TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 66, Issue II, June, 2023

CONCEPTUAL DESIGN AND EXECUTION OF A FLEXIBLE HYBRID MANUFACTURING SYSTEM

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Abstract: *This article presents the concept and execution of a Flexible Hybrid Manufacturing System (FHMS). FHMS represents an innovative approach to manufacturing, combining traditional and digital manufacturing technologies to enable efficient and flexible production of a wide range of products. The article details the concept of conceptual system design, including the identification and selection of appropriate technologies, integration of hardware and software components, and assembly of a manufacturing system prototype. A practical example of implementing an FHMS prototype is also presented, highlighting the benefits and challenges associated with this type of advanced manufacturing system. The article highlights the importance of FHMS's adaptability and flexibility, highlighting its potential to increase efficiency, quality, and competitiveness in manufacturing. The aim of the study is to contribute to the expanding body of knowledge on hybrid manufacturing systems and to provide specialists, engineers, and those involved in innovative manufacturing processes with information that they can utilize.*
Keywords: *Hybrid Manufacturing, Robotic Arm, Flexibility, 3D Printing, FDM, Milling.*

1. INTRODUCTION

The usage of automation manufacturing helped by robotics in contemporary production units is a result of the significant changes that new technologies have brought about in the industrial sector. Utilizing a hybrid manufacturing (HM) center is an advanced technique that blends conventional production techniques with a robotic arm and conveyor belt technology to boost output and efficiency. This article examines the design of a low-cost hybrid manufacturing system (HMS). The system assures the manufacturing, manipulation, and transport of the materials using a robotic arm and a conveyor belt. The purpose of this study was to explore the potential benefits and applications of integrating a robotic arm into a hybrid manufacturing process [1]. The hybrid manufacturing equipment (HME) used in this study is a new hybrid prototype system that combines traditional manufacturing techniques like milling for material removal with nonconventional additive technologies like 3D printing.

The system includes a robotic arm and a conveying belt, which work together to handle material and process tasks. The robotic arm is a prototype robotic manipulator which is programmed to perform precise and automated tasks. It is also equipped with various sensors, and actuators that have the potential to enable precise object manipulation, efficient material handling, and reliable performance. [2]. The conveying belt is a specialized material handling system that transports the finished parts within the manufacturing center. It is designed to move objects smoothly and efficiently along a predefined path, with adjustable speed and direction. The combination of the robotic arm and conveying belt in this HME allows for automated material handling, positioning, and processing tasks, resulting in improved efficiency, accuracy, and productivity in the manufacturing process. This integrated system represents a customized approach to modern manufacturing, leveraging advanced automation technology to enhance traditional manufacturing techniques and optimize overall production outcomes [3].

Received: 08.05.23; **Similarities**: 29.05.23: **Reviewed**: 05.06./16.05.23: **Accepted**:21.06.23.

2. MECHANICAL DESIGN AND AUTOMATION INTEGRATION

In this section will be presented the mechanical design and automation integration of the new FHMS prototype. The main system subassemblies will be introduced and analyzed from the design, manufacturing, and integration point of view.

2.1 Presentation of the Hybrid Manufacturing Equipment Prototype

The new HME prototype was realized by integrating a fuse deposition modeling (FDM) extruder into mini-CNC milling equipment. FDM is a relatively cheap process very easy to use and highly encountered in non-industrial 3D printing.

This manufacturing process has excellent capabilities like many other rapid prototyping technologies by providing good accuracy of the parts. One of the well-known limitations of this technology is the final surface finish of the parts where the staircase effect can be present [4]. The HME presented in Fig.1 is able to print parts that can be subjected to a milling operation on the same equipment. Performance metrics play a crucial role in the evaluation of the effectiveness of this HME prototype [5]. The parts that are manufactured need to fit in the operational workspace which is 300x200x100 mm.

While the 3D printing machine excels in generating complex shapes, the milling machine's limitation to 3 axes restricts its ability to mill all the surfaces resulting from the printing operation. Therefore, careful consideration must be given to the part's design to ensure compatibility with the milling process.

The main advantage of this equipment is related to the fact that the final roughness of the printed parts can be improved through milling operations on the same manufacturing equipment. The material used for the printing process was polylactic acid (PLA). The material was extruded through a nozzle of 0.4 mm with a temperature of 210°C.

