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Design of a 3D Printed Open Source Humanoid Robot

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Abstract
Nowadays, humanoid robots with great capabilities used in a variety of purposes to serve humans have become an integral part of our lives. In this study, we have developed a low-cost humanoid robot that can be fabricated with an open-source 3D printer. Firstly, the 3D-CAD model of the humanoid robot was created using source codes of the "InMoov" project which is originated by Gael Langevin who works as a designer on his project since 2012. The humanoid robot involves approximately 685 parts built from the PLA (Poly-Lactic Acid) raw material. After that, a new electronics system based on the embedded controllers which have been controlled with the python programming language has been designed. This robotic platform controlled with the help of voice commands has the capability to communicate with people. Furthermore, a skilled prosthetic hand controlled according to the commands from a smart glove, can grasp and holds objects, have been specially developed in this study. When comparing to the existing commercial humanoid robots, this humanoid robot developed as specific has a substructure which is not only low cost but also open to new improvements as well.

1. Introduction

The automatically operated machines named "Robot" can replace human activities, perform functions in a human-like manner, although it may not resemble human beings in appearance [1]. Humanoid robots have been built as similar to humans and are able to mimic human movements. The production of a robot usually covers the challenging design and construction processes for researchers in science and engineering fields [1, 2]. Especially, humanoid robots which have dual arms and resourceful hands demonstrate great significance in the home environments, health, and care service areas. They can be used for many services to human beings such as accompanying person, surgery operations, manipulation, and material handling etc. [3]. Recently, artificial intelligence studies about humanoid robots have become the most impressive field for clever robotics systems. Therefore, many large scientific research universities, institutions, and private sector delegates continue to work as intensely in this area.

Many humanoid robots have been fabricated in recent years. Some of them are ranked WABIAN-RV [4], ASIMO [5], HRP [6], NAO [7], "Pepper Robot" [8], KHR-1 [9], and Robot H10 [10] according to various categories.

However, some humanoid robots are too expensive or can often be bulky due to their non-optimized structure. In order to interact with humans easily, the robots with the light-weight structure are needed to equilibrate their energy efficiently. High accuracy humanoid robots with flexible structure need a lightweight and high stiffness structures controlled by the actuators [11]. As humanoid robots with heavy components cause to spend high power consumption it decreases battery life. Therefore,

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battery-based most humanoid robots are designed as lightweight due to the fact that they will help working longer [12,13]. Characteristically, there is a lot of production methods with a lightweight design. One of them is a 3D printing method which is also known as additive manufacturing (AM). AM is defined as the process of joining materials to create objects from 3D model data [14, 15]. The modern AM is occurred by the main current 3D printing techniques, namely fused deposition modeling (FDM), stereolithography and laser sintering processes from the late 1980ies. AM patents have been ranked between 1979 and 2000 [16].

3D printers build objects using an AM process. Material layers by placing on top of each other occur to form the base for the next layer. Most 3D printers use thermoplastic inks based on polymer. These polymers become soft and flexible under a certain temperature range. When the printing process is finished, they are re-solidify.

Commands for positioning the nozzle of the 3D printer are received by means of a print file format. There are many print file formats in use. Various CAD (Computer-Aided Design) programs such as AutoCAD, Solid Works, and Fusion 360 have been used to produce files. Nowadays, new design tools, cameras, laser scanners can directly generate a print file by capturing photos that have various angles from 3D objects [17].

In this study, it is aimed the design and development of a humanoid robotic project by using the 3D printer technology with the purpose of achieving research and educational targets for universities. Furthermore, a speech recognition system is roughly described on the humanoid robot as well as.

Section 2 and Section 3 introduce the material selection, fabrication of the various robot parts using the 3D printer according to the stereolithography file-formats obtained from the original "InMoov" project, and the creation of the upper body by assembling 3D printed parts, respectively. Section 4 gives detailed information about hardware designs of the humanoid robot such as main control system, servo motors, skillful hand, head, shoulder, elbow control, and theirs the electrical connections between each other.

2. Material and Method

Generally, PLA (polylactic acid) which is a kind of polymerized from natural sources is used in desktop printers [18]. PLA has a larger strength and lower fragility than the traditional ABS (acrylonitrile butadiene styrene). PLA parts obtained via 3D printers have often been very used in the medical field applications due to their biocompatibility properties as well [19].

