



IoT-Enabled High Load Density Miniature Force Sensor System for Intelligent Robot Foot Probing and Obstacle Avoidance

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Abstract: This project presents an enhanced version of a High Load Density Miniature Force Sensor for Probing with Robot Feet integrated with IoT-based monitoring and an Infrared (IR) obstacle detection system for intelligent robotic navigation and safety. The original system focuses on measuring multi-axis contact forces on robot feet using strain gauges embedded inside a compact sensing module. In the proposed enhancement, an IR sensor is incorporated to detect nearby obstacles during robot movement. Whenever an obstacle is identified, the robot leg movement is automatically stopped to prevent collision and improve operational safety. The force sensor continuously measures terrain interaction forces, while the IoT module enables real-time transmission of sensor data to cloud platforms or monitoring devices for remote observation and analysis. The system uses a microcontroller-based architecture for sensor processing, obstacle detection, and motion control. The integration of IoT improves accessibility, data logging, and remote monitoring capabilities, making the robot suitable for smart robotic applications in hazardous and unstructured environments. Experimental results show that the enhanced system successfully performs accurate force sensing, terrain probing, obstacle avoidance, and remote monitoring simultaneously. The proposed approach increases robot reliability, safety, and automation efficiency while maintaining compact size and low power consumption. This system can be effectively applied in search-and-rescue robots, industrial inspection robots, surveillance systems, and autonomous mobile robotic platforms.

Keywords: Force Sensor, Robotic Foot, Load Density Measurement, Obstacle Detection, Infrared (IR) Sensor, Internet of Things (IoT), Autonomous Robotics, Terrain Probing, Real-Time Monitoring, Smart Navigation

Introduction: Development of force sensors that mimic human tactile sensation has gained attention in various fields such as robotics, microelectromechanical systems (MEMS), and biomedical engineering [1], [2], [3], [4], [5]. Numerous force sensors based on a variety of transduction principles have been proposed: well-known examples include resistive [6], [7], [8], [9], capacitive [10], [11], piezoelectric [12], [13], and optical sensors [14], [15], [16]. Most of these force sensors require high sensitivity and a wide measurement range; however, in general, the relationship between these two characteristics is a trade-off. That is, increasing the sensitivity reduces the measurement range, or vice versa. The development of compact force sensors with high sensitivity and a wide

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measurement range remains a research challenge for robotic fingertips and small end effectors. Existing literature on robotic tactile sensing suggests that force sensors for robot hands, like human hands, require a spatial resolution on the millimeter scale, a force resolution of 0.01 N (1 gf), and a measurement range up to 10 N (1000 gf) [1]. Recently, a wider measurement range has been required for emerging robots, such as robots carrying heavy objects [19] and body-care and massage robots [20], [21], [22]. In practice, the maximum force of humans is roughly 450 N in males and 350 N in females [23], with force from a single finger reaching 175 N [24]. Thus, it is of interest whether a millimeter-scale force sensor with such a wide measurement range can be designed. Resonant force sensors, which use changes in resonant frequency of a structure as the detection principle, are known as sensors with high sensitivity, high resolution, long-term stability, and a wide measurement range. This principle has been partly applied in practice. For example, force sensors using double-ended tuning fork (DETF) oscillators are embedded in electronic balances [27]. It has good linearity, but achieving this linearity requires a complex mechanism, resulting in a size of several centimeters [28]. A resonant sensor using a crystal oscillator has been proposed as a smaller force sensor with a wider measurement range [29], [30]. It is approximately 2 mm in size and can measure an extremely wide range from 0.4 mN to 600 N with good linearity. However, because it uses the planar vibration of a quartz plate, its resonance frequency is high, on the order of several tens of MHz. These high frequencies introduce electromagnetic noise and may interfere with radio waves. Haptic feedback has been incorporated into a wide range of devices for various applications such as perception augmentation, enforcing safety barriers, and applying assistive control behaviors (virtual fixtures). Accordingly, haptic devices have become increasingly popular for surgical training as they can provide either tactile or force cues on the trainee as guidance/feedback on their performance. To give effective feedback, a haptic device should ideally be able to discern the motions and forces applied to the tool. However, many haptic trainers neglect force measurement due to a lack of affordable and easily integrable force/torque (F/T) sensor options. This paper seeks to resolve this issue with the design of a soft, low-cost, 6-axis F/T sensor designed specifically for integration within a laparoscopic haptic trainer for skill assessment and surgical training. The majority of commercially available 6-axis F/T sensors are comprised of miniature strain gauges applied to precise micro-machined metal flexures [1, 2, 3]. This method generates very accurate sensors, but comes at a very high cost of fabrication and specialized circuitry for amplification and signal conditioning. The typical price range for this type of design is several thousands of U.S. dollars. This proves to be a major limitation for incorporation of force sensing in haptic devices. Pursuing a low-cost design will improve the feasibility of exploiting force data for feedback in surgical assessment and increase access to such haptic trainers. The cost of fabrication of these F/T sensors may be reduced by 3-D printing the flexures into the sensor (e.g. [4]), but the cost and complexity of signal amplification and conditioning remains contra-indicated to the simplicity we seek per our application domain specifications. Other low-cost load cells have been proposed in the literature. For example, capacitance-based force sensors are significantly less expensive, but also tend to be less accurate than other force sensing methods [5, 6, 7]. Another approach attempts to create flexures with optical sensors [8, 9, 10] to reduce cost. However, these sensors are subject to reliability issues based on the accuracy of the 3D printer used. Another method for creating F/T sensors is to embed magnets inside