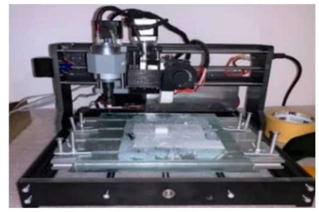


Fig. 1. HME Prototype

The cutting tool used was an HSS 3.75x39x70 mm milling tool with a speed rotation from 6000-10000 RPM. The equipment is controlled by 5 Nema 17 stepper motors. The extruder head and the milling equipment are displaced on the same x-axis but with an offset of 100 mm.

2.2 Presentation of the Robotic Arm

One of the key elements of FHMS is the robotic arm. This subassembly is the link element between the HME and the conveying belt. For this reason, in the designing stage, the structure of the robotic arm was chosen to be a very robust one, being able to incorporate all the driving elements and at the same time keep its functionality. The approach for this subassembly was to obtain 5 degrees of freedom as it is illustrated in Fig.2. The workspace of the robot arm was designed to cover both system components HME and conveying belt. The maximum operating range is a spherical cap of 450 mm radius measured from the center of the robot's pivot point.

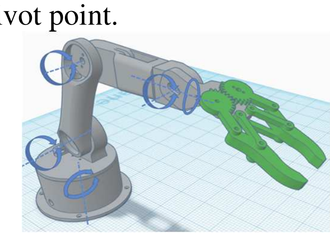


Fig.2. Five degrees of freedom robot arm model

The robotic arm performs a rotation movement around the base axis. Then, the shoulder will rotate up and down, while the elbow will move inward to outward. The wrist will perform two movements, one rotating from left to right similar to the base, and one moving up and down. The selection of the actuators for the active joints of the robot arm is the most important preliminary step before the actual design of the robotic system. By calculating the torque and estimating the length of each link and using an average part mass of 0.2 kg, the following result was obtained: the maximum torque at the base of the robot arm is approximately 1.009 Nm, while the other joints have torques ranging from 0.459 Nm downwards. Analyzing the results obtained from the torque calculations the motor that was chosen was an MG996R. It has a high torque of 1.078 Nm. The advantage of using this type of motor is the fact that it can be controlled through pulse width modulation (PWM). Based on these aspects the 3D models of the robotic arm were designed in SolidWorks software as follows: base, arm, forearm, wrist, end effector. The parts were 3D printed on Prusa I3 equipment. The printing parameters used were chosen based on previous research [6]. The material used was PLA. The total number of designed and printed elements was 10 and they were manufactured in 20 hours. The assembled robotic arm is presented in Fig.3.

Fig.3. Robotic Arm Prototype

2.3 Presentation of the Conveying Belt

The last element of the system that will be analyzed is the conveying belt. For this element was chosen the simplest structure of a conveying system with belts. Not being able to manufacture parts with big overall dimensions and the weight of the parts being relatively light gave us the chance to use a stepper motor Nema 17HS4401. The 4:1 gear ratio is achieved in this belt conveyor system by means of two key components: a 4 cm roller that drives the belt drum and a pulley that receives motion from the motor [7]. In Fig.4 is presented the 3D model of the conveying belt realized in SolidWorks software. The dimensions of the L profiles for the designed conveyor are 20 x 20 x 3. Additionally, the legs will be cylindrical with a diameter of 20 mm and a height of 120 mm.

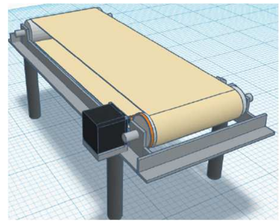


Fig.4 a) 3D Design of the conveying belt

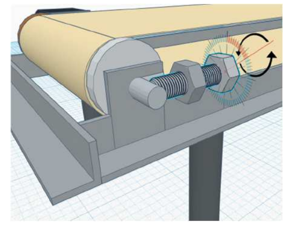


Fig.4 b) Belt tensioner concept

The drums are fixed to the chassis with the help of 2 aluminum plates with dimensions of 40 x 20 x 3 mm, placed at 15 mm from the ends of the profile. The drum rollers are also made of aluminum and have a length of 150 mm, an outer diameter of 40 mm, and an inner diameter of 26 mm. The axles are made of steel and have a length of 190 mm with a diameter of 8 mm. To allow the rotation of the drum axles, 6000-2RS type ball bearings with dimensions of 10 x 26 x 8 mm were used.

