Design and Development of CNC Wood Carving Machine based on ARM and FPGA

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Abstract - **Advancements in the domain of automation has been significantly fuelled by the implementation of Computer Numeric Control machines. The association of contemporary CNC systems along with advanced computational capability and memory storage capacity of modern computer systems has augmented the automation sector of industrial manufacturing, constructional engineering, medical, military fields etc. In this paper, the technology of CNC is extended into wood working. Traditional wood working practices demands adroit skills and has been time consuming. The key objective of this paper is to form a good efficiency and low cost hardware architecture that is G-code compatible and all operational with open software for the three dimensional wood carving purpose. This project concentrates on realizing the three dimensional linear, circular interpolations and real time processing for motion control using Spartan6 FPGA and future interfacing scopes are dealt using ARM LPC1769. The FPGA based implementation of motion controller which executes hardware interpolation offers reconfigurability, low power consumption, fast processing of logic, bringing about high efficiency and high precision to the work**

Keywords* — *ARM and FPGA, Circular Interpolation, CNC, Linear Interpolation, Open architecture, Wood carving.

I. INTRODUCTION

Wood works are a part of life from the oldest civilizations and straight up to the present lifestyle developments. The work is necessarily slow and requires substantial skills, which makes the work expensive. This is why machines got intervened into the art of carpentry and now-a-days, absolutely automated wood carving has been made possible with the application of CNC systems.

In this era where technology advancements are outpacing human roles, automated machines are gaining upper hands. The development of Numeric Control (NC) machines followed by Computer Numeric Control (CNC) machines has enhanced the reduction of human effort and increased productivity at quite cheaper rates. But majority of the innovations within CNC were made on a proprietary basis, where the hardware, system software and application programs were tightly coupled [1]. Global proliferation of computerization demanded flexibility of CNC operations through open architecture and developing hardware independent software so that the companies competing within market could cop up with the increasing consumer requirements and upgrade the existing consumers with regular updates. This could be achieved only with Open Architecture (OA). Open Architecture Control (OAC) system can be developed based on Linux. Linux-based research has led to the establishment of novel CNC wood carving machine with common and open operating system for user interface [1].

Motion controller is the major subsystem that is in charge of the actuation of all sorts of devices in industrial automation. An excellent control algorithm collaboratively with the control hardware structure ensures the success of a motion controller. Over years, various control algorithms have been introduced which could perform the required interpolations, but in a lower efficiency. Thus the selection of interpolation algorithm to be employed in the work plays a significant role in determining the performance of a CNC system [2]. The hiking requirements of motion control in 'real-time' for the modern high-speed CNC machines, software interpolator has proved to be advantageous but also seen to be affected by the constraint of synchronous output. Therefore the system efficiency, processing rate and precision of the interpolator algorithm face difficulties in tackling the performance necessities of real-time control and high speed. As a solution to this issue, a specially designed hardware logic circuit like ASIC or FPGA having parallel and lower power processing architectures can be

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employed which can manage efficient, real-time complex computations. When compared to ASIC, FPGA's have lower time to market and much simpler design cycle. Therefore, FPGA-based hardware interpolation is best suitable for high efficiency and high precision work in industrial automation.

Different algorithms for linear and circular, two dimensional and three dimensional interpolations were reviewed [3][4][5][6][7][8][9][10]. The finest ones with higher efficiencies are chosen for the project. Main aim of the paper is to implement a complete hardware for three dimensional wood carving along with the software part which involves hardware interpolation algorithms controlled by FPGA and further interfacing options for the future are offered with the use of ARM microcontroller. The whole system is made as an Open Architecture.

II. Proposed CNC Wood Carving System

Foremost step of implementation is the structural design of specialized wood carving machine hardware that satisfies all of the design constraints of the paper such as size(with the measurements of workpiece that can be processed), requisite mechanical strength(considering the material to be processed, speed of work, demanded motor torque), mechanism of working, working environment etc. Lead screw mechanism is employed rather than belt mechanisms that find applications in CNC systems dealing with light-weight endtools and workpieces. Eventhough lead screw systems have comparitevely slow movement, they produce much better precision and have superior load holding capacity.

