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Design and implementation of a voice-controlled prosthetic hand

Musa Hakan ASYALI[1,*], **Mustafa YILMAZ**[2], **Mahmut TOKMAKÇI**[3],
Kanber SEDEF[4], **Bekir Hakan AKSEBZECİ**[5], **Rohin MITTAL**[6]
[1] *Department of Electrical and Electronics Engineering, Zirve University, Gaziantep-TURKEY*
[*] *Kayseri Abdullah Gül University, Kayseri-TURKEY*
e-mail: asyali@gmail.com
[2] *Department of Industrial Design, Melikşah University, Kayseri-TURKEY*
[3] *Department of Biomedical Engineering, Erciyes University, Kayseri-TURKEY*
[4] *Department of Industrial Design, Melikşah University, Kayseri-TURKEY*
[5] *Department of Electrical and Electronics Engineering, Erciyes University, Kayseri-TURKEY*
[6] *Department of Electronics and Communication Engineering,*
Motilal Nehru National Institute of Technology, Allahabad-INDIA

Abstract

Current hand prostheses are mostly driven by electromyography (EMG) signal, and existing experiments have proved that multichannel EMG signal controls are not suitable due to early fatigue problems and high effort requirements to perform even simple activities. Therefore, in this study we present a new voice-controlled active hand prosthesis to perform several basic tasks.

We first designed a novel multifingered prosthetic hand with the ability of picking up and releasing objects. The prosthetic hand employs 3 DC motors and gears to transfer motion to the linked parts of the fingers. We used flexible thin-film resistive force sensors at the fingertips of the prosthetic hand to adjust the grip force at the fingers. The second part of the study involves the use of speech recognition to control the prosthetic hand. The control circuit that we designed consisted of an HM2007 speech recognition IC and a PIC microcontroller to drive the DC motors moving the fingers.

We implemented both the prosthetic hand and its speech recognition-based control electronics. As of now, we have programmed the control hardware to recognize simple pick up and release operations and have successfully tested them. In a future study, we will include more voice commands for the operation of the hand, such as a realistic handshake, and improve the cosmetics of the hand in order to make it look more natural.

Key Words: *Prosthetic hand, robotic hand, speech recognition*

1. Introduction

In this study, we designed a novel active prosthetic hand with multiple fingers. Potential benefits of such an active prosthetic hand are as follows. First, an active prosthetic hand will provide the capacity to do real work, mimicking the movement capability of a real hand and therefore improving the living standards and/or comfort of people who have lost their hand(s) for a variety of reasons. Second, a prosthetic hand with a proper cosmetic design and/or appearance will foster the self-esteem of the subject.

The most important requirement for the reliable and reasonable design of a prosthetic hand is to have a simple control system and user-friendly operations. Today's advanced commercial prosthetic hands are mostly controlled by electromyography (EMG) [1, 2]. EMG signals are recorded by using surface or needle electrodes that perceive electrical activity associated with the patient's arm muscles [3, 4]. The controller in the prosthetic hand interprets several channels of EMG acquired from the intact part of the arm, and consequently it drives the appropriate actuators to perform the intended activity.

Experiments have shown that though a number of subjects could control these prosthetic hands after some training and experimentation, the main shortcoming of this EMG-driven approach is that most of the subjects suffer from early fatigue, as they need to continuously send appropriate signals to their arm muscles [5-8]. Due to the high concentration required to control a wide range of concurrent inputs, until now only "single channel hands" have been agreed upon as an acceptable solution.

In order to improve mechanical manipulator grasp functionality, several studies have been done to quantify and better understand the nature of human grasping operations [9-11]. The most sophisticated commercially available hand prostheses use half a dozen feedback signals at most. None of these signals are indicative of the derivatives of the forces acting on the prosthesis. Clearly, human mechanoreceptors convey information pertaining not only to the magnitude of the applied grasp force, but also to the rate of change of force [10-13].

Various groups have shown that EMG-based control of a prosthesis with greater movement dexterity can be achieved using different combinations of extracted features and classification methods [14-17]. As far as the decoding of intramuscular myoelectric signals is concerned, Hargrove et al. [18] have recently shown that there was no significant difference when the decoding accuracy of the intramuscular EMG was compared to that of surface-based EMG signals in wrist and grip movements.

Due to the limitations and complexity of EMG-based hand prostheses, we decided to explore the option of a much simpler approach based on voice control. Assuming that the subject does not have any speech impairment, voice commands are much easier to interpret than the EMG signals to control the prosthetic hand. Therefore, the first and foremost advantage of this approach is that the associated prosthesis is extremely comfortable and easy to use, and there is no pain or fatigue involved in its use. Further advantages of the voice-controlled prosthetic hand design approach include: 1) simpler and therefore more energy efficient design of controller electronics; 2) simpler fitting of the hand, as there is no need to place surface or needle EMG electrodes; and 3) no need to train the user, allowing for a faster adaption time.

Our novel design of a voice-controlled active prosthesis hand consists of 3 sets of fingers controlled by 3 motors and gears with 3 degrees of freedom. This study encompasses all areas required to make a hand able to hold and release an object, including the design of the speech recognition circuit board and control circuit board.

