimensions of an equilateral triangle design sample with ten tries for each dimension (variable flange length, fixed bending angle equals to 60 degrees and bending radius equals to 3 mm) have been selected being produced using the bending machine, and the products have been formed two times. Firstly, using the proposed bending machine, in which the proposed algorithm is applied. Secondly, using the bending machine implemented without applying the proposed algorithm. The results have been compared in terms of error rates with respect to the standard design of products designed using CAD/CAM application. An enhancement has been recorded in terms of product accuracy and precision for the parameters of flange length, bending angle and bending radius. The overall accuracy level reaches up to 98.85228 % for a product manufactured using the proposed machine by applying the proposed algorithm compared with a product made with the machine designed without the proposed algorithm

Keywords: bending machine, accuracy, precision, equilateral triangle, flange length, bending angle, bending radius, proposed algorithm, CAD/CAM application

Faiz F. Mustafa
Doctor of Mechanical Engineering, Assistant Professor*
E-mail: dr.faiz@kecbu.uobaghdad.edu.iq

O. Hussein
Master of Electrical (Control) Engineering*
E-mail : omar.hussein@kecbu.uobaghdad.edu.iq

Osamah F. Fakhri
Master of Mechanical Engineering/applied or machine design
Department of Biomedical Engineering**
E-mail: usama@kecbu.uobaghdad.edu.iq

Ahmed H. Sabri
Doctor of Control Engineering
University Tenaga National
Sj Chua str., 34, Selangor, Malaysia, 68000
E-mail: ahs4771384@gmail.com

*Department of Automated Manufacturing Engineering**
**Al Khwarizmi College of Engineering
University of Baghdad
Aljadrya str., D534, Builiding 15, Baghdad, Iraq, 10070

Received date 16.07.2020
Accepted date 28.09.2020
Published date 13.10.2020

1. Introduction

In different sectors of industries and medical fields, automated machines spread widely nowadays [1]. In several countries, automation has been used in agriculture in a way that has made life easier for millions of people around the world by combining production machinery with control systems [2–5]. The industries are still considered to be seriously, more expensively and erroneously manufacturing complex engineering products with hand machines, though incorporating automation has made them simpler and more economically effective [6]. However, challenges in the global economy and the industrial section developments exacerbated as a result of a lack in the machine industry, especially the use of bending machines during different processes of manufacturing due to the problems of automated machine systems growing [7–10]. It has proven that the use of bending machines is necessary to include during a linear or rotating movement with different industrial processes [11]. For regular operation, the automated bending systems required precise control loop tuning with an excellent dynamic response to simplify commissioning and avoid control errors [12–16]. Therefore, studies that are devoted are important in the process of bending machine in the forming industries nowadays.

2. Literature review and problem statement

The need for a reliable automated bending machine in the industrial sectors is still rising; it did not reach the required precision for the use of bending and cutting operations [17, 18].

However, some traditional bending mechanism tried to implement the machine with more accurate and precise measurement. Some applications attempted to overcome the problem of machine efficiency and accuracy [19].

Presently, not many researchers have paid attention to higher integration and automatic bending production with high production efficiency [20]. A way to overcome these difficulties can be to use the proposed micro W-bending to accurately predict and effectively control the spring back as stated in [21], where product accuracy is not included. Also, utilizing a DC wire-bending machine implemented to bend the wire to any angle, as shown in [22], without the consideration of precision for the industrialized products. Besides, using a robot system for sheet bending to overcome the human beings shortage as mentioned in [23] in which the parameters of flange length, bending radius and bending angle do not put into their consideration.

Using the single head to bend, in the machine fabrication as stated in [24] but the production efficiency is slow. In addition, using a double head to bend with bending machinery has failed to achieve the asymmetric bending. Meanwhile, the efficiency is still low and maintenance is inconvenient. The wire-bending machine needs to be equipped with the clamping mechanism, which is used to clamp and whirl the wire [25].

Also, the existing clamping mechanism is complicated, difficult in maintenance, has unstable powertrain and low rotational accuracy. The mechanism, which is used to store and feed the wire, the wire pushed, and the tension is building up when the feeding speed is different from the receiving speed of the processing equipment. In this situation, the mechanism, which is unable to reset by itself, needs to be adjusted manually. This way not only reduces the production efficiency but also increases the labor costs. Also, using electric shock for multiple angle bending of the micro foil has been introduced as stated in [26] but it has not investigated the accuracy and precision of the products.