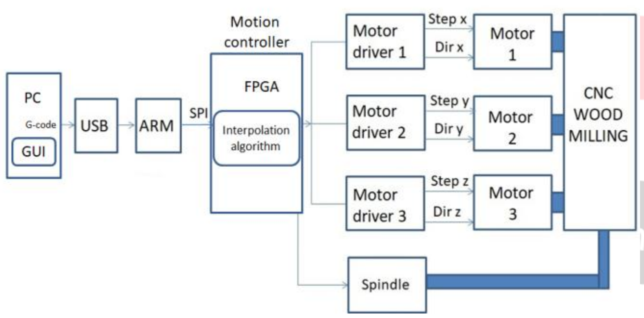

Fig 1. Block diagram

Figure 1 shows an overall block diagram of the proposed CNC based wood carving machine. Modelling of the design which is to be carved can be realized using CAD program(if the work intended is three dimensional) and later the corresponding G-codes are obtained using CAM applications. G-codes such synthesized can be then used to control the CNC machine. Communication between PC and LPC1769 is through USB interfacing available with the PCs. An user interface is created using Microsoft Visual Studio and installed in the PC that enables any communication that is to be done to the CNC device. All the overheads involved in the interface are eliminated and G-code is transformed into ASCII equivalent by the ARM microcontroller. ARM as its own has numerous means to obtain data and control the code. They can do so from its own data memory, from the host PC or from network. As it also provides different in-built interfaces and the source codes are openly available, hence this part of the PCB hardware can be used for future expansions within the machine thus enabling the advancements on the system more feasible. The co-ordinate information corresponding to each G-code is processed one-by-one and stored in ARM buffers. Further, FPGA fetches the data corresponding to G-code, calculates and logically processes the data for required motion. Latter, FPGA controls the motor controller driver in accordance with certain algorithm. Linear interpolation and Circular interpolation algorithms are implemented in FPGA Spartan 6 using Verilog HDL. This part is collectively called the motion controller of the machine. Motion controller FPGA is here between the ARM (that interprets the data from PC) and the stepper motor controller. Each axis of motion has individual dedicated motion control unit consisting of a motor driver and a motor. All the axes can be driven simultaneously since the implementation of hardware interpolation mechanism in FPGA. As it does parallel processing of data, any number of axes connected will be all in action together. The optimum motion along a required trajectory is attained through interpolation algorithms. Different algorithms can be used for the linear and circular interpolations and the most optimum one is chosen for the real time pulse generation to the motor.

By-point comparison method algorithm explained in [5] is used for circular interpolation in this project. The algorithm explained in [3] is followed for linear interpolation. But the novel interpolation discussed in the paper doesn't work for two conditions and those were fixed in this thesis. The flaws and solutions are as follows:

1) Condition Fi= 0 was not explained in [9]. In this thesis, that error is overcome by considering the same condition for Fi=0, as well as for Fi<0.
2) The algorithm in [9] explains only about the lines passing through the origin, that is, a line with equation 'y=mx', and not for the line 'y = mx+c', where y is the y co-ordinate and x is the x co-ordinate of the final point to which the tool has to move from the current location. This error is overcome by considering the starting co-ordinates of any interpolation as the origin and completing the interpolation just like tracing from origin to a point (x,y).

III. Hardware Implementation

The overall expanded block diagram of the implemented hardware setup is as shown in figure 2.

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Hardware consists of a PC with the GUI for wood carving machine installed in it, a UART module for PC to ARM communication. We have the ARM+FPGA board in which spi lines of the ARM and FPGA are already internally connected. Then extra connections to denote the type of interpolation, start/stop signal and end of job acknowledgement from FPGA to ARM are added. The direction, enable and step pulses for all the three axes are output from FPGA and connected to corresponding motor drivers and later to the corresponding motors. Then we have the wood carving machine made in which the motor movements are finally converted to the movement of the spindle in x, y and z directions. Tool bits for carving wood are mounted on the spindle.