In this paper, we describe the mechatronic platform of our prosthetic hand, equipped with both efferent voice-based controllers and afferent vibrotactile feedback, allowing the user to close the loop in grasping tasks. The control architecture, the simple vibrotactile sensory feedback system, the speech recognition circuit board, and the control circuit board development are also presented. Finally, a description of the performed grasping experiments and a discussion of ideas for future development of the prosthetic hand and its control are provided.

The mechanical and kinematic aspects of our design are discussed in full detail in [19]. Therefore, the emphasis of this paper is more on the speech recognition-based control electronics of the active prosthetic hand.

2. Materials and methods

The human hand is considered to be the best gripping mechanism. Thus, our design makes use of the human hand's design and employs the same type of mechanism used by the human hand. The design can be divided into 2 parts:

- Mechanical design and
- Design of the prosthetic hand control electronics.

The main considerations taken during the design process was to design a hand that resembles the human hand; the size should be similar, light and not too bulky, and the overall cost should be low.

In designing the mechanic part of the hand, we employed Solid Works 2009 3D CAD software (Dassault Systèmes SolidWorks Corp., Concord, MA, USA). We then utilized a 3D printer for rapid prototype development. All parts were built or printed on that printer using acrylonitrile butadiene styrene (ABS). The gears of the prosthetic hand were custom built at a mechanics shop using C1020 steel.

2.1. Mechanical design

A human finger is composed of 3 main joints that have 3 degrees of freedom. We preferred relative motion between the joints for easy control and simplicity in the prosthetic hand's fingers. Open and closed positions of the index finger can be seen in Figures 1 and 2, respectively. The axis of rotation of all joints is coincident in a single axis in the open position.

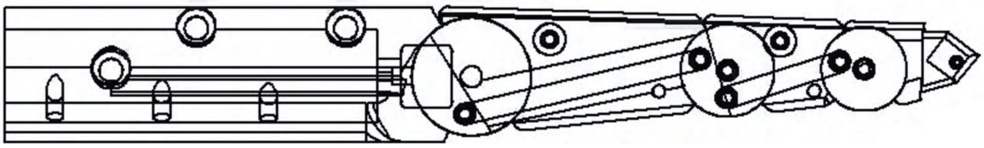

Figure 1. Open position of the index finger.

The first joint axis of rotation is driven by a DC motor, and the second and third limbs move relative to the first limb. Movement and rotation of the second limb is done by the first transfer bar, which fixes to the main body on one side. The additional movement and rotation of the third limb are done by the second transfer bar, which is fixed to the first limb on one side.

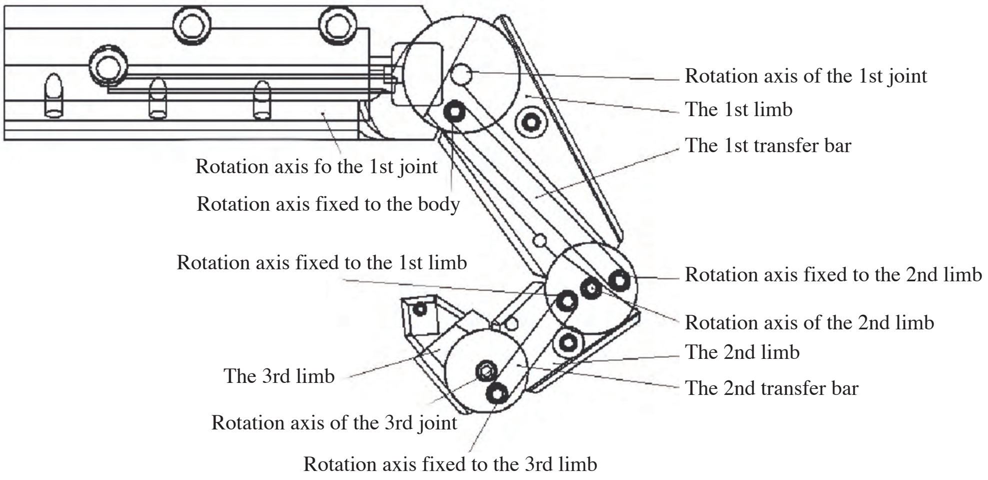

Figure 2. Closed position of the index finger.

The thumb has 2 moving limbs, which are different from the other fingers, so it uses only 1 transfer bar, as shown in Figure 3. The degree of desired gripping force is adjusted by force sensors placed at the finger tips (Figure 4).

The other 3 fingers are driven by 1 DC motor. These fingers are fixed to each other using transfer pins, as shown in Figure 5.

The general mechanical assembly of the prosthetic hand designed is shown in Figure 6.

