Smart Doorbell for the Hearing Impaired Using FPGA.

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***Abstract*— This paper presents a device which is very beneficial for the people with hearing impairment or hearing related problems. This project leverages a push button to replicate the doorbell, a camera module to get the live feed of the visitors at the door, a knock sensor to detect the knocks on the door, a microphone sensor, to detect sounds like human speech it also works like the knock sensor, if knock sensor faces any problem microphone sensor works as a substitute of it, a LDR is also used to control the intensity of the LED according to the ambient light conditions, a vibration motor is used to alert the user by giving vibratory feedback, with control unit being the FPGA. Digital Signal Processing is also integrated with the device to filter the signals reaching the knock sensor and microphone sensor so that they don't get triggered because of unwanted noises. The device gives two types of feedbacks, tactile and visual feedback with the help of a vibration motor and LED.**

Keywords—FPGA, LDR, Digital Signal Processing, visual and tactile feedback.

I. Introduction

In the era of growing technology, technological advancements to improve the quality of life of the people with disabilities are also rising significantly. Keeping all those advancements in mind, this project is proposed to help the people with hearing disabilities to make their daily life more inclusive and convenient. One of the major problem faced by the people with hearing impairments is when no one is in the house along side them they won't be able to know the presence of visitor at the door which is a notable issue so in order to tackle that the proposed project is a affordable and feasible solution which is both accurate and efficient. The device uses an FPGA, knock sensor, microphone sensor, push button, camera module and a vibration motor. One of the major issue faced by such a device is the effect of noise, to tackle it is integrated with a band-pass FIR filter designed in MATLAB.

Specifically FPGA is used for this project because FPGA can perform tasks like parallel processing, signal processing, etc. The FPGA acts as a central unit for controlling the working of the entire system. The device makes use of advanced but easily understandable technologies to make an efficient, sustainable, robust and a user friendly device, ensuring no visitor is missed especially when there is no one in the house except the person who is suffering from hearing impairments. To alert the user about the visitor the device provides two types of feedbacks, tactile and visual feedback, with the help of a vibration motor and an LED. The intensity of the LED is controlled with the help of an LDR or the light sensor, depending on the ambient light conditions ensuring visible visual feedback in any kind of light conditions irrespective of day and night. These features make the device more adaptive and reliable under different circumstances. This system is a perfect example of how simple technologies can play a major role in improving the quality of life of the needy people.

The idea of smart doorbell is beyond the idea of just a normal doorbell. The device is a perfect illustration on how software and hardware can be integrated to create a device which is efficient, reliable and easy to use. It's designed using multiple sensors and programming in multiple software's like ModelSim and MATLAB using Verilog Programming and MATLAB programming respectively, showcasing a practical application of modern electronics and embedded systems. The system is not only designed for present use, but can be easily added with new features over the time. The proposed system aims to make the device accessible to everyone, offering both security and convenient features to the individuals with hearing impairments and also a step towards more inclusive technology. The proposed system is a perfect example of how innovatively technology can be used to make the world accessible to each and every individual irrespective of their health conditions.

This device is definitely going to be a very helpful gadget for the people with hearing impairments. The proposed system is cheap and efficient, as it uses simple sensors making the system cheap, and the control unit of the system is an FPGA which has the ability to perform tasks like parallel processing and digital signal processing, because of these task performing abilities of the FPGA, the proposed system works as expected fulfilling all the requirements making the system accurate, efficient and robust.

II. Related Works

Many research works have been done which align with the research done for the proposed device. Every research work resulted in significant updates of the device. Every related work mentioned has played a major role in assisting the successful completion of this research. The related works have helped in designing the system in one way or the other. The idea of the system is taken from a system which was implemented using IoT[1], which consisted of an Arduino Microcontroller and LED's placed in different rooms to provide visual feedback to the user about the presence of the visitor at the door, a camera module was also placed to capture the pictures of the visitors at the door, the research work gave major insights about the proposed system. Another research work used a Pi-Cam for alerting the hearing impaired individuals[2], it was a combination of IoT and wireless communication, the cam captures the visitors at the door and the wireless alert system gives feedbacks to the visitor at the door the feedbacks were tactile or visual, this work gave a clear understanding about wireless communication and feedback mechanism for the proposed system.