Despite the above trends, the academic shortage has been highlighted in the implementation of accurate and precise bending machines.

3. The aim and objectives of the study

The aim of the present study is to design and develop a highly accurate machine used for wire bending.

To achieve this aim, a researcher needs to implement the following tasks:

– to design a bending machine used in different wire bending processes;

– to develop an algorithm, which is utilized with the bending machine and produces more accurate and precise products;

– to verify the accuracy and precision of products and compared them with different products industrialized using other bending machine.

4. Bending machine design

Bending machine is defined as a machine that is able to bend single pieces as well as small batches with the same precision and efficiency as series-produced parts. A group of combined parts which integrates for the reason of the bending process.

The proposed machine is classified into two central parts: controller and mechanical parts as shown in Fig. 1, which illustrates the integrated parts.

The controller part is represented in the above figure, in which number (1) represents the central controller, number (2) represents the sub-controllers and number (3) represents motor drivers. It is assembled together for the reason of managing the bending process. The mechanical part is represented, in which «B» represents a wire feeding mechanism, «C» represents the bending mechanism, «D» represents the guiding channel, «E» represents the cutting mechanism and «F» represents the machine frame.

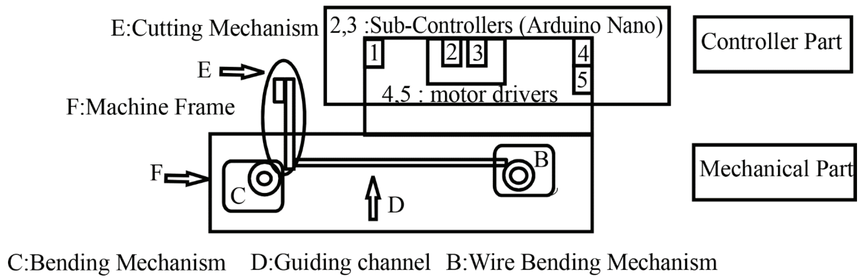

Fig. 1. Bending Machine Block Diagram

4. 1. Controller part

The controller part is considered the main part assembled for the reason of controlling the other parts. It consists of a central controller (Arduino UNO), two PID sub-controllers (Arduino Nano) and two DC motor drivers. The central controller is an Arduino Uno board, which interfaces the machine with the user's PC via USB cable, the communication between the PC and the UNO is accomplished through the serial monitor using the Microsoft Visual Studio software. The central controller reads the input (angle/wire length) from the user via a serial monitor, saves and converts it into Byte length number (transition protocol sends one byte at a time). Data transmitted to the PID controllers, the transmitted values (bending angle/flange length) represent the set point of any finished product.

Another essential task for the central controller is controlling the feeding and cutting mechanisms by sending a drive signal to the servomotor. An Arduino Nano board is programmed with PID close loop control algorithm for the purpose of bending and feeding [27, 28]. The set point (bending angle/flange length) is received from the central controller via the I2C protocol. The feedback signal is obtained based on the optical encoders coupled with the motor and according to the feedback and set points, the output signal of the PID is calculated then sent to the motor driver to drive it to the required set point. The modules of the motor drivers used in this prototype are a high power BTS7960 chip, which is a fully integrated chip with high-current half-bridge motor drive, as shown in Fig. 2.

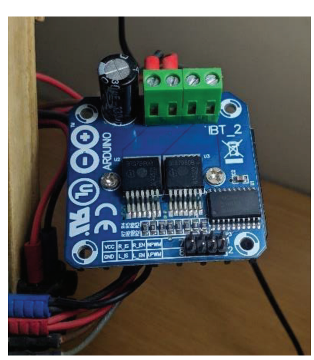

Fig. 2. Motor Drivers Modules

The operating voltage range starts from 5.5 V to 27 V DC with 43 maximum ampere, Pulse modulation (PM) up to 25 kHz combined with active freewheeling. The power source is 12 V, 40 Ampere-hour calcium battery, which is the maximum allowed voltage for the motors used in the machine.

4. 2. Mechanical part

The second important part named as a mechanical part, in which five parts are accomplished together to complete the bending process is represented as follows.