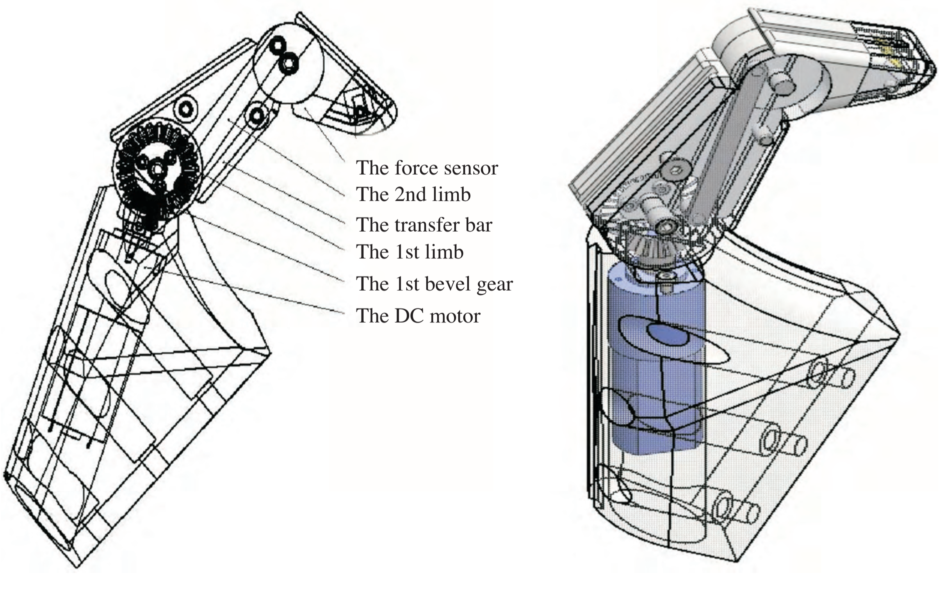

Figure 3. Thumb design of the prosthetic hand.

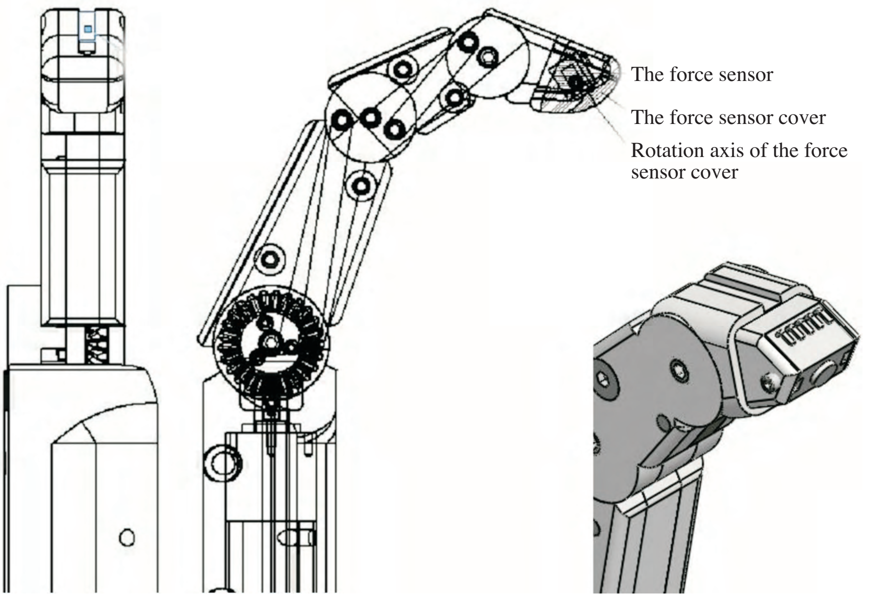

Figure 4. Mechanism for force sensor.

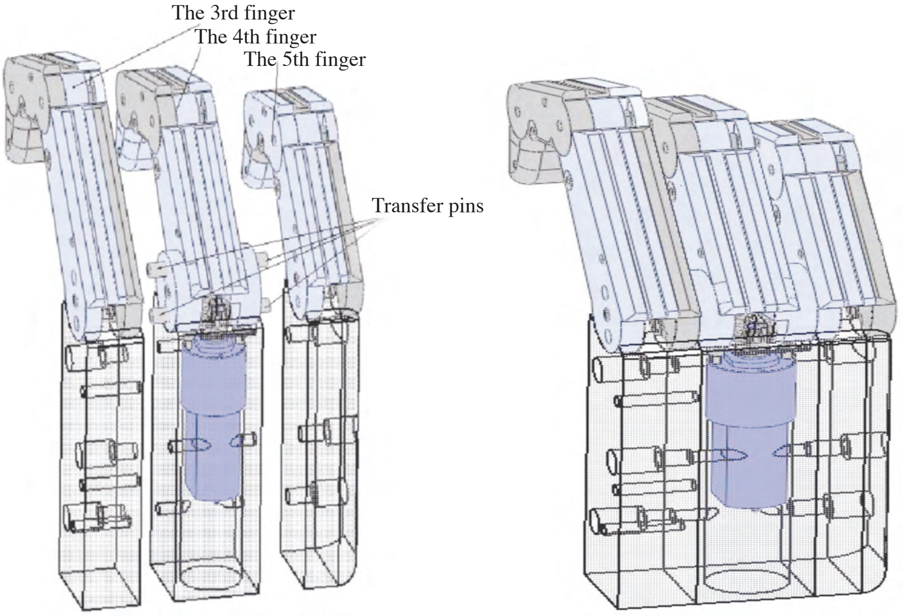

Figure 5. Three-finger mechanism.

2.2. Design of the prosthetic hand control

The actuation of the prosthetic hand is accomplished by voice commands. The voice commands, such as “pick up” and “release,” are processed by a special voice command recognition circuit (to be described next), and appropriate drive signals are sent to the DC motors. The controller electronics, in addition to sending these drive signals, also picks up force sensor signals and cuts the motor drive signals when the level of desired (preprogrammed) grip force is reached. The prosthetic hand control block diagram is shown in Figure 7.