There is another research work which gave an idea about the wearable technology[3] which was implemented using nRF24L01 wireless module which assisted in detection of doorbell press and tactile feedbacks were given to alert the user about the visitor immediately, this work gave major insights about making the proposed system portable and convenient by designing it as a wearable device. The other research work implemented a door alert system[4] which is based on IoT, it is integrated with multiple sensors, cameras and other wireless communication modules to detect intrusions or the visitors and notify the user with the help of notifications on smartphones or other connected devices, this work gave clear insights on integrating the device with other devices like smartphones making the system wireless. The other research work implemented the smart doorbell alert system[5] it uses a motion sensor to detect movements at the door and alert the user, it uses neo-pixels to alert the user when the bell is ranged, it gave an idea of adding a motion sensor in the future.

There is another research work which implemented a smart doorbell for smart home automation[6] which uses biometric technology using voice, iris or facial recognition, it is designed as a wearable device. This work gave great clarity on how the proposed system can be integrated with additional features, this increases the security of the home when the hearing impaired individuals are alone at home. The other work implemented a wireless smart doorbell with sensors and IP camera[7], the device is integrated with a mobile app to enable remote monitoring. This work gave a clear-cut idea on integrating the system with a mobile app for the hearing impaired people to monitor the movements of visitors remotely as well. The other work implements a security system specifically for people with hearing inability[8] with features like knock detection and feedback alerts through SMS. This work gave the idea of integrating the device with a knock sensor for detecting the knocks, thus improving the detection part of the system.

The other research work is based on a wearable orthotic device[9], this device gave insights on how accurately a wearable device can be made for specific purposes. The other research work implemented a controlling device for smart home[10] this device is a perfect example of helping the people with inabilities, this paper gave a good insight on how to integrate the device with the smartphone and control the device with the smartphone, thus enabling the user to control the working of the system through the smartphone, this is helpful for the people with both inability to move and those with hearing impairment. The other research work implemented a Medi-Suit for the bedridden people[11] which is a wearable device it is designed to continuously monitor the health condition of the bed-ridden patients, this work gave a clear insight of how a wearable device can be implemented in multiple ways, it gave a major insight on developing a wearable device and further improve it. The other research work implemented a smart bulb with brightness control[12], this system controls the intensity of the LED’s , this work gave a clear insight on how the intensity of the LED’s can be controlled for better visibility to the user.

There is another work which implemented a smart doorbell with face recognition[13], this system integrates face recognition with the doorbell setup, making the system more flexible and secure. This work gave a greater insight which helped the proposed system, as the hearing impaired people in the home will be safer as no one can break into their house because of the face recognition technique. The other work implements, smart home is implemented using a FSM, finite state machine model[14]. This system clearly shows the control of everything based on the different states and transitions, this work gave a greater insight on implementing the proposed system in similar fashion as the smart home. The other work implemented a multi-tiered alert system for intrusion and disaster prevention[15], the system is integrated with alarms along with notifications for responses to any unusual instance. This work gave a greater insight on how to implement multiple alert mechanisms in the proposed system.

Every research work have contributed equally in the accomplishment of the proposed system, right from the idea stage till the completion of the device. All the research paper had their own importance in the design process of the proposed system, few research papers gave the idea of designing such type of a device[1][4][5][14][15], while some papers gave the ideas of the features to be integrated with the device[2][3][6][12], and the others gave a brief idea about how the device can be improved by integrating it with new features over the time[7][8][9][10][11][13]. The proposed new system is made such that the problems faced by the older research works are resolved making the new device a prominent one.

III. DESIGN AND IMPLEMENTATION

A. *System Architecture*

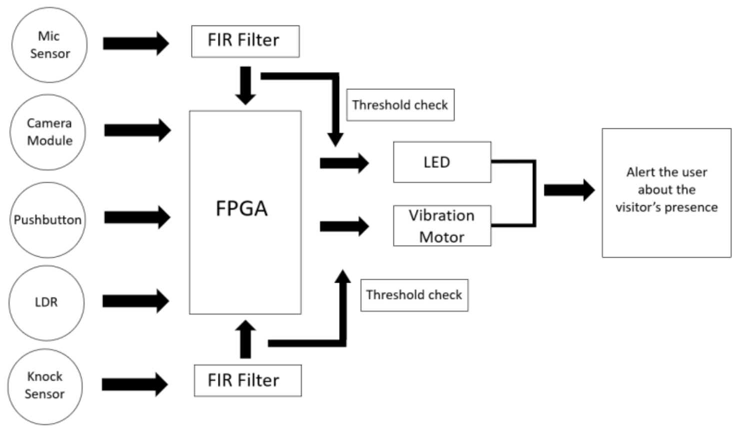

Fig.1 System Architecture of the proposed system.