1. Wire feeding mechanism.

The central part of the wire feeding mechanism consists of a cylinder and pulley. It is responsible for the wire feeding for the machine as illustrated in Fig. 3.

Fig. 3. Wire Feeding Mechanisim

The cylinder has a diameter of 16.5 mm with a rough surface to prevent the wire from slipping during the feeding process. This cylinder is mounted on a gearbox coupled with a 12 V car wiper DC motor. At the same time, the pulley with a diameter of 18 mm freely rotates around the fixture via ball bearing. In contrast, the pulley with a diameter of 18 mm freely rotates around the installation via ball bearing. The function of the pulley fixture is to push the wire against a cylinder to prevent slipping, using a strong spring. The pulley surface has a groove to prevent the cable from escaping out vertically during feeding.

2. Wire bending mechanism.

The process of wire bending mechanism can be explained as follows; the bending head consists of three parts, base cylinder, die and bending pin. The base cylinder is fixed on a hollow gearbox shaft coupled to 12 V DC motor. The die, which is a cylinder with a 5.5 mm diameter, is mounted on the center of the base cylinder and rotate together. The die moves up and down via a mini-servomotor to let the finish wire parts be easily removed after cutting. Finally, the bending pin, which has a circular cross-section with a 2.2 mm diameter, is mounted to the circumference of the base cylinder, and this pen is responsible for bending the wire around the die.

3. Guiding channel.

The wire guiding channel is a hollow cylinder with a specification of 3 mm diameter and 210 mm length. The primary purpose of this channel is connecting the feeding and bending mechanisms together and ensures a straight entrance between the die and the pin of the bending head.

4. Cutting mechanism.

The final part of the bending machine process for the product forming, in which the operations of feeding, bending, and all the necessary procedures have been achieved successfully. The cutting mechanism consists of a plier actuated with a high-power servomotor fixed on the machine frame used for cutting purposes as represented in Fig. 4.

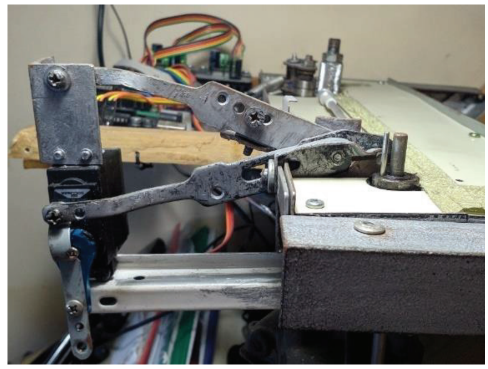

Fig. 4. Cutting Mechanism of the Bending Machine

The cutting mechanism control is totally based on signals from the central controller after the process of feeding and bending has been implemented correctly. After the ending of the overall operation of the product forming (Feeding, Bending and Cutting mechanisms), the process of produced shaping is repeated sequentially.

5. Machine frame.

A structural frame, which supports the mechanical and electronic parts, other components and physical construction is combined together for the bending machine figuration. The specification of the machine frame used in this prototype is a rectangular frame with a dimension of (410×120 mm) made of 1/4» angle beam carbon steel.

5. Algorithm development for bending machine

The main goal of this work is to implement and develop a more accurate wire bending machine, in which the needs of this accurate machine have been highlighted. The main point depends on the proposed algorithm, which has been developed based on separating the controller of the process. The central controller is responsible mainly for controlling the sub-controller, where the sub-controllers are programmed using PID to manage the entire mechanisms of feeding and bending separately. To ensure that the outcomes of these mechanisms are compatible with the input data from the central controller.

The overall processes of the proposed accurate bending machine are summarized as follows:

– targeted shape selected for the bending process;

– using GUI, the degree of bending angles and number of sides for the targeted shape have been identified;

– data of the targeted shape has been loaded in the central controller;

– the second controller has been activated based on the data gathered from the central controller for the feeding purposes;

– feeding processes have been carried out and evaluated through the central controller, based on standard data. PID controller has examined the feeding parameters to obtain the optimum value;

– bending processes have been accomplished based on the data gathered from the central controller and checked with the standard bending data;

– cutting processes have also been implemented after feeding, and bending processes, the overall shape has been examined to match the standard value of the targeted form.