Table 1 shows the 3D print file formats in use. The humanoid robot in this project is created using the Stereo-Lithography (.STL) format. The 3D fabrication system creates a 3D printed object using additive processes for one extruder. In an additive process, an object is fabricated by layer by layer until the object is created.

Nowadays, as printers developed, both open-source and registered 3D file formats will be developed. For example, the 3D Manufacturing Format (*.3MF) was pronounced in 2015. The 3MF format is tailor-made for additive manufacturing and provides valuable benefits such as Full-Color Support, Build Tray Support, Unicode -Human Readable, etc. to additive manufacturing workflows that other formats lack [20].

Table 1. Some 3D Print File Formats

File Format	Description
*.STL	Stereo lithography; 3D single color.
*.WRL	Virtual Reality Modeling Language for multi-color 3D printing (at least two extruder)
*.OBJ	Image format with 3D coordinates
*.X3G	Used by Makerbot Replicator
*.PLY	Polygon format for scanners
*.3MF	XML based data format

Figure 1 indicates additive manufacturing method through the 3D printing process. Figure 2 and Figure 3 show the photos of varies parts which are 3D printed according to obtained *.stl file formats from original "InMoov" project, respectively [21].

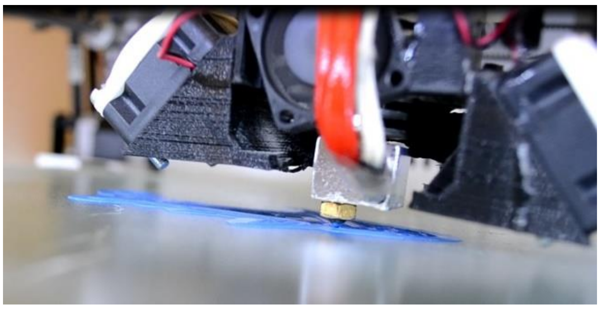

Figure 1. Additive manufacturing with 3D

3. The Completely 3D Printed Upper Body

The first open-source robot "InMoov" can be printed in 3D, compounded, and programmable. The InMoov project has been launched in 2012 by French sculptor and designer Gaël Langevin. It has been developed ever since by a worldwide community of robotics enthusiasts [21].

All parts of this humanoid robot which has the biodegradable PLA-based filament structure can be built by using the 3D printer. The 3D printer which has a working area of 200x300x180 mm has been chosen for the production of robot parts. The humanoid robot's "skin," joints, gears, and many other pieces have been 3D printed. Some of the robotic parts, its head design, and the upper body obtained by assembling 3D printed parts are shown in Figure.2, Figure.3, and Figure 4, respectively in detail.