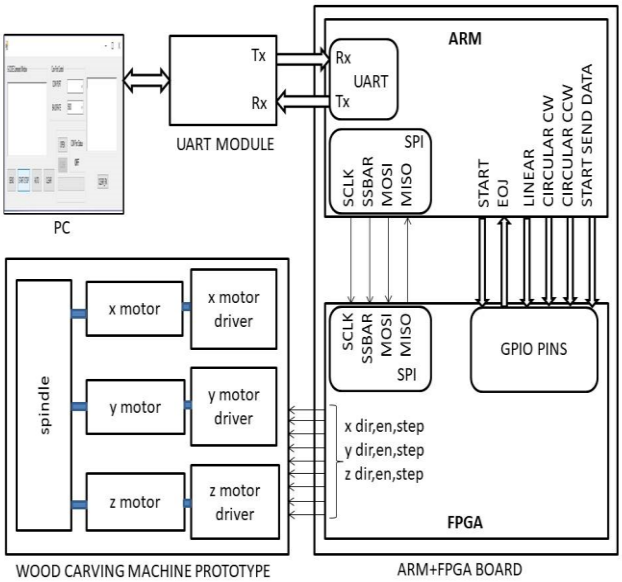

Fig 2. Block diagram of hardware setup

The ARM plus FPGA board developed for the project is as shown in figure 3.

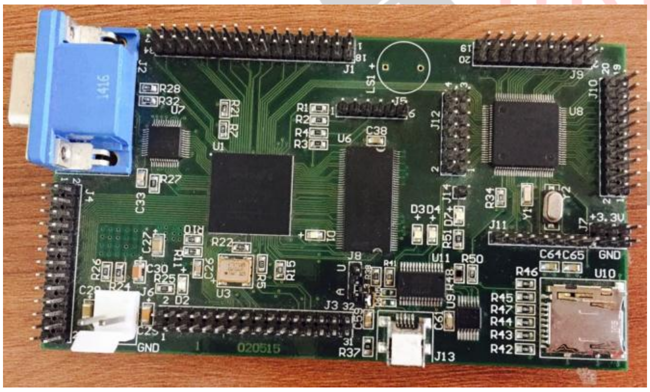

Fig 3. ARM plus FPGA PCB

The implemented hardware is as shown in Figure 4.

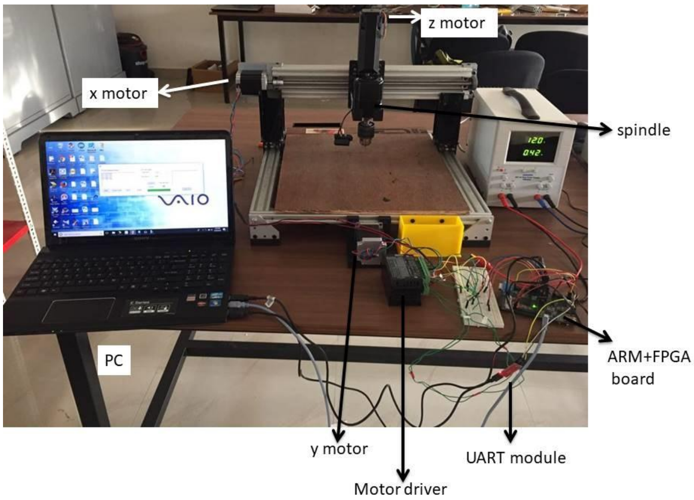

Fig 4. Hardware setup

IV. SOFTWARE IMPLEMENTATION

The software share of the project consists of

1) GUI development with Visual Studio software for communicating with the wood carving machine.
2) UART communication between PC and ARM for transmitting G-codes.
3) ARM programming for the conversion of received g-code into co-ordinate details for sending them to FPGA. The software used for programming ARM is LPC Xpresso.
4) SPI interface implementation in ARM to send data to FPGA.
5) SPI interface implementation in FPGA to receive data from ARM.
6) Linear and circular interpolation algorithm implementation in FPGA using Verilog HDL. The software used for programming FPGA is Xilinx ISE.
7) The parts to be printed in 3d printer for hardware prototype were designed in PTC Creo Parametric 3.0.
8) Others software involved in the project are Docklight for testing the serial data transmission in the development stage of software and Flash Magic for downloading the program developed in LPC Xpresso into the board

A. GUI

A GUI (Graphical User Interface) application is created using Visual Studio to act as an HMI (Human Machine Interface) . All sorts of communication to be done with the CNC are to be made possible with this application so that it acts as a real-time interface between the user and the machine. Visual Studio software supports 36 programming languages with which you can develop a project. The language I chose to implement the code in Visual studio is C#. Figure 5 shows the GUI created for this project.