The structure of the proposed algorithm used in this prototype of the bending machine is illustrated, as shown in Fig. 5, where the parameters of the bending machine have been complied together for the more accurate bending process.

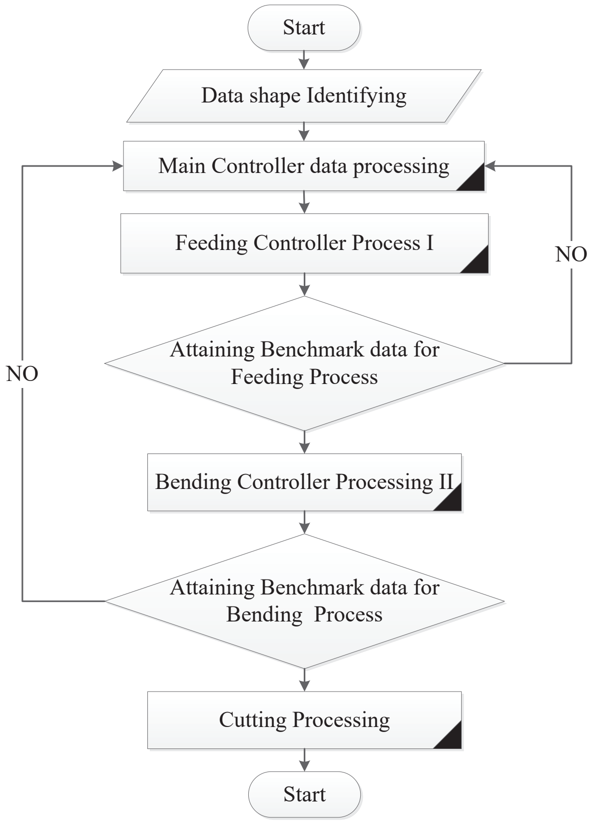

Fig. 5. Bending Machine Process Flow Chart

The wire bending machine has been designed, developed and tested in the premises of applied mechanics and electrical laboratories/the department of automated manufacturing engineering/AL Khwarizmi College of engineering/university of Baghdad.

6. Accuracy and precision verification

A wire with a specification of 1.2 mm diameter made from mild carbon has been used for creating the prototype in which data have been gathered and recorded regarding the flange length, bending angle, as well as bending radius as represented in Fig. 6.

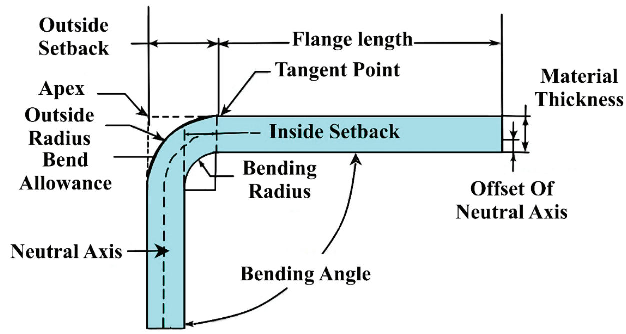

Fig. 6. Bending Diagram Parameters

Ten different dimensions of an equilateral triangle design sample with ten tries for each dimension (variable flange length, fixed bending angle equals to 60 degrees and bending radius equals to 3 mm) have been selected being produced using the bending machine, and the products have been formed two times. Firstly, using the proposed bending machine, in which the proposed algorithm is applied. Secondly, using a bending machine implemented without applying the proposed algorithm.

Calculations of flange lengths, bending angle and bending radius have been made for each product industrialized and the results have been compared in terms of error rates with respect to the standard design of the product designed using CAD/CAM application.

The flange length measurement accuracy calculations for the equilateral triangle product of different dimensions are listed in Table 1. Also, the accuracy of bending angle and bending radius measurements for the equilateral triangle product of different dimensions is listed in Table 2, 3, respectively.

Flange length, bending angle and bending radius measurements of the products manufactured using the proposed bending machine for different dimensions and trails of products show up highly accurate measurements if compared with the measurement of the products manufactured using a bending machine designed without the proposed algorithm [30, 31]. Overall accuracy (flange length, bending angle and bending radius measurements) witnessed an accuracy increase reaching up to 98.85228 %.