flexible material and measure the change in magnetic field using a Hall-effect sensor. This is an attractive option due to their simple electronics and construction.

LITERATURE SURVEY: The heavy-duty legged robots are one of the basic forms of mobile robots. Unlike the wheeled and tracked robots, they can freely change the landing points during the actual walking. They adjust their posture at any time by changing the support between feet and terrain, which can ensure stability during the support process. The heavy-duty legged robots make direct contact with the terrain and need to adapt to different types and inclinations of terrain. It increases the requirements for the feet. The feet can play a supporting, load-bearing, and antiskid role. Also, they need to have multiple degrees of freedom to adapt to the forward and turning movements of the heavy-duty legged robots. The feet of the heavy-duty legged robots need to meet special requirements such as bearing heavy loads, adapting to different terrains, and having flexible degrees of freedom. The section briefly reviews two types of related work, namely the foot configurations and sole pattern shapes of different heavy-duty legged robots.

Supporting Foot Configurations of Heavy-Duty Legged Robots

Feet with Passive Adaptive Joints: Spheres, ellipsoids, and rectangles have been found to be the most common shapes of feet [15]. Common configurations such as cylindrical feet, semi-cylindrical feet, spherical feet, hemispherical feet, square feet, and special feet are summarized.

Cylindrical Supporting Foot Configurations

The Tokyo Institute of Technology has developed the TITAN series of robots. In 2002, the latest generation model machine called TITAN XI was developed, and the robot is shown in **Figure 1a**. It is a hydraulically driven quadruped robot. The robot can walk steadily and continuously on slopes covered with reinforced concrete frames. It can achieve intermittent crawling gait based on map information. Terrain adaptive gait makes the robot's motion more stable. The robot's feet are cylindrical [16]. TITAN IX is a quadruped robot with cylindrical foot shapes for humanitarian landmine detection missions [17]. TITAN III is a quadruped robot with cylindrical feet [18], as shown in **Figure 1b**.



Figure 1. Robots of TITAN series, COMET-IV, and NMIIIA: (a) TITAN XI [16]; (b) TITAN III [18]; (c) COMET-IV and (d) NMIIIA [1].

The COMET-IV robot developed by Chiba University is a heavy-duty hexapod robot based on hydraulic drive, as shown in **Figure 1c**. The weight of the robot is approximately 2120 kg. Its load-bearing capacity is approximately 424 kg. The overall size is approximately 2.8 m × 3.3 m × 2.5 m. Each leg has four degrees of freedom (DOFs). It can walk on uneven terrain. The robot's feet are cylindrical. The Dante II robot, designed for exploring planetary surfaces, operates semi-autonomously and is equipped with eight legs. It weighs 770 kg, has the capacity to carry a 130 kg payload, and is capable of navigating slopes up to 30 degrees. The feet of the robot are cylindrical [20].

The NMIIIA robot was successfully developed in 1985, as shown in **Figure 1d**. It is a crewed hexapod robot developed by the former Soviet Union during the implementation of lunar exploration activities. It is used for star surface exploration and load bearing. The robot has a mass of 750 kg, a load-bearing capacity of 80 kg, and a moving speed of 0.7 km/h. Its feet are cylindrical [1].