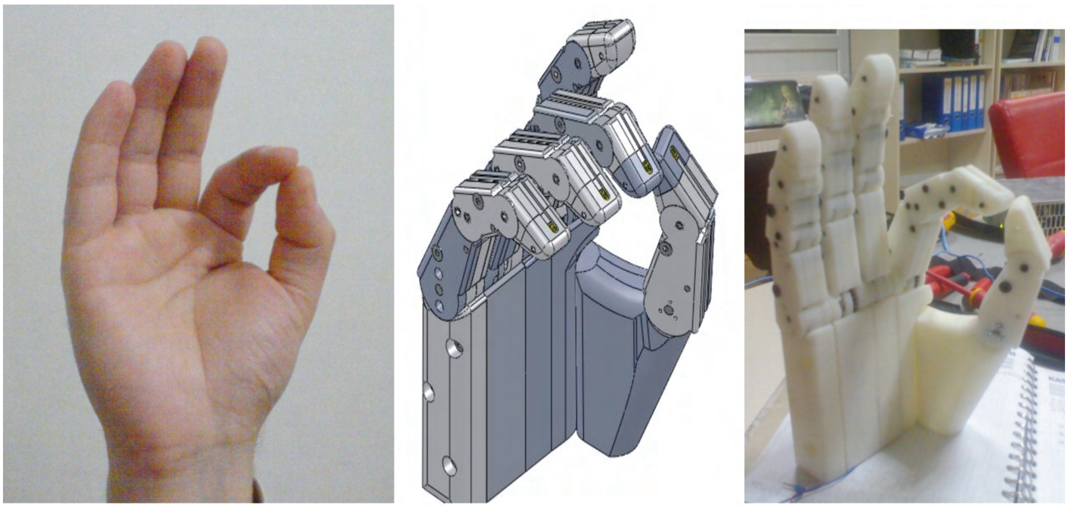

Figure 6. General assembly of the prosthetic hand.

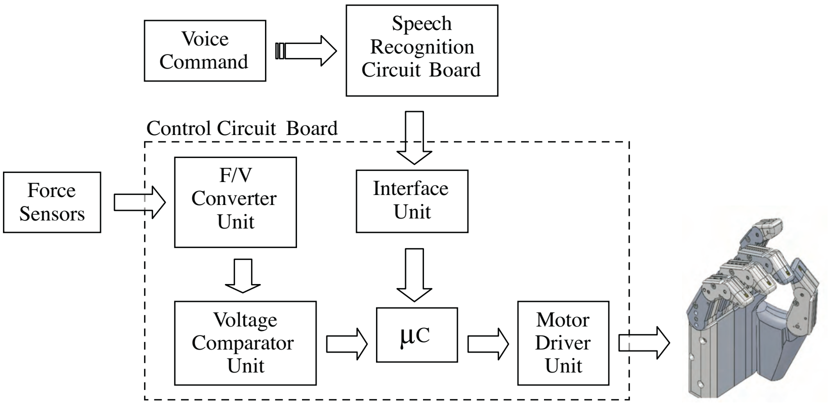

Figure 7. Parts of the prosthetic hand control system.

Depending on the nature (i.e. grip force requirement) of the recognized command, the preset voltage level of the voltage comparator unit in Figure 7 can be adjusted. In our case, since we designed the controller circuit to recognize only 2 commands initially, namely *pick up* and *release*, we adjusted the preset voltage level of the comparator manually until the hand held a simple plastic ball. Therefore, the force sensors, force-to-voltage (F/V) converter unit, and the voltage comparator unit in the block diagram constitute a simple ON/OFF control system. Until the grip force voltage value returned by the F/V converter unit reaches the preset voltage value in the comparator unit, a *drive* signal (digital 1) is sent to the microcontroller (μC), which then drives the step motors appropriately. When the grip force voltage value returned by the F/V converter unit exceeds the preset voltage value in the comparator unit, a *no drive* signal (digital 0) is sent to the microcontroller (μC), which then ceases or stops to drive the step motors.

2.2.1. Speech recognition circuit

The speech recognition circuit (SRC) is capable of controlling the prosthetic hand using voice commands (Images SI, Inc., Staten Island, NY, USA) [20]. The ability to communicate with a prosthetic hand through speech is the ultimate user interface. The user needs minimal experimentation and/or training with the prosthetic hand before using it for any practical purpose.

The main component of the SRC is the HM2007 speech recognition chip. The HM2007 chip is a CMOS voice recognition chip with voice analysis, recognition process, and system control functions. The other major components are the 64K CMOS Static RAM chip, a microphone, a 12-button keypad, and a 74LS373 chip, as shown in Figure 8. Data can be written and read from the SRAM chip, and the 74LS373 functions as a latch with 3-state outputs.

The SRC is a speaker-dependent system, whereby it is only able to recognize the individual that trained the circuit. However, there is the constraint of the circuit concerning the style of speech it can recognize. For example, it can only recognize words that are spoken separately, with a pause between each word. The microphone built on the SRC is able to clearly detect voices from a distance of 1 foot. The SRC circuit has a response time of less than 300 ms and it requires a 5 V DC power supply.