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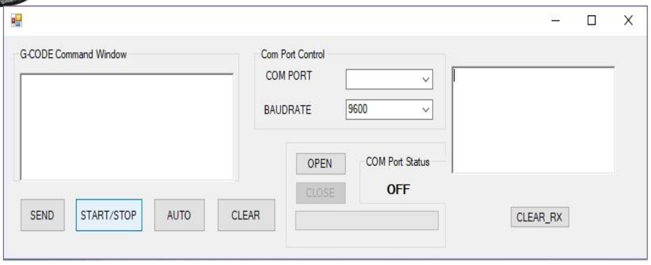

Fig 5. GUI window

The GUI window incorporates the following options:

1. A text box to enter G-code by the user. G-code can be generated by any CAD/CAM software. In this project, I use Inkscape software to generate g-codes.
2. A button to send G-code through UART
3. A button to control start/stop the working of CNC wood carving.
4. An 'auto' button, which does both the sending of g-code and starting the work together.
5. A button to clear the textbox.
6. A COM port selection port to select the port for UART communication between PC and ARM.
7. A baud rate selection box in to select the baud rate in which the communication is intended. The commonly used baud rates are 2400, 4800, 9600 and 19,200 bauds.
8. 'Open' button to open the selected port. This button has to pressed after selecting the COM port and fixing the baud rates.
9. 'Close' button to close the opened port if the communication is over.
10. The COM port status can be viewed as 'ON' after pressing the open button and the progress bar will show green once the selected COM port is open. If you are trying to send g-code or try to start the work or if the port is not made open, it will show an error message box.
11. A text box to see the transmitted portion within the entire data entered and the received data through UART
12. A clear button to clear the transmit and receive text box.

B. ARM PROGRAMMING

ARM has a major role in this project. ARM does the conversion of g-code entered by the user into the required co-ordinate information for the interpolation process to occur. G-code is send in ASCII format from the GUI and retrieving the co-ordinate information and converting it into integer so that the data can be used as end point of the next interpolation job to be done is done by ARM.

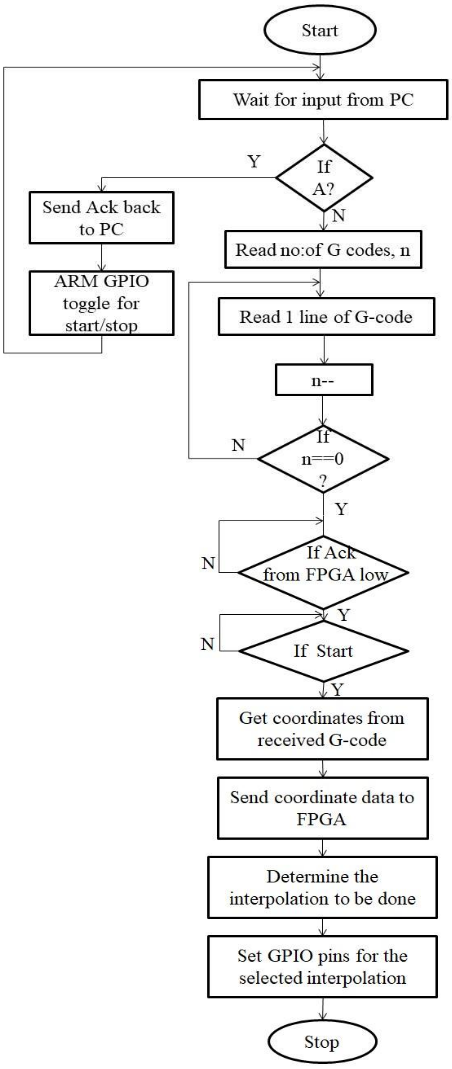

Fig 6. ARM flowchart

Here, a memory is definitely needed since there can be a large number of g-codes representing a single carve work. If FPGA were solely used for the project, then implementing a distributed RAM or a block RAM or a FIFO might have required. But just arrays are used to buffer in the data since the involvement of ARM, and then data is fetched one by one and processed and send to FPGA. FPGA acknowledges back to ARM on the completion of one interpolation job by the. ARM sends the next data only after receiving the end of job acknowledgment from FPGA.