Table 1

Flange length measurement accuracy

Number of sample	Flange length (mm)	Mean Value Flange Length of the proposed algorithm (mm)	Accuracy %	Mean Value Flange Length without the proposed algorithm (mm) [29]	Accuracy %
1	14	14.0522	99.99627 %	14.889	99.9365 %
2	18	18.085	99.99528 %	19.0252	99.94304 %
3	22	22.03	99.99864 %	21.568	100.0196 %
4	26	26.0255	99.99902 %	26.8569	99.96704 %
5	33	33.0125	99.99962 %	33.8522	99.97418 %
6	37	37.0173	99.99953 %	38.99	99.94622 %
7	40	40.052	99.9987 %	40.9852	99.97537 %
8	42	42.00613	99.99985 %	43.1052	99.97369 %
9	45	45.0325	99.99928 %	45.865	99.98078 %
10	47	47.0052	99.99989 %	48.85	99.96064 %
Overall Accuracy			99.99861 %	Overall Accuracy	99.96771 %

Table 2

Bending angle measurement accuracy

Number of sample	Bending angle of the proposed algorithm (degree)	Accuracy %	Bending angle without the proposed algorithm (degree) [29]	Accuracy %
1	59.8	99.667	57.3	95.5
2	59.8	99.667	58.5	97.5
3	60	100	59	98.3333
4	59.5	99.16667	57.55	95.91667
5	58.5	97.5	56	93.3333
6	59.1	98.5	58.1	96.83333
7	59.9	99.83333	55.54	92.56667
8	59.85	99.75	57.8	96.33333
9	59.025	98.375	58.1	96.83333
10	59.12	98.53333	57.5	95.833333
Overall Accuracy		99.09923 %	Overall Accuracy	95.89833 %

Table 3

Bending radius accuracy measurements

Number of sample	Bending radius of the proposed algorithm (mm)	Accuracy %	Bending radius without the proposed algorithm (mm) [29]	Accuracy %
1	2.889	96.3	2.7	90
2	2.9522	98.40667	2.65	88.3333
3	2.75	91.6667	2.81	93.6667
4	3	100	2.7522	91.74
5	2.99	99.6667	2.5852	86.17333
6	3	100	2.758	91.93333
7	2.92	97.3333	2.852	95.06667
8	2.852	95.0667	2.755	91.83333
9	2.985	99.5	2.6544	88.48
10	2.8995	96.65	2.444	81.46667
Overall Accuracy		97.459 %	Overall Accuracy	89.86933 %

Variations in the product parameters (flange length) for different dimension samples have been clarified, as shown in Fig. 7.

Besides, accuracy enhancement, precision in terms of product measurements have been highlighted. The use of the proposed algorithm showed an increase in product precision in terms of flange length, bending angle and bending radius measurements as shown and explained in Fig. 8. The wire after bending processes is shown in Fig. 9.