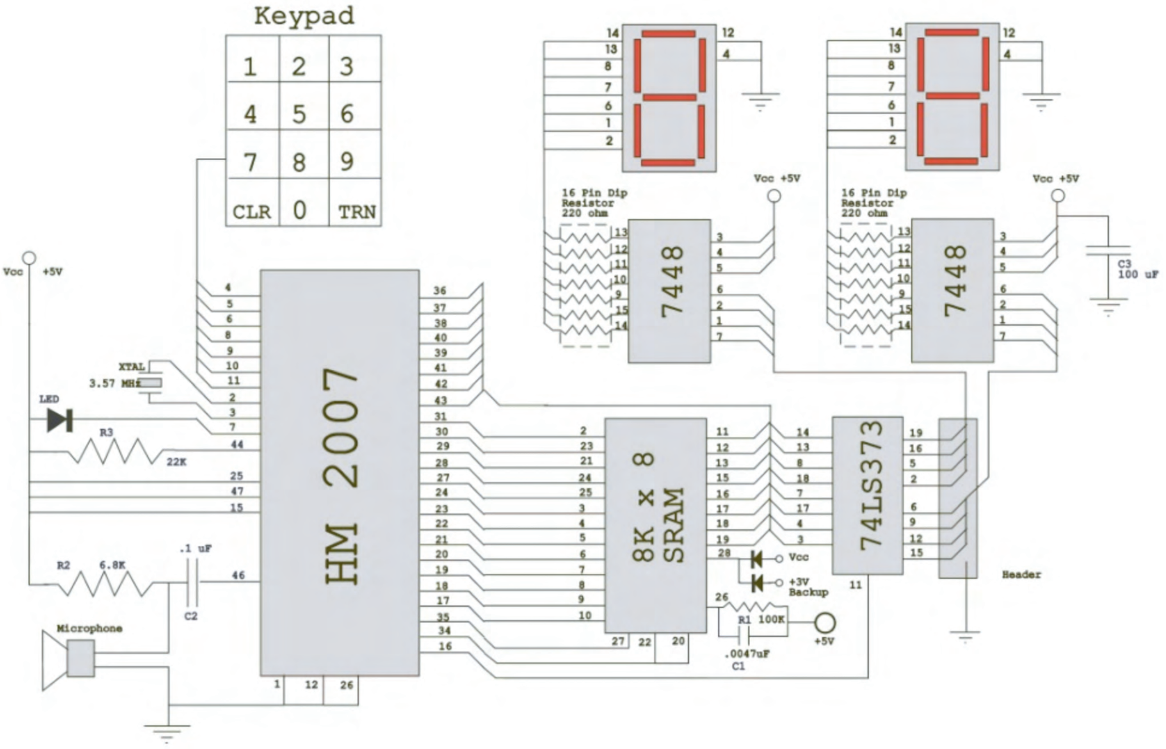

Figure 8. Schematic diagram of speech recognition circuit board.

The circuit shown in Figure 8 was constructed on a printed circuit board (PCB) for testing and training. Testing and training the HM2007 chip in manual mode requires the keypad and microphone. When the circuit is powered on, the HM2007 checks the static RAM, displays “00” on the 7-segment, and also turns on the LED. The system is then in a “ready” state and ready to be trained.

The training procedure of the circuit consists of the following steps:

1. Press ‘01’ and the 7-segment will display ‘01.’ LED will turn off.
2. Then press ‘train’ and LED will turn on again.
3. Hold the microphone close to user and say the training word.

4. If word is recognized by the circuit, LED will blink.
5. Repeat the training word & ‘01’ will display if it is accepted properly.
6. Continue training with other words.

If the word is not recognized, the chip provides the following error codes:

55 → Word too long.
66 → Word too short.
77 → No match.

In order to make the recognition system individual (speaker)-independent, we used more than 1 word space for each target word and set the chip for a vocabulary of 20 words. We then used 2 word spaces per target word. We chose words such that they would have the same least significant digit (LSD) on the digital display. Therefore, ‘01’ and ‘11’ can be chosen for the first target word, ‘02’ and ‘12’ can be chosen for second target word, and so on.

2.2.2. Force sensors

As the human hand has the property of extending (opening) and shrinking (closing) according to the signals sent by the brain, the same concepts were utilized in our design. Therefore, we designed and implemented a prosthetic hand resembling the human hand, which is able to grip, hold, and release various objects. This section deals with having a proper grip on the object the hand is holding. For this, FlexiForce force sensors (Tekscan, Inc., South Boston, MA, USA) [21] were attached at the finger tips. These sensors, along with their associated amplification circuits, generate feedback voltage signals in order to hold the object firmly without applying much pressure on the object.