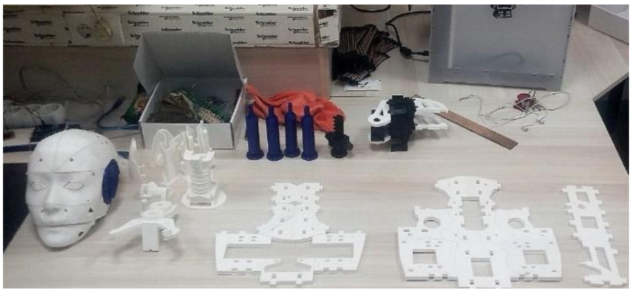

Figure 2. InMoov open source humanoid robotic parts

Figure 3. InMoov open source humanoid robot head design

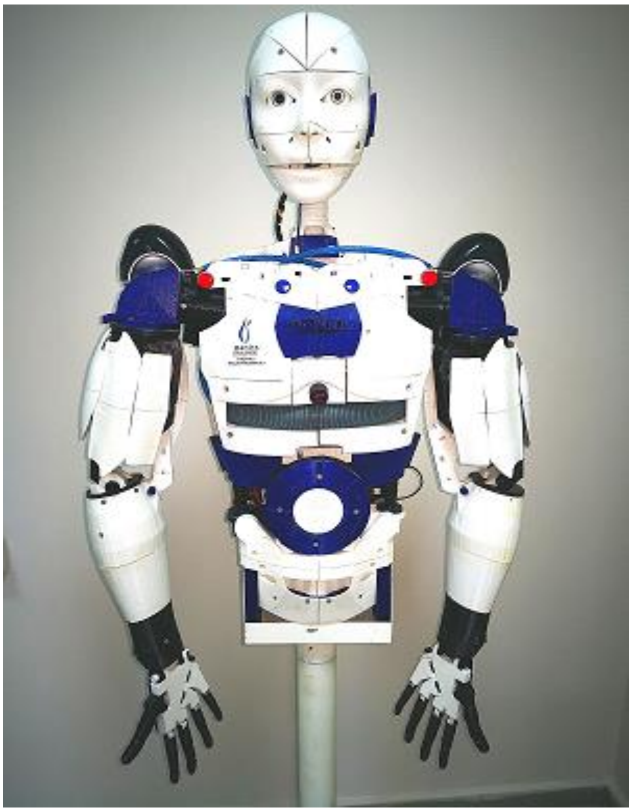

Figure 4. The front view of the humanoid robot

4. Hardware Design of the Humanoid Robot

4.1. Control System

In this study, it has been used a Raspberry Pi 3 Model B for hardware design of the humanoid robot. The Raspberry Pi with open-source code is an inexpensive, and can be used by connection it to a monitor, and using a standard mouse and keyboard. Table 2 indicates specific parameters of the Raspberry Pi 3 Model B [22].

The Raspberry Pi B model has a Cortex-A53 processor that applies the ARMv8-A architecture. This processor can be between one and four cores, it includes an L1 memory system for each and a single shared L2 cache.

Two 5V pins and two 3.3V pins are to be presented on the board, while OV is ground pins that are not configurable. The remaining all pins have 3.3V values. It means outputs are set to 3.3V and inputs are 3.3V-tolerant.

Both input and output pins of the GPIO are designated as high-3.3V or low-0V. This situation can be realized as easily with the use of internal pull-up or pull-down resistors. Pull-up resistors have been fixed for Pins GPIO2 and GPIO3, however, other pins can be configured with software.

The Cortex-A53 processor controls both static and dynamic power dissipation. The Cortex-A53 process with individual cores support four main levels of power management such as power domains, power modes, event communications and power management controller with communication [23].

The most important one of the Raspberry Pi's main parts is the GPIO (General Purpose Input Output) which has 40 pins are indicated in Figure 5.

Furthermore, the GPIO pins can be used as alternatively for various functions. Some of them are available on all pins, others on specific pins. The GPIO pins are ranked as four categories such as PWM - Pulse Width Modulation, SPI - Serial Peripheral Interface, I^2C - Inter-Integrated Circuit, Serial Communication Ports-TX/RX.

Table 2. Specific parameters of the Raspberry Pi3 Model B

SoC	BCM2835/2837
CPU	A53 @ 1.2 GHz.
Instruction Set	ARMv8-A
GPU	400 MHz
RAM	1GB SDRAM
Storage	Micro-SD
Ethernet	10/100
Wireless	802.11n/Bluetooth h4.0
Video Output	HDMI/Composite
Audio Output	HDMI/Headphones
GPIO	40

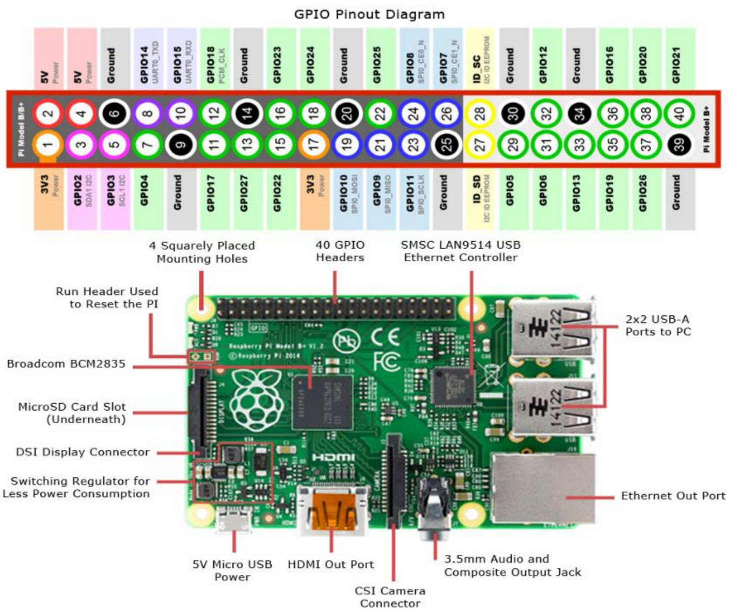

Figure 5. Raspberry Pi B model and its GPIO Pinout Diagram [22]

4.2. Servo Motors

Servo motors are used as two type generally to motion control of the humanoid robot such as head, shoulder, elbow, wrist, skillful hand etc. Two type servo motors are chosen for this study. One of them is MG996 type servo motor which controls both the left and the right skillful hand together. The MG996 servo has a metal gearing system resulting in extra high 10 kg stalling torque in a tiny package. It has some properties which are shown Figure 6, and Table 3 [24].