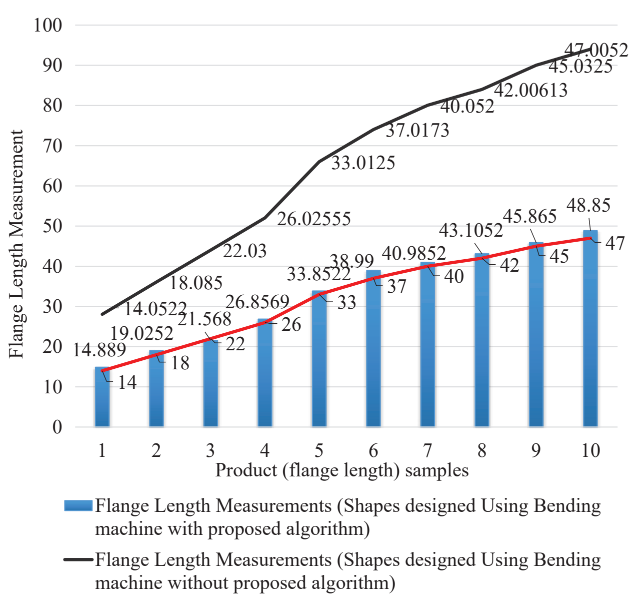

Fig. 7. Flange Length Measurement Accuracy

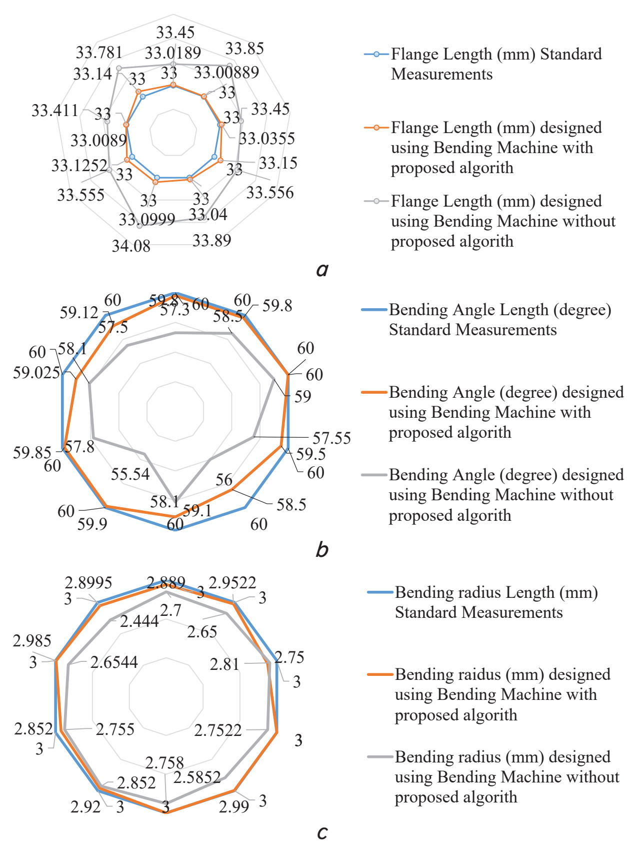

Fig. 8. Measurement precision: *a* — Flange length measurement precision; *b* — Bending angle measurement precision; *c* — Bending radius measurement precision

Fig. 9. Wire after bending processes

The reason beyond this enhancement is that the proposed algorithm has separated the functions of feeding, bending and cutting individually set and managed using the PID controller and the overall functions have been controlled using the main controller, in which these features have proven the ability to produce more accurate products. In addition, accuracy, as well as precision of products, has been amended for the parameters of flange length, bending angle, as well as bending radius. Despite the above improvement of machine output, a limitation has been recorded in terms of wire material and thickness. Due to the simplicity of the prototype, it is difficult to utilize the machine for the manufacturing of products with big dimensions and researchers intended to develop the prototype to be more applicable for any industrial formation.

7. Discussion of experimental results

Utilization of the wire bending machine has testified high importance, in which the need of using the bending machine has raised with the growth of industries. The current study has proven that the development of a bending machine is necessary in the field of forming industries and this study proved that this machine is able to produce a product of any design. An enhancement is necessary to include in this machine by increasing the ability of this machine for the bending process for any material to reach the optimum stage of the utilization of bending machine in the industrial sectors.

The current study also has shown that the utilization of the proposed algorithm has tremendously helped the production of accurate products, since the separation of process controller has raised the accuracy and precision measurements of the products.

The current study is also considered useful for industries that require a product with high-precision measurements.

As compared with previous studies, the proposed machine gained a high level of accuracy of measurements for the fabricated products, as well as the precision of measurement for the products. A reason beyond this enhancement belongs to the handiness of the proposed algorithm, which helped the reduction of error rate between the produced products and standard products.

8. Conclusions

1. Design and development of wire bending machine have been achieved successfully, in which the machine is able to create any frame shapes such as hexagonal, recant angular and circular frames depending on the set point of the structure. This machine has been practiced to implement an equilateral triangle using a wire with a 1.2 mm diameter made from mild carbon.

2. Development of the algorithm programmed with this machine has proven that this algorithm is necessary for obtaining accurate products. The product accuracy has improved, the parameters of flange length, bending angle and bending radius witnessed an increase in its accuracy with respect to error rate from the standard measurements.

3. The precision of the product shows a high record, in which the proposed algorithm has helped to decrease the error rate in each parameter for all industrial operations. The overall accuracy has improved to be 98.85228 % after carrying out the proposed algorithm if compared with other machines that do not use the proposed algorithm.

Acknowledgments

The authors want to acknowledge that this research was approved by the scientific committee of the automated manufacturing Engineering department – Al-Khwarizmi college of engineering – university of Baghdad within the research plan of 2019.