The force sensors are the ultrathin (0.02 mm) and flexible printed circuit, which can be easily integrated into most applications. With its paper-thin construction, flexibility, and force measurement ability, these sensors can measure forces between almost any 2 surfaces. These thin-film force sensors have relatively better force sensing properties, linearity, hysteresis, drift, and temperature sensitivity compared with other force sensors [21]. The active sensing area of the sensors is a circle, 9.5 mm in diameter, at the nonconnector end of the 51 × 14 mm rectangular sensor. Application of force in the force sensing area results in a change of resistance of the sensing area, in inverse proportion with the force applied. When the sensor is unloaded, its resistance is very high (greater than 5 $M\Omega$); when a force is applied to the sensor, the resistance decreases. The entire sensing area of the FlexiForce sensor is treated as a single contact point. For this reason, the applied load should be distributed evenly across the sensing area to ensure accurate and repeatable force readings.

2.2.3. Control circuit board

The microcontroller (μC) acts as the brain of the prosthetic hand. The control decisions are made by this controller and the output signals are also sent to the motor driver unit by the same IC.

Microcontroller

We used a PIC16F84A in this control circuit as a microcontroller. The PIC16F84A belongs to the midrange family of the PIC microcontroller devices (Microchip Technology Inc., Chandler, AZ, USA) [22]. It is an 18-pin, FLASH/EEPROM 8-bit microcontroller. The program memory contains 1K words, which translates to 1024 instructions, since each 14-bit program memory word is the same width as each device instruction. The data memory (RAM) contains 68 bytes. The data EEPROM is 64 bytes. There are also 13 I/O pins (PORTA & PORTB) that are user-configured on a pin-to-pin basis.

The inputs from the voice recognition circuit and from the voltage comparator unit are sent as input to the microcontroller, as in Figure 9. A program is written using the PIC-C compiler in C language, whose hex code is then burnt into the IC using a K128 USB programmer. The code consists of various commands that help the hand take required decisions according to the command given by the user.

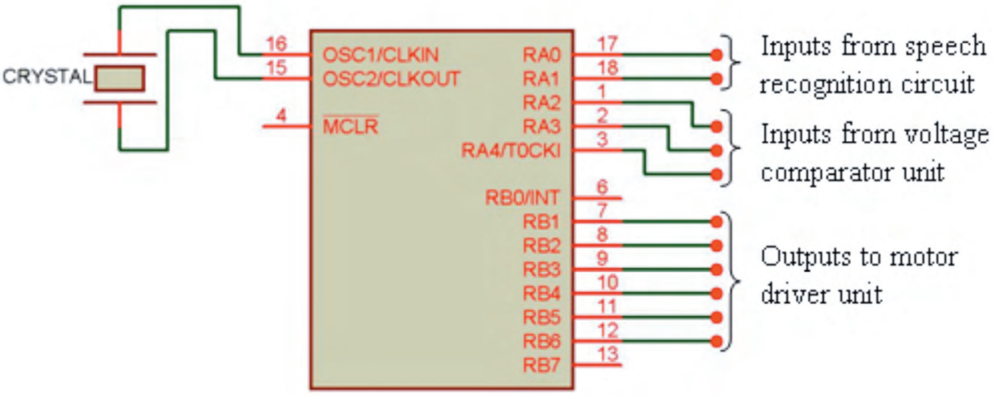

Figure 9. Pin configuration of the PIC16F84A microcontroller.

Interface unit (interfacing the speech recognition circuit with microcontroller)

The microcontroller must not work when the speech recognition circuit generates error codes. In order to exclude these error codes from being recognized by the microcontroller, we designed an interface unit. This unit comprises 2 logic gates, a latch, and a BCD-to-decimal converter. The combination of NAND gate and OR gate is used at the speech recognition circuit's most significant digit (MSD) output. The output of this combination is used as ENABLE of the 74LS373 latch. The binary values of the speech recognition circuit's least significant digit (LSD) output are inputs for the same latch, as in Figure 10. The binary output is converted to decimal value using IC4028. Hence, whenever an error code is generated, the number is ignored; otherwise, a decimal value of LSD is generated as output.

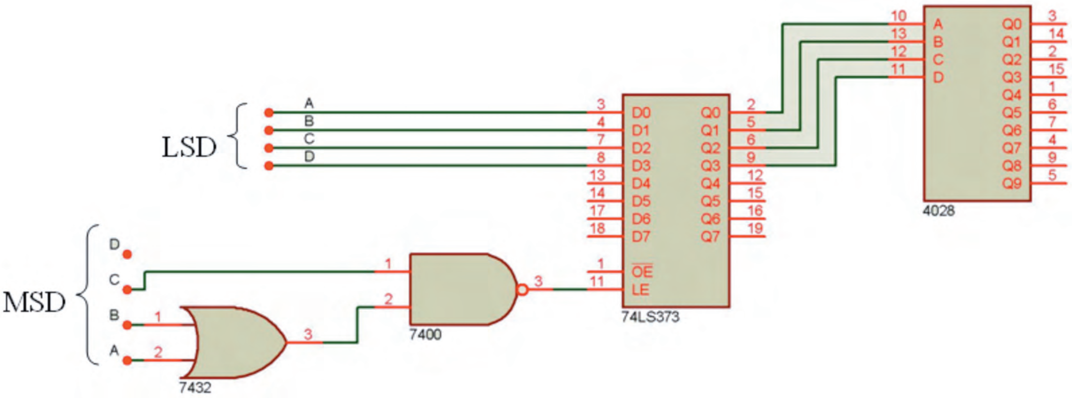

Figure 10. Interface unit.