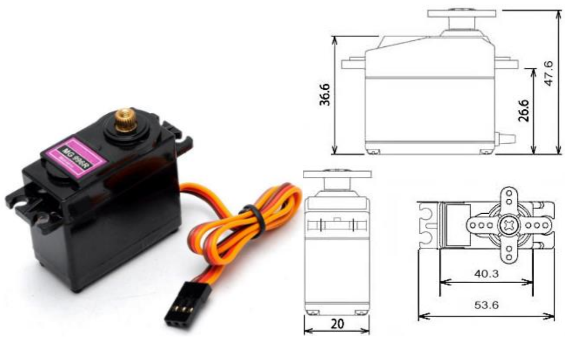

Figure 6. Real view of MG996 servo motor with its dimensions drawing

Table 3. Specifications of the MG996 type servo motor

Rotation	180 °
Weight	55gr.
Sizes	40.7 x 19.7 x 42.9 mm
Stop Torque and Current	9.4 kgf/cm at 4.8V, 11kgf/cm (2.5A) at 6V
Working Voltage Ranges	4.8V – 6.6V
Current Drawn	500 mA – 900 mA (6V)
Dead Bandwidth	1 µs
Wire Length	300mm
Temperature range	0 – 55 ºC

Another type servo motor is the Hitec HS805BB which has been used for the control of humanoid robot arms and its head. Some properties of the Hitec HS805BB are shown as detailed in Figure 7, and Table 4 [25].

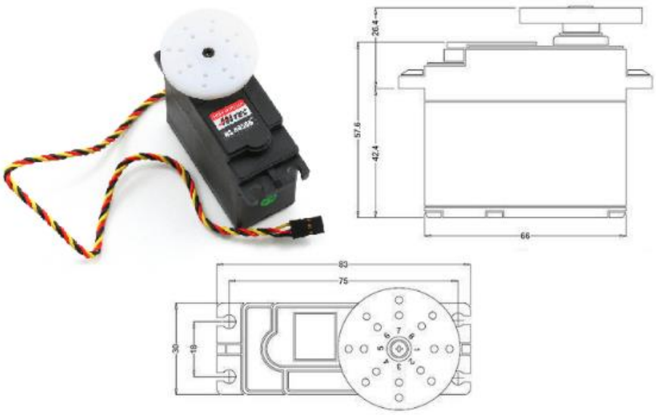

Figure 7. Real view of HS-805BB servo motor with its dimensions drawing

Table 4. Specifications of the HS-805BB type servo motor

Rotation	180 º
Control System	Pulse Width Control 1500 µs Neutral
Weight	152gr.
Sizes	Around 66 x 30 x 57.6 mm
Stop Torque and Current	19.8kgf/cm at 4.8V, 24.7kgf/cm (2.5A) at 6V
Operating Angle	45º/One Side Pulse Traveling 400 µs
Direction	Clock Wise/Pulse Trav. 1500-1900 µs
Working Voltage Ranges	4.8V – 6.0V
Current Drain	8 mA/IDLE – 700 mA No Load.
Dead Bandwidth	8 µs
Wire Length	300mm
Temperature range	-20 - 60 ºC

4.3. Skillful Hand

The left or right dexterous hand has five fingers and a wrist joint, respectively. The fingers are moved with the aid of the rope through five servo motors (MG966). It uses two ropes for each finger. One of them bends finger while other provides to come back to straight. When the left or right-hand touches an object, the fingers can clutch automatically it. Furthermore, it needs another servo motor-MG966 for the wrist joint. The wrist joint has back and forth rotation capabilities via the servo motor.

To improve various applications such as prosthesis, the skillful hand can be controlled by a data glove. As shown in Figure 8, the skillful hand can grip and grab some objects through data glove. When a human wears the data glove, it can be controlled simultaneously the prosthesis hand by moving own healthy fingers into the glove.