Figure 1 shows the system architecture diagram of the proposed system. The central control unit of the system is an FPGA, all the sensors and the pushbutton i.e. the doorbell are connected to the FPGA. When the pushbutton is pressed, the signal is sent to the FPGA where it is processed and synchronized with the clock. The filtering unit will filter the noises. The FIR filter is designed in MATLAB to integrate it with ModelSim software a hex file is generated in MATLAB which is then read with the help of verilog programming. The filter is integrated with knock and mic sensors to remove the noise from the system and avoid unnecessary triggering of the system. The signals from knock sensor and mic sensor are sent to the FPGA where the signal filtering is done and system is triggered only if the frequency of the signal is in the selected range else the signal will be filtered out. In order to alert the user that the system is triggered two feedback output components are attached, an LED for visual feedback and a vibration motor for tactile or vibratory feedback.

The system uses a camera module as well which always stays in ON state except during reset providing live streaming feature to the user. An LDR is also used to control the intensity of the LED in various environmental lighting conditions making the system more efficient and robust. All these input signals are sent to the FPGA where the signals are synchronized with the clock as mentioned above. The signals from knock sensor and mic sensor after getting filtered are checked with the threshold value if the received value is greater than the threshold the system is triggered. Whereas, pushbutton directly triggers the system when pressed unlike knock and microphone inputs it doesn't go under signal filtering and threshold comparison. The camera module just works like a CCTV camera but it doesn't have any role in triggering the system on detecting the visitor at the door. This is the overall architecture of the proposed new system.

Module diagram-:

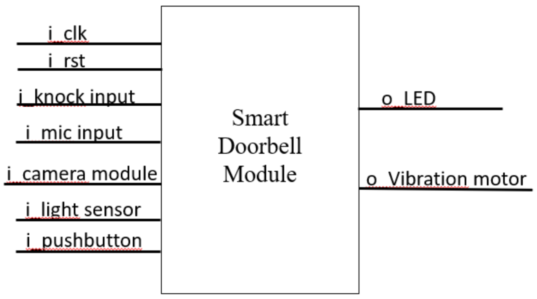

Fig.2 Module Diagram of the proposed system

Port name	Input/Output	Function of the port
i_clk	Input	To provide clock signal for synchronization of the system
i_rst	Input	To reset the entire system to its initial state
i_push_button	Input	Signal from the pushbutton for detecting doorbell presses
i_knock_input	Input	Signal from the knock sensor for detecting knocks
i_mic_input	Input	Signal from the knock sensor for detecting claps or loud noises
i_light_sensor	Input	Signal from the LDR to measure the ambient light
i_camera_module	Input	Signal from camera module to get the live feed of visitors
o_LED	Output	Output signal to provide visual feedbacks to the user
o_Vibration_motor	Output	Output signal to provide tactile feedbacks to the user

Fig.3 Module Description Table

The above figure 2 shows the module diagram of the proposed device, it consists of clock, reset, knock sensor, microphone sensor, light sensor and push button as inputs, LED and vibration motor act as the outputs of the system. Knock sensor is used to detect the knocks, the microphone sensor is used to detect the knocks and along with the knocks it can also detect sounds like human voice as well, it can work as a substitute to the knock sensor if in case the knock sensor is malfunctioned. The camera module is used to get the live feed of the visitors at the door. Pushbutton works like a doorbell. The light sensor controls the brightness of the LED based on the ambient light conditions. The FIR filter works as a bandpass filter to filter the input signals reaching the FPGA from knock and microphone inputs and pass them to the output only if the signals cross the threshold else the signals will be rejected, this is essential because by doing this triggering of system due to noise can be avoided. LED and vibration motors act as outputs as they provide feedbacks to alert the user about the visitor.