In our design, we have assumed that the *pick up* operation will be carried out when the required word for the same task is trained at memory location '01' of the speech recognition circuit. Similarly, the *release* operation will be carried out when the required word is trained at the '02' memory location. Hence, the decimal output '1' obtained from the IC4028 is taken as one input of the microcontroller and the decimal output '2' acts as a second input, since we are dealing with only the LSD in our design.

The decimal outputs of the IC4028 are given as input to a PIC16F84A microcontroller. The microcontroller is then connected to the motor driver unit, which controls the motors in the prosthetic hand.

Force-to-voltage converter unit

This unit is used to adjust the force sensor outputs in the 0-5 V range. To perform this operation, we utilized an operational amplifier (OP-AMP) for each sensor output. Therefore, this unit comprises of 3 OP-AMP's. We used -5 V as the excitation voltage at one terminal of each force sensor, and the other terminal was used for inverting input to the OP-AMP (LM741), as shown in Figure 11. The amplifier produces an analog output in this case, based on the sensor resistance (R_S) and the reference resistance (R_F).

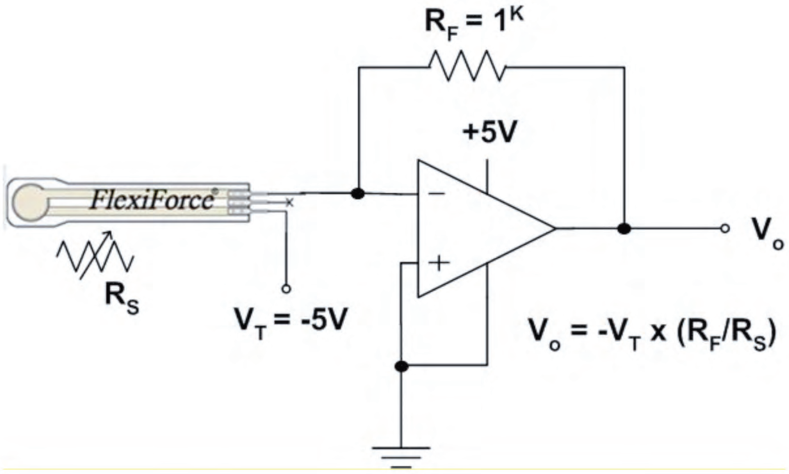

Figure 11. Force-to-voltage converter circuit for each force sensor output.

Voltage comparator unit

The outputs obtained from the force sensors are analog; however, the inputs to the microcontroller can only be digital. Therefore, a voltage comparator unit is used in this circuit, which compares it with some preset value and also generates digital output accordingly, as shown in Figure 12.

The analog voltage (V_{OUT}) generated by the F/V converter circuit has to be compared with some predefined value in order to prevent the motors from applying much force to the object. This analog voltage of the sensor circuit is fed as noninverting input to the comparator LM324, which is basically a quad amplifier that can work in the range of 3-32 V. The inverting input is given a reference voltage, with which we need to compare the sensor voltage.

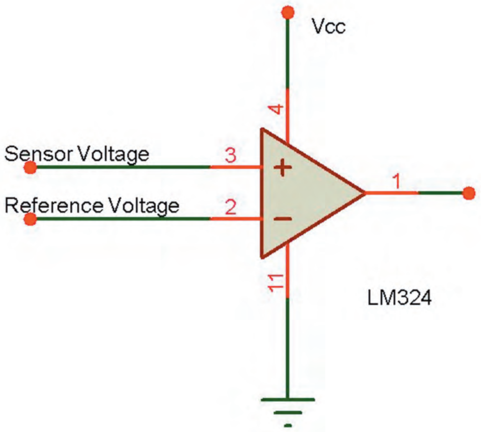

Figure 12. Voltage comparator circuit using LM324.

If $V^+ < V^-$, the output from the comparator circuit is low.

If $V^+ > V^-$, the output from the comparator circuit is high.

The output of this circuit is digital and, hence, can be used as microcontroller inputs.

Motor driver unit

This unit consists of 2 L293D integrated circuits (IC), which are a dual H-Bridge motor driver. This IC is an integrated high-voltage, high-current 4 channel driver designed to accept standard DTL or TTL logic levels and drive inductive loads (such as relays, solenoids, DC, and stepping motors) and switching power transistors. The given IC has 2 channels. With 1 IC we can interface 2 DC motors, which can be controlled both clockwise and counterclockwise. The L293D has an output current of 600 mA and a peak output current of 1.2 A per channel. Moreover, for protection of the circuit from back EMF from motors, output diodes are included within the IC. As shown in Figure 13, 3 pins are needed for interfacing a DC motor (IN1, IN2, and ENABLE1).

Table. Truth table for operation of a motor.

IN1	IN2	Description
0	0	Motor stops
0	1	Motor rotates counterclockwise
1	0	Motor rotates clockwise
1	1	Motor stops

The truth table shown in the Table is valid only when the enable pin of the concerned channel is kept high. A schematic for interfacing a DC motor using L293D is shown in Figure 13.

In our design, we kept the supply voltage, V_S, as 12 V, which is required to run the motor, and the V_{SS} as a logic supply of 5 V. The enable pins are always high and IN1 and IN2 are the inputs from the microcontroller, which then gives the output at OUT1 and OUT2 according to the program written for the microcontroller. The similar connection is done on channel 2.