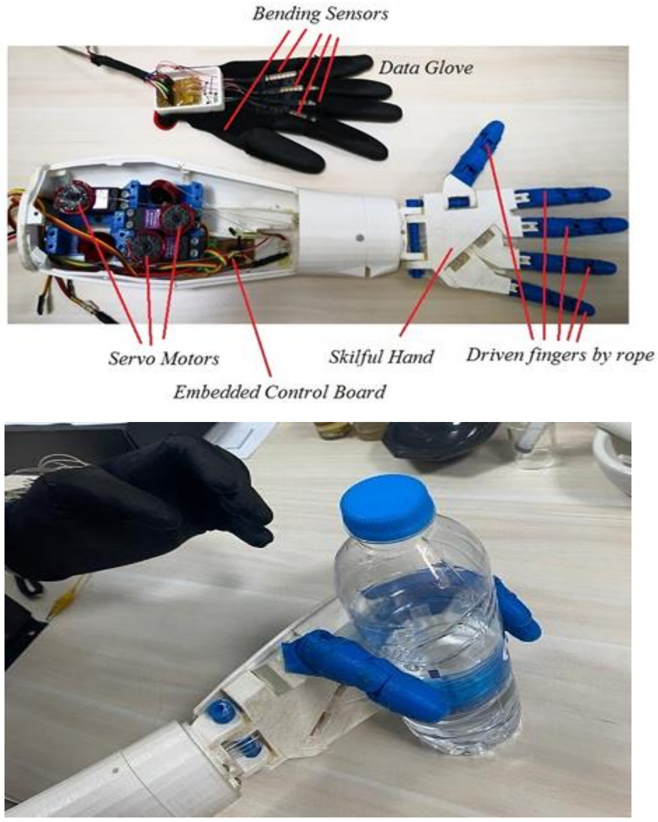

Figure 8. Left skillful hand of the humanoid robot and its control by the glove

Each of the five bending sensors are placed bonded on the top of every finger on the data glove. The bending sensors' resistance values are changed according to finger motions. In order to evaluate the change of the hand motions by bending sensor, an Arduino UNO card is used. The changes in the hand gesture convert to a series of voltage through a resistance voltage divider circuit. The bending angle and motion can be defined by using voltage signals associated with various resistance values.

The pseudo-code between the glove and the skillful hand is indicated in Figure.9.

sketch_dec12a.ino

```
#include <Servo.h>
const int pot1=A0;
const int pot2=A1;
const int pot3=A2;
const int pot4=A3;
const int pot5=A4;
Servo servo1;
Servo servo2;
Servo servo3;
Servo servo4;
Servo servo5;
int flexdurum1=0;
int flexdurum2=0;
int flexdurum3=0;
int flexdurum4=0;
int flexdurum5=0;
int pos1=0;
int pos2=0;
int pos3=0;
int pos4=0;
int pos5=0;
void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
servo1.attach(3);
servo2.attach(5);
servo3.attach(6);
servo4.attach(9);
servo5.attach(10);
}
void loop() {
flexdurum1=analogRead(pot1);
pos1=map(flexdurum1,0,1023,0,180);
{
  servo1.write(pos1);
}
flexdurum2=analogRead(pot2);
pos2=map(flexdurum2,0,1023,0,180);
{
  servo2.write(pos2);
}
flexdurum3=analogRead(pot3);
pos3=map(flexdurum3,0,1023,0,180);
{
  servo3.write(pos3);
}
flexdurum4=analogRead(pot4);
pos4=map(flexdurum4,0,1023,0,180);
{
  servo4.write(pos4);
}
flexdurum5=analogRead(pot5);
pos5=map(flexdurum5,0,1023,0,180);
{
  servo5.write(pos5);
}
}
```

Figure 9. The pseudo-code between the glove and the skillful hand

4.4. Head, Shoulder and Elbow Control

Head, jaw, shoulder, and elbow control sections have been driven by the Hitec HS805BB servos. The control modules consist of totally nine servo motors as three pieces on the head section including the jaw control, four pieces for two shoulders, and two pieces for elbows. The shoulder control section of the humanoid robot is shown in Figure 10.