B. Flow Chart

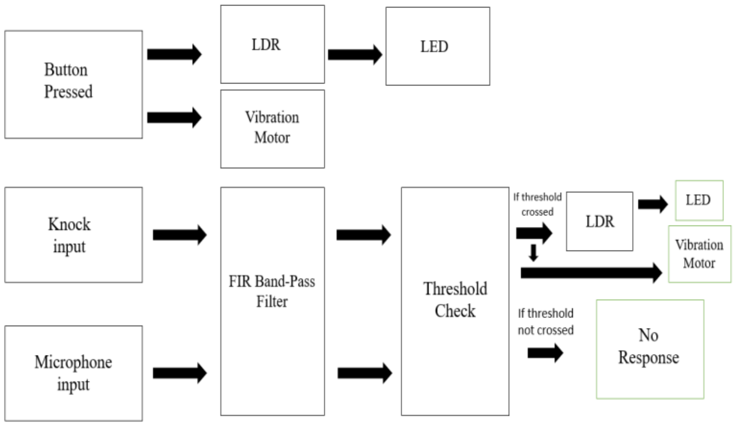

Fig.4 Flow chart of the working of proposed system

The above flow diagram shown in figure 4, shows the working of the device, and how the output is obtained, when the push button is pressed both LED and Vibration Motor go high, LED gives visual feedback and Vibration motor gives tactile or vibratory feedback to the user, the brightness of the LED is controlled by the light sensor i.e. LDR. The knock and Microphone inputs pass through a FIR Band-Pass filter designed in MATLAB software, then they go through a threshold check if they lie in the particular threshold the signals will trigger the vibration motor and the LED if not there won't be any output response of the system, by doing so the device effectively rejects the noisy components of the signals and only triggers the system when the signals of a particular frequency. If the knock sensor is not working then there is no need to worry because microphone sensor can act as a substitute to the knock sensor by detecting the knocks and along with it, microphone sensor can also detect signals like human voice.

To summarize, the flow chart shows the complete work flow of the proposed system, it includes processes like ambient light detection for controlling the intensity of the LED, band pass filtering and threshold check for noise removal to avoid unwanted triggering of the system leading to false alerts and eventually degrading the efficiency of the system. The expected output of the system is predicted from the flow chart as it clearly shows how the input signals travel through the system and go through different kinds of processes right from the input stage till the output stage where the output of the system is obtained in the form of alerts to the user. A new user can easily understand the working of the system by looking at the flow chart as it is made in such a way that it is understandable for a person who is a new user. This flow chart is the best way to make the new user understand the working of the proposed device and to make him/her familiar with the system so that they can maintain the device on their own without the need of specialized technicians, implying that the system is easily maintainable.

C. Timing Diagram

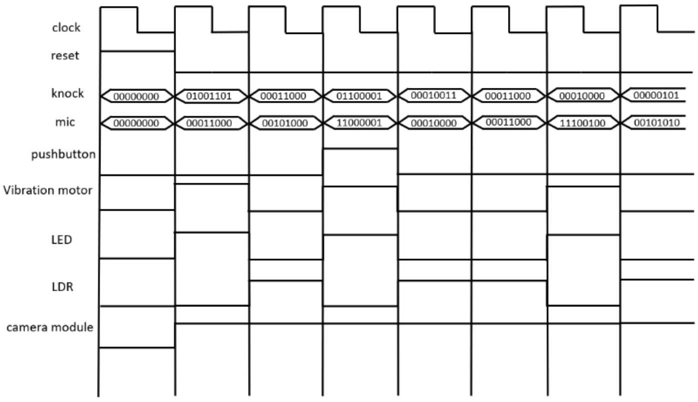

Fig.5 Expected output of the system

The timing diagram shown in the above figure 5, is the expected output of the proposed system. The clock and reset are used to synchronize the different parts of the circuit and the reset signal is used to restore the original state of the system, whenever the reset stays high the entire output of the system is null or the original state which should be attained by the system. Knock input and mic input are the signals which will be taken as inputs by the knock sensor and the microphone sensor, these sensors respond to audio signals and as we know that the audio signals are highly prone to noise the signals should be filtered before they get into the knock sensor and microphone sensor. Low pass filter or High pass filter will not be an optimum choice for noise filtering as they might become very feeble signals or very high like noise so in order send a particular range of signals bandpass filter has to be used for the filtering of the signals.

The Band-pass filter is designed in MATLAB software using MATLAB programming, it is a FIR Bandpass hamming filter. The bandpass filter is designed in such a way that the high frequency noises are removed and only the desired frequencies are taken, after completing the design of the bandpass filter a hex file is generated in MATLAB itself, then the generated hex file is read with the help of Verilog Programming, as Verilog cannot read the signals directly. After reading the hex file the filter is integrated with the knock and microphone inputs by instantiating filter coefficients into knock and microphone sensor modules, after doing all these steps the knock in and microphone in are compared with the threshold values and if the values are in the threshold value range the LED and vibration motor outputs go high else there won't be any response and the brightness of the LED is controlled by the LDR sensor. If the LDR is low that means the intensity of the light will be high and if the LDR is high the intensity of the light will be low. It all depends upon the ambient lighting conditions.