Since the incorporation of ARM microcontroller in this project, it increases the scope of further improvements in the project. Any type of interfaces can be implemented easily in ARM than FPGA as it has dedicated pins for most of the currently existing interfaces. As CNC is a huge machine whose performance increases by including more interfaces with the external world and also within the machine. For example, this project is done as open loop. If it is made into closed loop by using an encoder for each axis, then it will enhance the precision of work. Also a display to show the current (x, y) co-ordinates of the tool, a keypad as an another HMI etc. can be included.

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ARM process flow is depicted in Figure 6. ARM is connected to PC at one end and FPGA at the other. At the beginning of a work, ARM waits for an input from PC. As soon as PC is trying to access the motion controller, ARM should check whether it is trying to send data or start/stop a work. This provision is included since the user may feel to stop the ongoing work anytime, So ARM must be constantly checking whether there is a start/stop button press. If yes, simply toggle a GPIO pin connected ARM to FPGA for indicating start/stop. If the button is pressed while no work is active at the time, it indicates a start of work and if it is pressed while a work is active, it indicates a stop of work. Now, if the first input to ARM at an idle state is not a start/stop command, then it indicates that the user is trying to send a G-code. Then it is programmed in Visual basic to automatically count the number of g-codes and send that data. Then ARM will receive the whole set of data. ARM checks for a pin status from FPGA that indicates whether an interpolation is active. If not, then ARM will convert the first line of g-code into coordinate information and radius information (if it is circular interpolation) and send them to FPGA through SPI interfacing and also recognizes the type of interpolation and it is communicated to FPGA through four GPIO pins in following format:

Table 1. GPIO status of interpolation

GPIO[Pin 3, pin2, pin 1, pin 0]	Information
0001	Linear interpolation
0010	Circular clockwise interpolation
0100	Circular counter clockwise interpolation
1000	Start of SPI data to FPGA

C. FPGA PROGRAMMING

FPGA is the motion controller in this project. It receives the co-ordinate and radius information from ARM and uses it as the end coordinates for the next interpolation to be done. Each g-code line contains one interpolation to be done. FPGA executes the interpolation algorithm and calculates the direction of motion of the tool, number of pulses to be given for the motor for the required motion and the enable signal for the motor. The direction, step and enable outputs from FPGA are connected to motor driver and later the driver provides corresponding current to the motors. FPGA produces signal for the 3 axes same time.

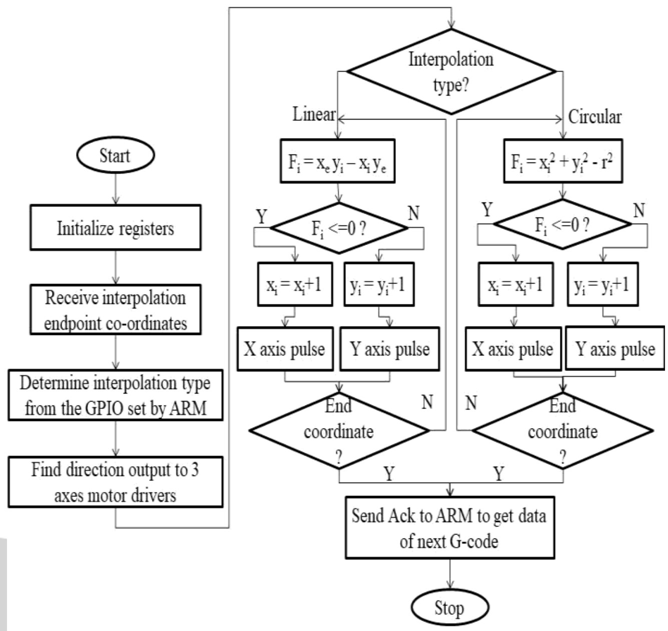

Fig 7. FPGA flowchart

Figure 7 shows the implemented interpolation algorithm in FPGA. On receiving the co-ordinate information, it checks out the four GPIO pins connected to ARM for the purpose of conveying the type of interpolation. Then the control splits off into different states for linear, circular clockwise and circular counter clockwise interpolations and later inside each state, the corresponding algorithm is executed. The direction of movement of each motor is calculated depending on the quadrant and start and end points of the interpolation in both cases of linear and circular interpolations. Then the error function is calculated as in [3] and [5].

For linear interpolation,

$$Fi = Xe * Yi - Ye * Xi$$

Where (Xi,Yi) are the initial co-ordinates and (Xe,Ye) are the end co-ordinates of the interpolation to be done.