References

1. Telrandhe, R. G., Ikhar, D. R., Gawande, A. C. (2020). Development and Fabrication of Automated Paper Recycling Machine. Advances in Materials and Manufacturing Engineering, 289–295. doi: https://doi.org/10.1007/978-981-15-1307-7_32
2. Rembold, U. (1985). Computer-integrated manufacturing technology and systems. Marcel Dekker Inc., 790.
3. Wright, D. N., Vardoy, A.-S. B., Belle, B. D., Visser Taklo, M. M., Hagel, O., Xie, L. et. al. (2017). Bending machine for testing reliability of flexible electronics. 2017 IMAPS Nordic Conference on Microelectronics Packaging (NordPac). doi: https://doi.org/10.1109/nordpac.2017.7993162
4. Abdulsattar, N. N. N., Mustafa, F. F., Hadi, S. M. (2019). Design and Implementation of SCADA System for Sugar Production Line. Al-Khwarizmi Engineering Journal, 15 (2), 80–88. doi: https://doi.org/10.22153/kej.2019.01.002
5. Karem, I. S., A.Wahabt, T. A. J., Yahyh, M. J. (2017). Design and Implementation for 3-DoF SCARA Robot based PLC. Al-Khwarizmi Engineering Journal, 13 (2). doi: https://doi.org/10.22153/kej.2017.01.002
6. Kunakov, E. P. (2018). Improvement of the Technological Process of Pipe Bending with the Introduction of Digital Technologies and Information Security Requirements. 2018 IEEE International Conference «Quality Management, Transport and Information Security, Information Technologies» (IT&QM&IS). doi: https://doi.org/10.1109/itmqis.2018.8525005
7. Qin, Y. (Ed.) (2015). Micromanufacturing engineering and technology. William Andrew, 858. doi: https://doi.org/10.1016/c2013-0-19351-8