IV. Experiments and Results

A. Test Bench

The test bench for the proposed device is written in such a way such that the working of the device is clearly evident. In the test bench all the signals are instantiated from the top level design module along with the clock, reset and other signals. The test bench is used to take different test cases to verify if the designed system is working properly or not. The signals like, clock, reset , knock in, mic in, button, LED, vibration, camera active and light output are instantiated in the test bench instantiating the variables helps in linking the top module code with the test bench. In the test bench ten scenarios are taken. Each case is different from the other the test cases so that the results don't overlap with one another. In the test bench the time period is also mentioned i.e. the duration of each signal is decided in the test bench and a finish statement is also there which signifies the completion of the simulation.

Test bench we can give manual inputs as well which is done in the test bench of the proposed system the test bench is written such that some of the signals satisfy the conditions to be met and some of the conditions don't in this way the working of the system can be seen evidently and if any error arises it can be identified easily looking at the test bench waveforms which are generated by the test bench code of our proposed design. In the top module, the behaviour of the system is defined like the LED is taken as the conjugate of the LDR sensor, vibration motor is taken in synchronous with the LED output. The camera module is taken as high always because the camera module is used to take the live feed of the visitors at the door to let the user know who is at the door whenever the alert is triggered. Ten test cases taken in the test bench code should be verified , if it is verified then it implies that the system is working effectively as required.

B. Simulation Results

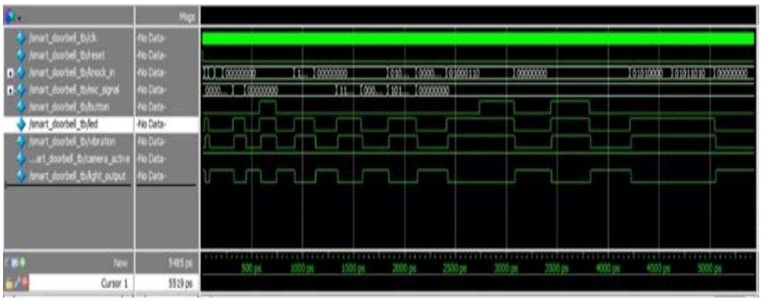

Fig. 6 : Simulated output of the system.

Test case 1-: Normal Knock detection.

Test case 2-: Light Knock detection.

Test case 3-: Microphone detecting speech.

Test case 4-: Button press without knock or speech

Test case 5-: Loud Knock

Test case 6-: Microphone detecting loud sound

Test case 7-: Simultaneous knock and speech

Test case 8-: Button press after knock

Test case 9-: Button press with no signal

Test case 10-: Multiple knocks in quick succession

Figure 6 shows the simulated results of the proposed system. All the test cases mentioned above are taken to see if the system is working perfectly as expected or not. After the simulation it is evident that the system is working perfectly as expected. The system is perfectly detecting all kinds of signals which were expected to be detected like, soft and loud knocks, push button press, or simultaneous knock and mic triggering and some more cases, all these cases are successfully satisfied as per the expected output. All these test cases are considered keeping the real world scenarios in mind.

V. CONCLUSION

The proposed device is an innovation done using simple yet advanced technologies, the device is easy to use and easy to maintain, the user can easily understand the working of the device, the device is efficient, accurate and sustainable which is one of the biggest advantages of the device. The feedback mechanisms play a major role in alerting the user about the visitor at the door. In the proposed system it is ensured that the feedback or alert mechanism take place efficiently. Since the device uses FPGA as it's central control unit all the tasks are performed simultaneously due to the parallel processing ability of the FPGA. The use of FPGA makes the device more dynamic as it is possible to manipulate the code in the program files according to the requirements. Hence FPGA is chosen as the control unit for the proposed device. Thus, making it a reliable and efficient device. The accomplishment of the project not only signifies the application of theoretical knowledge but also shows the contribution towards creating impactful solutions for the society.

VI. FUTURE WORKS

In future as new technology emerges newer features can be added to the proposed system. The device can be integrated with a mobile app, this enables the user to perform all the operations remotely, without the need of physical interference. This enhances the adaptability of the device by targeting the individuals with physical disabilities along with hearing disabilities. This system can be integrated with image processing techniques like face detection and other algorithms, since the device uses a camera module, this could be an effective advancement. The machine learning algorithms can also be integrated with the system to detect different types of sounds and tell the user by what sound is the system triggered. LED's can be added for detecting if any fault has occurred in the system, individual LED's for individual sensors will make it more convenient. The main motto of the proposed system is to make the system affordable and available to everyone. As the device uses FPGA the system can be modified greatly according to our requirements there is a high scope of advancements to this system to tackle the problems faced by the hearing impaired people in the future.