If the error function is less than or equal to zero, x axis is incremented by one unit. If the error is greater than zero y axis is incremented by one unit. After each movement, checking is done whether the end point has reached or not. If reached the end point, then it represents the end of job.

For circular interpolation,

$$Fi = x^2 + y^2 - r^2$$

If the error function is less than or equal to zero, x axis is incremented by one unit. If the error is greater than zero y axis is incremented by one unit. As per the quadrant in which the cure belong, the corresponding increment or decrement relative to the motion is given by table 2. For example consider our end point is on first quadrant and direction of motion is clockwise then the value of X coordinate should have to increment and Y coordinate should have to decrement for to make the trajectory. Similarly if the cure is on cure is on first quadrant and

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direction of motion is anticlockwise then the value of X coordinate should have to decrement and Y coordinate should have to increment for to make the trajectory. Next case is the cure is on second quadrant and direction of motion is anti-clockwise then the value of X coordinate should have to decrement and Y coordinate should have to decrement for to make the trajectory and the cure is on cure is on second quadrant and direction of motion is clockwise then the value of X coordinate should have to increment and Y coordinate should have to increment for to make the trajectory.

Table 3. Unit Increment in Coordinates

Direction	Clockwise				Anti-clockwise			
Quadrant	1st	2nd	3rd	4th	1st	2nd	3rd	4th
xi	1	-1	1	-1	-1	1	-1	1
yi	-1	1	-1	1	1	-1	1	-1

After each movement, checking is done whether the end point has reached or not. If reached the end point, then it represents the end of job.

As the end of job state is reached, an acknowledgement is given to ARM representing the end of the current interpolation and as a request to send the data corresponding to next g-code to execute the next interpolation. This continues for each line of g-code until the last line is reached and the work is complete.

V. Results

The intended CNC wood carving machine hardware prototype was successfully assembled and both linear, circular interpolations were tested in hardware. The proposed algorithm is found to be accurate and the algorithm for linear and circular algorithms are easy to implement and avoids repeated complex multiplications compared to the other reviewed algorithms.

UART interfacing was implemented in ARM for the communication between PC and ARM using LPC Xpresso software and checked using a GUI developed with Visual Studio software. The developed GUI was successful in transferring G-code file and other interfacing such as Start/Stop control of the machine was made possible with the window. Output from ARM is the co-ordinate and radius information fetched from a single G-code and the same is sent via SPI pins of ARM to FPGA. 8 bit transmission and MODE 0 SPI is used in this project. So each data is sent in 8 bit binary form with the 8 clocks. SPI data received by the FPGA is used for generating interpolation parameters. MODE 0 SPI is implemented in FPGA in Slave mode.

Later, the working of interpolation algorithm was tested in hardware. A pattern was successfully carved in softwood as shown in figure 8. The pattern has both linear and circular interpolations involved.

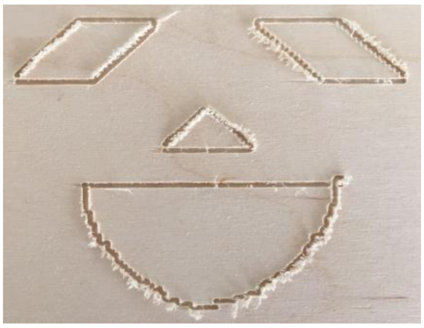

Fig 8. Hardware outcome on softwood

VI. Conclusion

The proposed work introduces a 3-axis CNC wood carving machine based on ARM and FPGA with the entire software and hardware shares involved. The proposed algorithm is proved to be easy to implement and avoids repeated complex multiplications compared to the other reviewed algorithms. Interpolation algorithms are implemented in Verilog HDL with the Spartan-6 low-end FPGA. A completely open hardware for the purpose of three dimensional wood working is targeted with good efficiency and at low cost. The machine operation can be extended to multi axis platform in future. It supports further customisation with expansion oppurtunities and reconfigurability of the open properties. Modularity is attained within ARM and FPGA as the two controllers are implemented separately and with different purposes. This has added up to the flexibility for future expansions. Optimized linear, circular interpolation algorithms with hardware implementations are used for the motor control which makes real time complex computations efficient and more feasible.

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