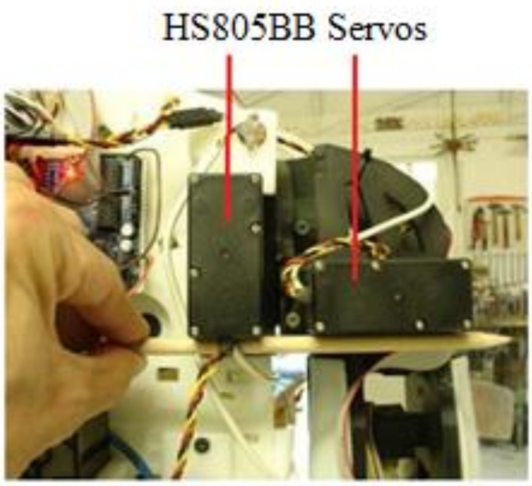

Figure 10. Shoulder joint of the humanoid robot [21]

4.5. Pulse Width Modulation (PWM) Control

Generally, a servo motor's electronics circuitry is built right inside the motor unit and has a positioning shaft with a variable, which usually is fitted with a gear. Most servo motors have three pins in which two of these are voltage terminals and the other is the signal terminal. The control signal is a pulse-width modulation (PWM) which is a way to control analog devices with a digital signal output. The servo motor's angular position owing to a high pulse is shown in Figure11.

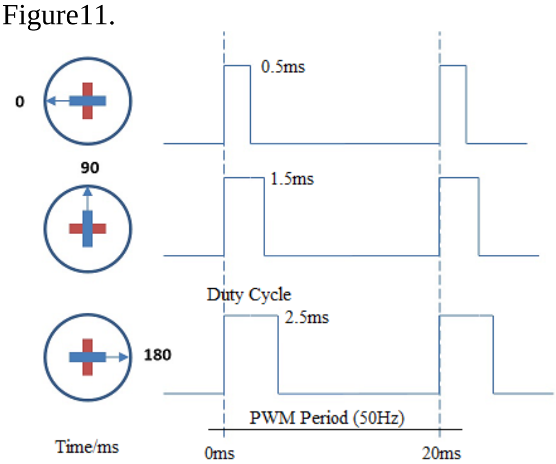

Figure 11. The duty-cycles of the square control signal

Typically, servo motors require a PWM signal with a 20 msn period and a pulse width between 0.5–2.5 msn. 0.5 msn equals to the minimum rotation angle, while 2.5 msn coincides with the maximum rotation angle. The middle position is almost 1.5 msn as the average of the pulse widths. The MG996 and HS805BB type servo motors have same maximum angle of 180°.

The desired position is controlled by the obtained PWM signal from the Raspberry Pi 3 Model B. The servo motor's speed changes according to the difference between the actual position and the desired position. If the motor is near the requested position, it will turn slowly, otherwise, it will turn fast to reach the desired position. This automatic speed control is provided by proportional control. To obtain the requested position, servos motors are controlled as continually [26].

4.6. The Electrical Connection of the 3D Printed Humanoid Robot Platform

The whole system is divided into five sub-modules as the left hand, the left arm, the right hand, the right arm, and the head. These mentioned five parts are directly controlled by the Raspberry Pi 3 Model B controller. The humanoid robot's electrical connection diagram is presented as detailed in Figure 12. Furthermore, for human-robot interactions, the microphone provides hearing of the humanoid robot, while the loud-speaker enables its speaking. Also, the mentioned system allows of the use of the various camera for image processing and face recognition applications, too.

Furthermore, in order to improve various applications on the humanoid robot, it may use in several programming languages such as Linux, Python, C, HTML5, CSS, Scratch, and JavaScript. Especially, for human-robot interaction based on speech recognition systems, it can be used Google Voice and various speech API services through an internet connection in the Raspberry Pi 3 Model B.