The belt will have a length of 400-430 mm, depending on the desired tension, and a width of 130 mm. The motor was mounted 30 mm away from the belt end due to the length of the transmission belt. Fig.5. illustrates the setup of the motor from two views.

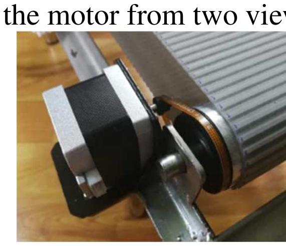


Fig.5. a) 3D view of the conveying belt

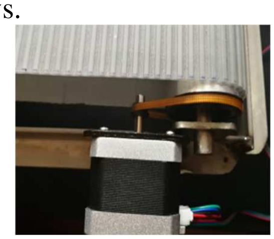


Fig.5. a) Top view of the conveying belt

The material chosen for the belt was Polyvinyl Chloride (PVC) for many considers as follows. PVC is a material with high resistance to wear, is flexible, is easy to provide maintenance, is resistant to humidity, and is cost-accessible.

3. SENSORS AND INTEGRATION

In order to realize a working and feasible flexible HMS it is required to know the state of its element at any time. The control of all three subassemblies needs to be merged into a single controller system. For this reason, a few types of sensors were used. For the HME, NTC 100 thermistors were used to control the temperature for the 3D printing operation. Another sensor used in the operation was the proximity sensor, which is used for bed leveling, detecting the distance between the manufacturing bed and tools. This type of sensor was used for filament detection in the extruder. Another important utilization of the sensor was for monitoring the manufacturing operation. It was used to monitor the progress of the print job by detecting the movement of the print head along the X, Y, or Z-axis. This information can be used to estimate print time, track print progress, or trigger events based on print head movement.

When discussing the sensors used on a conveying belt, it is important to understand their critical role in the operation and functionality of the system. The conveying belt system is equipped with an infrared sensor HC-SR04 used for obstacle detection. The sensor will be mounted in the middle of the belt, where the robotic arm will place the parts. Another important sensor is the TCS230 RGB sensor for color detection. It will be placed together with the other sensor in the middle of the belt. It is an important element that starts the belt and gives the direction of the conveyor.

Moving on to the integration of the system, the Arduino board plays a crucial role in coordinating and controlling the various components of the manufacturing center. With its versatility and programmability, the Arduino board serves as the brain of the system, overseeing the interactions between the HME, robotic arm, conveying belt, and other components. As is presented in Fig.6. the system is controlled by two Arduino UNO R3 boards interconnected. One board is used for the HME, and the other one is for the robotic arm and conveyor belt. Even if they are interconnected and communicate with each other a separate analysis can be made. The Arduino board from HME is communicating with the Shield Module which controls the 5 stepper motors for manufacturing operation. It is equipped with sockets for 5 A4988 stepper drivers. It is supplied separately with the voltage necessary for the operation of the motors. The Shield was equipped with an additional filtering capacitor for each driver. The Arduino board is communicating also with the temperature sensors and proximity sensors. The motor drivers are crucial to the precision of the equipment's movements, and they must be calibrated to ensure accurate positioning of the extruder and milling head [8]. The second Arduino board is used to control the 6 servo motors from the robotic arm and one stepper motor from the conveying belt.

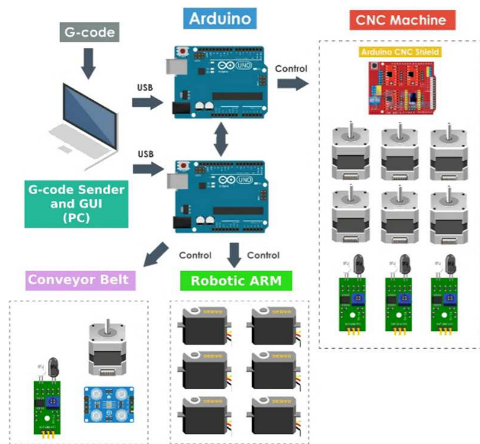


Fig.6. Integration Diagram

The Arduino board is communicating also with the proximity sensors. The reason for using 2 Arduino boards was related to the number of ports from the boards which was not sufficient. Another important aspect was the high-power consumption of all the electric parts which could negatively impact our board. Without any backup system and the production is forced to stop.