These motors are fitted in the fingers of the prosthetic hand, which can move in both clockwise and counterclockwise directions. Hence, the voice command is able to run the motor in both directions.

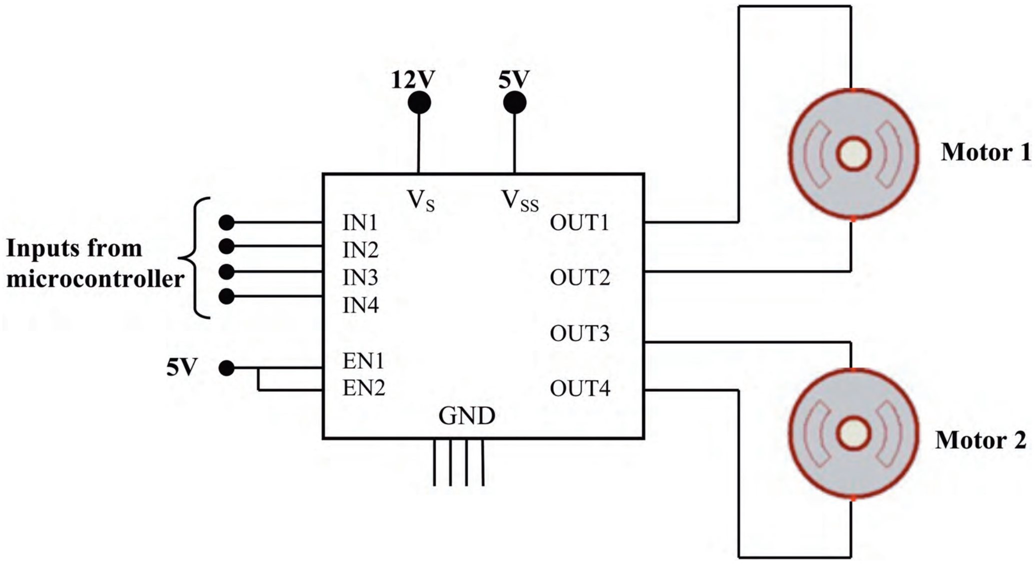

Figure 13. Schematic of L293D motor driver.

3. Discussion and conclusion

In this study, we designed and implemented a novel voice-controlled prosthetic hand. Our comprehensive study involved both mechanical and electronic controller designs of the hand. We were able to operate the prototype of the designed prosthetic hand at laboratory conditions for simple pick up and release tasks successfully.

In our design of the prosthetic hand, the driving force for finger movements was obtained using miniature high-speed DC motors with a gearbox. Each finger's only main joint is driven by the DC motor; the remaining 2 joints are moved through a special mechanism involving motion transmission bars. After design and testing of the prosthetic hand in the software environment, we manufactured a prototype of the prosthetic hand using rapid prototyping techniques. The design of the controller electronics for the prosthetic hand is described in detail in section 2; here we will suffice by repeating the point that the core of the controller is the HM2007 speech recognition IC. We have successfully demonstrated that our design can be trained using voice commands and can perform certain actions like picking up and releasing an object. Therefore, we have also shown that synchronization or real time operation of a speech recognition controller and a DC motor controller is possible.

At this point, we would like to reiterate the advantages of our voice-controlled prosthetic hand design in comparison with the EMG interpretation-based hand prostheses that are widely available on the market today. As there is no pain or fatigue involved during its use, our design is extremely comfortable and easy to use. All the user needs to do is to utter the voice command associated with the desired task. As such, there is no risk of doing a wrong or unintended operation. If the uttered voice command is not recognized by the controller due to noise problems, for instance, the prosthetic hand will simply perform no action. Further advantages of our approach can be summarized as: 1) simpler fitting of the prosthetic hand, as there is no need to place surface or needle EMG electrodes; 2) almost no need to train the user, therefore giving a faster adaption time; and 3) although we did not perform any rigorous tests, we also expect that our design will be more energy efficient compared to the existing prosthetic hands on the market, because it employs only 3 DC motors and has relatively simple (undemanding) controller electronics.

Other considerations taken during the design process were to design a hand that resembles the human hand; the size should be similar and light, not too bulky, and the overall cost should be low. We estimate the overall cost of our design, without research and development costs, to be around 400 USD. With mass production, this figure could be further reduced.

As for potential improvements in our design, we would like to address the following issues in our future design. Currently, our design is limited by recognition capability of just 2 commands, namely *pick up* and *release*; in a future study/model, we will increase this capability. There is plenty of unused capacity in the speech recognition part of our design; we can go up to 40 commands. Therefore, our design can be further improved in order to perform more complex tasks. Another area for potential improvements is that we currently apply the same level of force to all 3 fingers. Later on, we may program the controller to drive each of the 3 DC motors to reach different grip force levels, depending on the nature of the task. At this stage, we have worked as a group of mechanical, biomedical, and electrical-electronics engineers to implement and test the design. After increasing the operation capability of the designed hand with more voice commands and further tests, we will include clinicians in our research team to fit and try our design on real subjects. Our ultimate goal is to offer a simple and affordable alternative to existing expensive and complicated prosthetic hands.

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