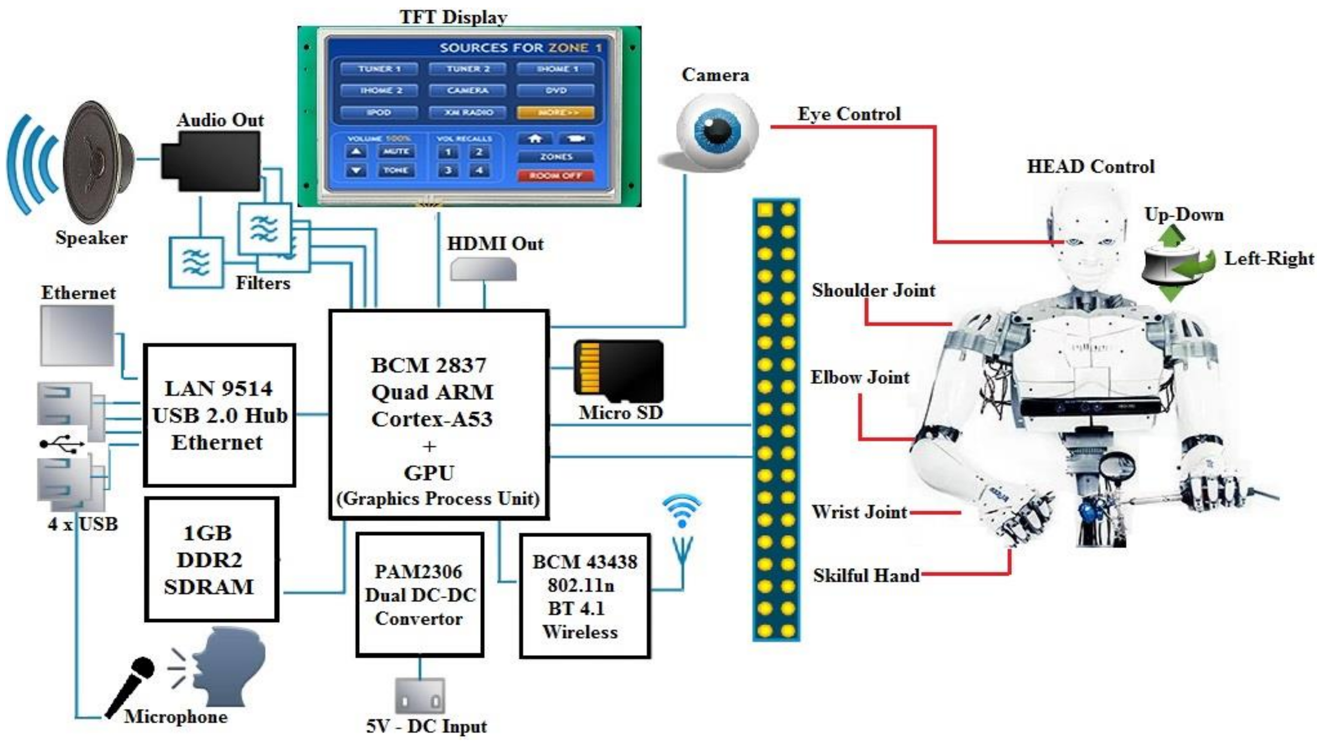

Figure 12. Connection of humanoid robot to peripherals

5. Conclusion and Suggestions

In this study, a fully functional low-cost 3D printed dual-arm humanoid robot was successfully fabricated using the open-source codes of the 3D printed humanoid robot based on "InMoov". The main control design of the humanoid robot was built on the architecture of the Raspberry Pi 3 Model B. Head, jaw, shoulder, and elbow control sections associated with the humanoid robot were driven by modules consisting of nine servo motors. Additionally; in order to realize various applications based on the prosthesis, the skillful hand which can be controlled simultaneously with a data glove was also carried out in this study. For human-robot interaction based on speech recognition systems, Google Voice and various speech API services were used via an internet connection in the Raspberry Pi 3 Model B. The python programing language has a flexible and efficient substructure that can support many speech recognition engines.

This humanoid robot fabricated for educational purposes covers also a few scientific areas which support a well-rounded mechatronics experience for a team of students that have different majors. For instance, it involves CAD-CAM works for mechanical engineering students; electronic circuits (resistors, transistors, capacitors, inductors, diodes, integrated circuits, microcontroller), sensors, and data acquisition systems for electrical and electronics engineering students; as well as potential programming works are suitable for computer science students. Furthermore, this humanoid robot system can be used to simulate human intelligence through some methods such as Artificial Intelligence (AI), Machine Learning, and Deep Learning, too.

Contributions of the authors

Levent Paralı : Drafted and wrote the manuscript, provided technical support, and performed the experimental analyses and performance evaluations.

Mehmet Esen : Wrote the software of realized humanoid robot using the python programming language.

Ali Sarı: Performed some experiments on the humanoid robot, and prepared its working algorithm.

Conflict of Interest Statement

The authors state that did not have conflict of interests

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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