4. TESTING: A CASE STUDY

The testing of the FHMS prototype's performance and capabilities are demonstrated through a case study, showcasing its effectiveness in real-world manufacturing scenarios. For a better understanding of the process and to present how the new FHMS prototype is achieving efficient and automated production, a detailed workflow analysis is presented in Fig. 7.

To validate the FHMS prototype, a rectangular parallelepiped with dimensions of 20 mm x 20 mm x 20 mm was designed and prepared for printing using Cura software. The parts were printed in different colors, black and white. Printing parameters such as printing temperature (210 °C), bed temperature (60 °C), printing speed (65 mm/s), layer height (0.25 mm), nozzle diameter (0.5 mm), infill (100%), retraction (5 mm), cooling fan (100%), Z-hop (0.2 mm), spindle speed for milling (10,000 RPM), feed rate (1,000 mm/min), depth of cut (0.5 mm), and tool engagement (20%) were used. The coordinates where the part is always manufactured are x=0, y=0, and z=0.

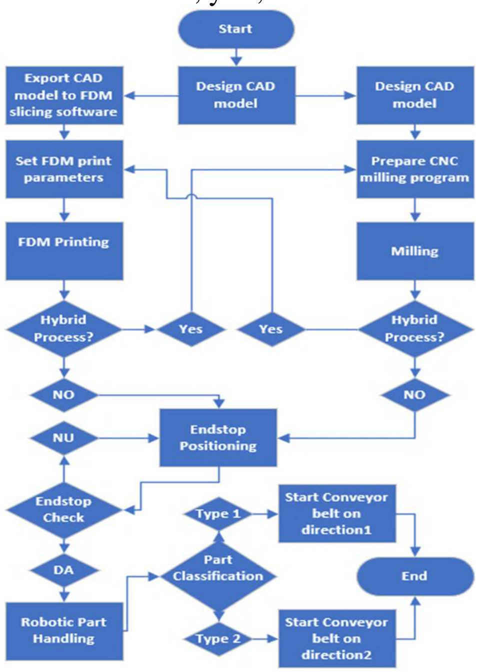
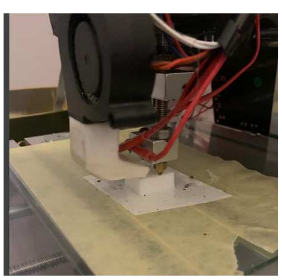


Fig.7. Workflow diagram of the HME

After the manufacturing process is over the robotic arm receives the signal from the end stoppers that the manufacturing process is over, and the tools are already in the home point and take the part from the manufacturing table.



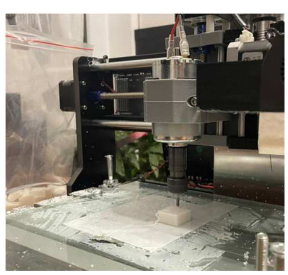
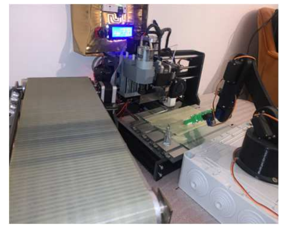


Fig.8. a) 3D Printing **Fig.8. b)** Milling

The part is placed on the conveying system in the middle where the sensors can detect the color of the part as it is presented in Fig.9. When the proximity sensors detect the part, and the RGB sensors detect the color of the part they send a signal to the Arduino board.



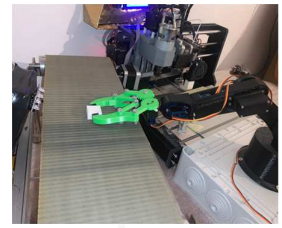


Fig.9.a) Extraction Operation **Fig.9.a)** Conveyance Operation

The Arduino sends a signal to start the conveying belt in the direction that was programmed for that specific color, right or left. This operation can be seen also in Fig.10.

Fig.10. Transport Operation

At the same time while the part is transported to the special containers, the robotic arm is going to its initial coordinates. It was created also a Graphical User Interface (GUI) for manual control of the system. In Fig.11 is presented the GUI with all the commands that can be executed in real-time.