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Verilog Programs-:

```
module light_sensor (
input led_state,
output reg light_output
 );
always @(*) begin
light_output = ~led_state;
end
endmodule

module vibration_motor (
input knock_signal,
input mic_signal,
 input button_signal,
output
reg vibration
);
always @(*) begin
vibration = knock_signal | mic_signal | button_signal;
end
endmodule

module fir_filter (
input clk, reset, input [7:0] signal_in,
output reg [7:0] signal_filtered
); reg signed [31:0] coeffs [0:63];
 reg signed [31:0] shift_reg [0:63];
reg signed [31:0] acc;
integer i;
initial begin
 for (i = 0; i < 64; i = i + 1) begin
coeffs[i] = 0;
end //
$readmemh("fir_coeffs.hex", coeffs);
end
always @(posedge clk or posedge reset) begin
if (reset) begin
for (i = 0; i < 64; i = i + 1) begin
shift_reg[i] <= 0;
end
acc <= 0;
signal_filtered <= 0;
end
else begin
acc = 0;
shift_reg[0] <= signal_in;
for (i = 1; i < 64; i = i + 1) begin
shift_reg[i] <= shift_reg[i-1];
 // Shift operation
acc = acc + coeffs[i] * shift_reg[i];
end
signal_filtered <= acc[31:24];
end
end
endmodule

module smart_doorbell_top(
 input wire clk, reset, input wire [7:0] knock_in, mic_signal,
 input wire button,
output reg led, vibration,
output wire camera_active, // Set as a wire since it's always active
```

```
output reg light_output );
 wire knock_detected, mic_detected; // Knock and microphone detection thresholds
parameter KNOCK_THRESHOLD = 8'd75;
 parameter MIC_THRESHOLD = 8'd150; // Knock detection logic
assign knock_detected = (knock_in > KNOCK_THRESHOLD); // Microphone detection logic
assign mic_detected = (mic_signal > MIC_THRESHOLD); // Camera is always active
assign camera_active = 1'b1;
 always @(posedge clk or posedge reset) begin
 if (reset) begin led <= 0; vibration <= 0; light_output <= 1; // Light is off when LED is off
end
else begin led <= knock_detected || mic_detected || button; vibration <= led; // Vibration directly follows LED
 light_output <= ~led;
end
end
endmodule

module push_button (
 input clk, input reset, input button,
output reg button_pressed
);
 always @(posedge clk or posedge reset) begin
if (reset) button_pressed <= 0;
 else button_pressed <= button;
end
endmodule

module knock_sensor (
input clk, input reset, input [7:0] knock_in,
output reg knock_detected
);
wire [7:0] filtered_knock;
fir_filter knock_filter (.clk(clk), .reset(reset), .signal_in(knock_in), .signal_filtered(filtered_knock));
parameter KNOCK_THRESHOLD = 8'd75;
 always @(posedge clk or posedge reset) begin
if (reset) knock_detected <= 0;
 else knock_detected <= (filtered_knock >= KNOCK_THRESHOLD);
end
endmodule

module camera_module (
 output reg camera_active
 );
 initial begin camera_active = 1;
end
endmodule

module microphone_sensor (
input clk, input reset, input [7:0] mic_signal,
output reg mic_detected
);
wire [7:0] filtered_mic;
fir_filter mic_filter (.clk(clk), .reset(reset), .signal_in(mic_signal), .signal_filtered(filtered_mic));
parameter MIC_THRESHOLD = 8'd150;
always @(posedge clk or posedge reset) begin
if (reset) mic_detected <= 0;
else mic_detected <= (filtered_mic >= MIC_THRESHOLD);
end
endmodule
```

MATLAB CODE-:

```
N = 30;
 fs = 8000;
 fc1 = 1000;
fc2 = 3000;
wc1 = fc1 / (fs / 2);
 wc2 = fc2 / (fs / 2);
 h = fir1(N, [wc1 wc2], 'bandpass', hamming(N + 1));
 fileID = fopen('fir_coeffs.hex', 'w');
if fileID == -1 error('Error opening file. Check file permissions or path.');
end
for i = 1:length(h)
coeff_fixed = round(h(i) * 32768);
if coeff_fixed < 0 coeff_fixed = coeff_fixed + 65536;
end
fprintf(fileID, '%04X\n', coeff_fixed);
end
fclose(fileID);
 disp('Hex file "fir_coeffs.hex" has been created successfully.');
```