8. Fu, M. W., Chan, W. L. (2012). A review on the state-of-the-art microforming technologies. The International Journal of Advanced Manufacturing Technology, 67 (9-12), 2411–2437. doi: https://doi.org/10.1007/s00170-012-4661-7
9. Hu, Z., Labudovic, M., Wang, H., Kovacevic, R. (2001). Computer simulation and experimental investigation of sheet metal bending using laser beam scanning. International Journal of Machine Tools and Manufacture, 41 (4), 589–607. doi: https://doi.org/10.1016/s0890-6955(00)00058-4
10. Duflou, J. R., Váncza, J., Aerens, R. (2005). Computer aided process planning for sheet metal bending: A state of the art. Computers in Industry, 56 (7), 747–771. doi: https://doi.org/10.1016/j.compind.2005.04.001
11. Jabavathi, J. D., Sait, H., Rajkumar, K., Ehsan, R. M., Vinod, S. (2019). Servo Inverter Design for High Performance Multi-axis CNC Tube Bending Machine. 2019 Fifth International Conference on Electrical Energy Systems (ICEES). doi: https://doi.org/10.1109/icees.2019.8719299
12. Yang, S.-M., Lin, K.-W. (2016). Automatic Control Loop Tuning for Permanent-Magnet AC Servo Motor Drives. IEEE Transactions on Industrial Electronics, 63 (3), 1499–1506. doi: https://doi.org/10.1109/tie.2015.2495300
13. Jung, J.-W., Leu, V. Q., Do, T. D., Kim, E.-K., Choi, H. H. (2015). Adaptive PID Speed Control Design for Permanent Magnet Synchronous Motor Drives. IEEE Transactions on Power Electronics, 30 (2), 900–908. doi: https://doi.org/10.1109/tpel.2014.2311462
14. Simhachalam, D., Dey, C., Mudi, R. K. (2012). An auto-tuning PD controller for DC servo position control system. 2012 2nd International Conference on Power, Control and Embedded Systems. doi: https://doi.org/10.1109/icpces.2012.6508121
15. Kim, K.-H. (2005). Nonlinear speed control for a PM synchronous motor with a sequential parameter auto-tuning algorithm. IEE Proceedings - Electric Power Applications, 152 (5), 1253. doi: https://doi.org/10.1049/ip-epa:20050037
16. Calvini, M., Carpita, M., Formentini, A., Marchesoni, M. (2015). PSO-Based Self-Commissioning of Electrical Motor Drives. IEEE Transactions on Industrial Electronics, 62 (2), 768–776. doi: https://doi.org/10.1109/tie.2014.2349478
17. S Karnaukh, S. G., Markov, O. E., Aliieva, L. I., Kukhar, V. V. (2020). Designing and researching of the equipment for cutting by breaking of rolled stock. The International Journal of Advanced Manufacturing Technology, 109 (9-12), 2457–2464. doi: https://doi.org/10.1007/s00170-020-05824-7
18. Karnaukh, S., Karnaukh, D. (2011). Research of the Influence of Deformation Speed on Energy and Power Adjectives of the Process of Three-point Cold Bend Breaking and on Alignment Integrity of Raw Parts. Metallurgical and Mining Industry, 3 (7), 107–114. Available at: https://www.metaljournal.com.ua/assets/Uploads/attachments/107Karnaukh.pdf
19. Barabash, A. V., Gavril'chenko, E. Y., Gribkov, E. P., Markov, O. E. (2014). Straightening of sheet with correction of waviness. Steel in Translation, 44 (12), 916–920. doi: https://doi.org/10.3103/s096709121412002x
20. Lu, C. (2013). Research and design of key mechanical structure of the 3d numerical control bending wire machine. Xi' an University of Architecture and Technology.
21. Liu, X., Du, Y., Lu, X., Zhao, S. (2019). Springback Prediction and Forming Accuracy Control of Micro W-bending Using Support Vector Machine. 2019 6th International Conference on Frontiers of Industrial Engineering (ICFIE). doi: https://doi.org/10.1109/icfie.2019.8907687
22. Tang, W., Zhu, H., Zhu, M., Li, Q., Zhang, J. (2016). Research on Key Technology of Wire-Bending and Equipment Development. Management Science and Engineering, 10 (1), 14–20. doi: http://doi.org/10.3968/8212
23. Lin, H.-I., Carvajal, D. H. (2016). Automatic following in a sheet metal bending process. 2016 International Automatic Control Conference (CACS). doi: https://doi.org/10.1109/cacs.2016.7973898
24. Yoshikawa, M., Katoh, A., Sasaki, K. (2005). A Failure Assessment Method for a Pipe Bend Subjected to Both a Bending Moment and Internal Pressure. Journal of Pressure Vessel Technology, 128 (4), 605–617. doi: https://doi.org/10.1115/1.2349574
25. Webster, R. J., Romano, J. M., Cowan, N. J. (2009). Mechanics of Precurved-Tube Continuum Robots. IEEE Transactions on Robotics, 25 (1), 67–78. doi: https://doi.org/10.1109/tro.2008.2006868
26. Yeo, S. H., Tan, K. H. (2004). A novel approach in microfoil bending using an electrodischarge machine. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 218 (10), 1403–1407. doi: https://doi.org/10.1243/0954405042323469
27. Rasheed, L. T. (2020). Bat Algorithm Based an Adaptive PID Controller Design for Buck Converter Model. Journal of Engineering, 26 (7), 62–82. doi: https://doi.org/10.31026/j.eng.2020.07.05
28. Abdulwahhab, O. W., Abbas, N. H. (2017). A New Analytic Method to Tune a Fractional Order PID Controller. Journal of Engineering, 23 (12), 1–12. Available at: https://www.iasj.net/iasj/download/3e1589d43d854b3b
29. Shah, A. kumar, Kumar, N., Vignesh, M., Khanna, P. (2018). Design and Fabrication of Automatic Rebar Bending Machine. 2018 International Conference on Computing, Power and Communication Technologies (GUCON). doi: https://doi.org/10.1109/gucon.2018.8675068
30. Perea-Lowery, L., Minja, I. K., Lassila, L., Ramakrishnaiah, R., Vallittu, P. K. (2020). Assessment of CAD-CAM polymers for digitally fabricated complete dentures. The Journal of Prosthetic Dentistry. doi: https://doi.org/10.1016/j.prosdent.2019.12.008
31. Esanakula, J. R., Naik, J. V., Rajendra, D., Rangadu, V. P. (2019). Online Knowledge-Based System for CAD Modeling and Manufacturing: An Approach. Advances in Intelligent Systems and Computing, 259–268. doi: https://doi.org/10.1007/978-981-13-6095-4_19