5. CONCLUSION

The integration of a robotic arm for placing parts on a conveying belt in a hybrid manufacturing process has shown promising results. The system has demonstrated potential for scalability in mass production as it effectively reduces manufacturing time and increases productivity by eliminating the need for human intervention. Additionally, the remote operation capability adds to the system's versatility and potential for use in various industries. Exploring possibilities for remote monitoring and control could further enhance the system's capabilities. Overall, using a robotic arm for conveyor belt placement presents exciting prospects for advancing manufacturing processes and improving productivity while also highlighting the need for continuous improvement to fully harness its potential for mass production scenarios.

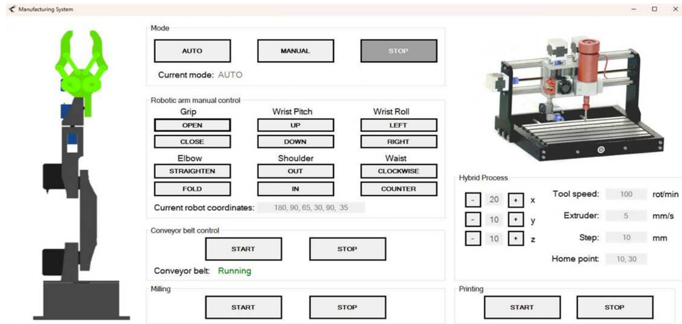


Fig.11. Graphical User Interface of the HMS

6. ACKNOWLEDGMENT

This research was financially supported by the Project “Entrepreneurial competencies and excellence research in doctoral and postdoctoral programs -Antredoc”, a project co-founded by the European Social Found financing agreement no.56437/24.07.201

7. REFERENCES

[1] G. Q. Zhang *et al.*, *Use of Industrial Robots in Additive Manufacturing - A Survey and Feasibility Study*," ISR/Robotik 2014, 41st International Symposium on Robotics, Munich, Germany, 2014, pp. 1-6.

[2] Mikell P.G., *Fundamentals of modern manufacturing: materials, processes, and systems*,4th ed. John Wiley & Sons, 2010.

[3] Li, H., Wu, G., *Enhancing productivity in manufacturing centers with hybrid manufacturing equipment*. Computers in Industry, 89, 124-139, 2017.

[4] R. Anitha, S. Arunachalam, *Critical parameters influencing the quality of prototypes in fused deposition modeling*, Process. Technol., 118(1–3) 385–388, 2001.

[5] Pascu S., Pop A., Balc N., *Design and Development of SP Hybrid Manufacturing Prototype combining 3D printing and CNC Milling,2023.*

[6] Pascu S., Pop A., Balc N., *Optimization of hybrid manufacturing process parameters, to minimize surface roughness and material usage, with an integrated artificial neuronal linear network model,2023.*

[7]Konakalla N. S. A., Vaitla R., Pothamsetty K. V., *Design and selecting the proper of Conveyor Belt*, Science, and Education Jurnal Volume 3, Issue 3,2022.

[8] Jaroslav S., Roman P., Pavel B., MiloŜ S., *Raspberry Pi and Arduino boards in control education*, Volume 46, Issue 17, Pages 7-12, April-June20.

PROIECTAREA CONCEPTUALA SI EXECUTIA UNUI SISTEM HIBRID DE FABRICATIE

Acest articol prezintă conceptul şi execuţia unui Sistem de Fabricaţie Hibrid Flexibil (FHMS). FHMS reprezintă o abordare inovatoare în fabricaţie, combinând tehnologii de fabricaţie tradiţionale şi digitale pentru a permite producţia eficientă şi flexibilă a unei game largi de produse. Articolul detaliază conceptul de proiectare conceptuală a sistemului, inclusiv identificarea şi selecţia tehnologiilor potrivite, integrarea componentelor hardware şi software şi asamblarea unui prototip de sistem de fabricaţie. De asemenea, este prezentat un exemplu practic de implementare a unui prototip FHMS, evidenţiind beneficiile şi provocările asociate cu acest tip de sistem avansat de fabricaţie. Articolul evidenţiază importanţa adaptabilităţii şi flexibilităţii FHMS, subliniind potenţialul său de a creşte eficienţa, calitatea şi competitivitatea în fabricaţie. Scopul acestui studiu este de a contribui la corpusul de cunoştinţe în expansiune privind sistemele de fabricaţie hibride şi de a furniza specialiştilor, inginerilor şi celor implicaţi în procesele de fabricaţie inovatoare informaţii pe care le pot utiliza.

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