The SILO4 robot developed in Spain also has cylindrical feet [21]. The passive joint of the foot contains three rotational degrees of freedom (DOFs). The three-axis force sensors are installed on the robot's feet. The outdoor experiment and ankle joint are shown in **Figure 2**.

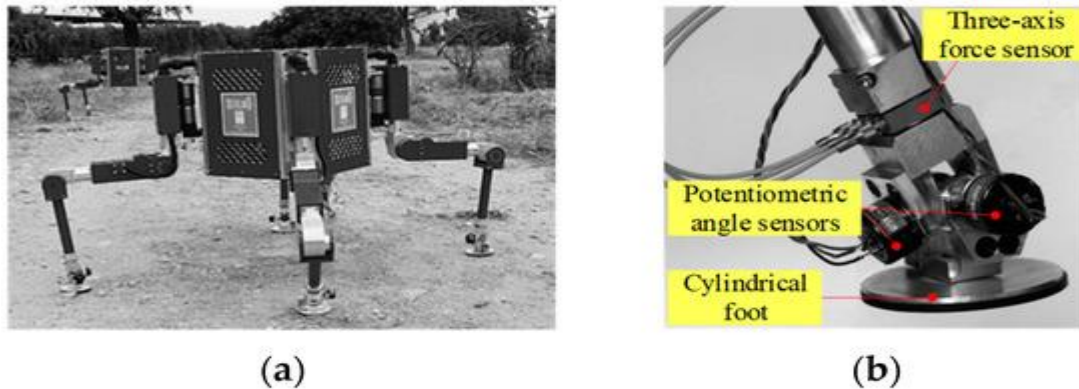


Figure 2. SILO-4 robot [21]: (a) outdoor experiment; (b) ankle-integrated sensor system.

Zhuang developed a terrain electric-driven hexapod robot with a high load ratio, ElSpider. Six supporting legs of the robot are uniformly distributed on the body of the central symmetric structure. A single leg adopts a structure with three active and four passive degrees of freedom.

EXISTING TECHNIQUE:

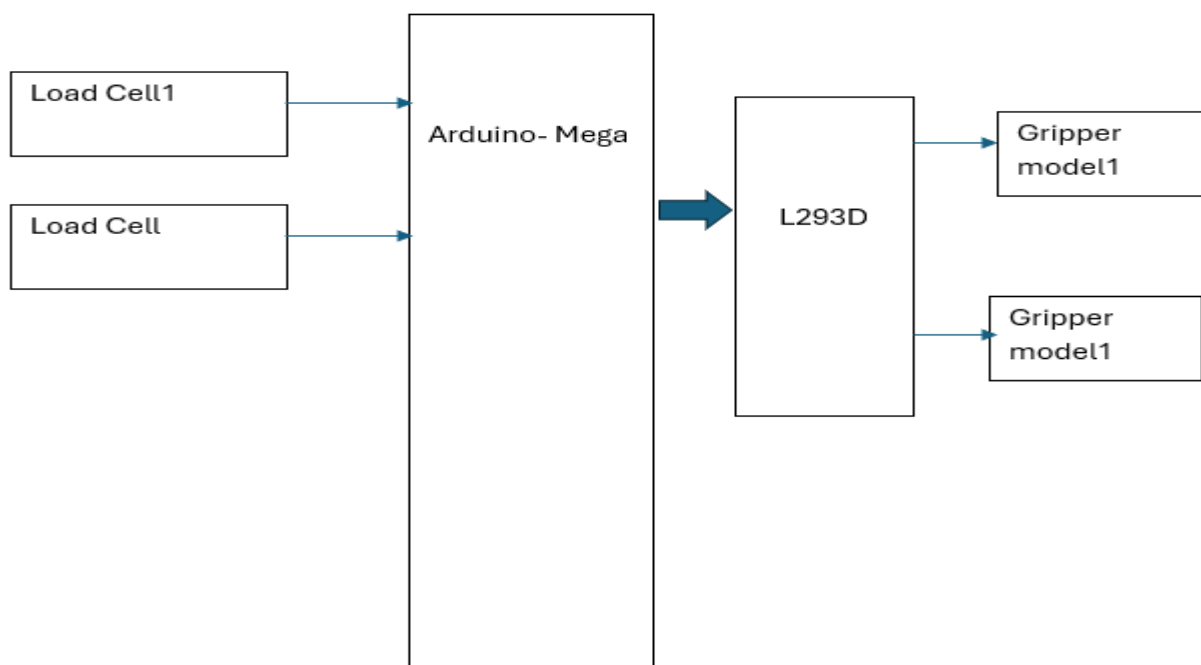


Fig: 3 Existing Block diagram

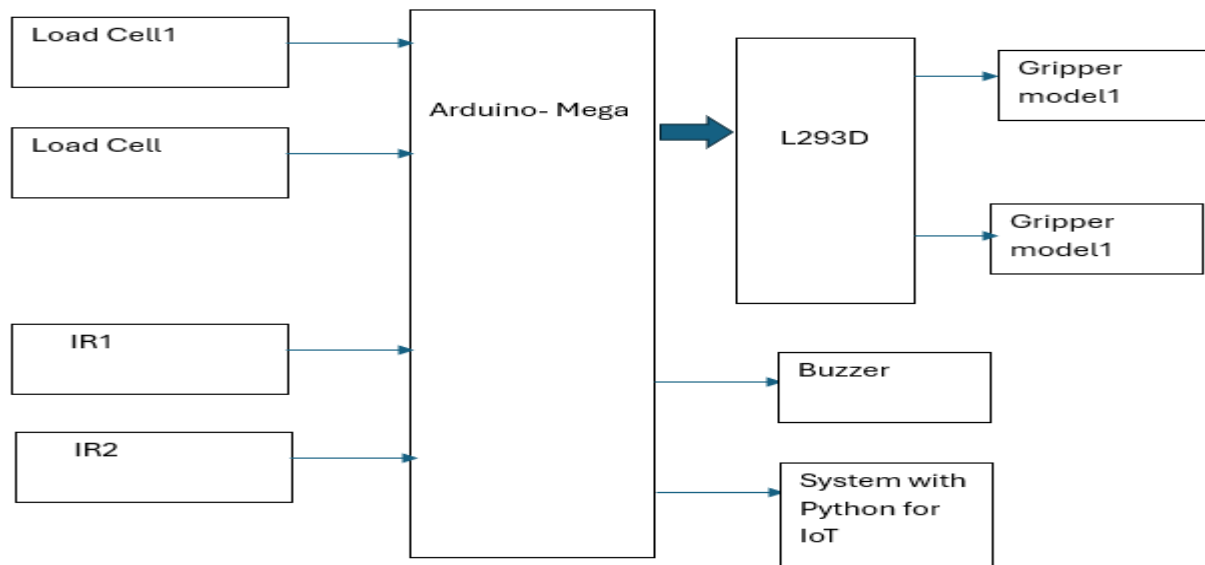
PROPOSED BLOCK DIAGRAM:

Fig: 4 Proposed Block diagram

The sensor converts mechanical deformation into electrical signals using four strain gauges mounted symmetrically on the alluminum sensing module (DacSeMo). Forces along x, y, axes generate different strain patterns, which are processed through calibration matrices to determine the exact contact force. The paper titled **“A High Load Density Miniature Force Sensor for Probing With Robot Feet”** proposes a compact and lightweight multi-axis force sensor specifically designed for legged robots. The sensor is integrated into the robot foot (dactyl) and uses strain gauges mounted on an alluminum structure to measure forces in three dimensions.

ARDUINO MEGA The Arduino Mega is based on ATmega2560 Microcontroller. The ATmega2560 is an 8-bit microcontroller. We need a simple USB cable to connect to the computer and the AC to DC adapter or battery to get started with it. The Arduino Mega is organized using the Arduino (IDE), which can run on various platforms. Here, IDE stands for Integrated Development Environment.

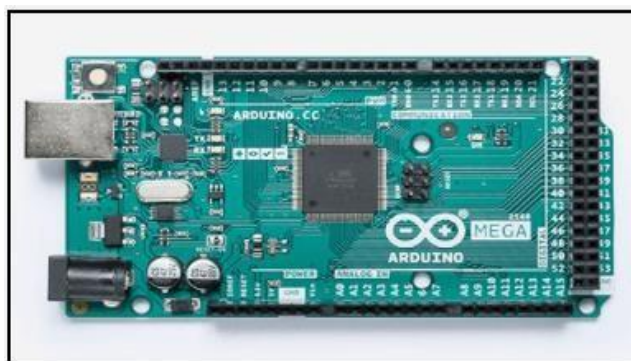


Figure :5 Arduino Mega board

The functioning of the Arduino Mega is similar to other Arduino Boards. We need not require extra components for its working.

Arduino Mega use

The advantage of using the Arduino Mega board over other boards is that it gives the advantage of working with more memory space.

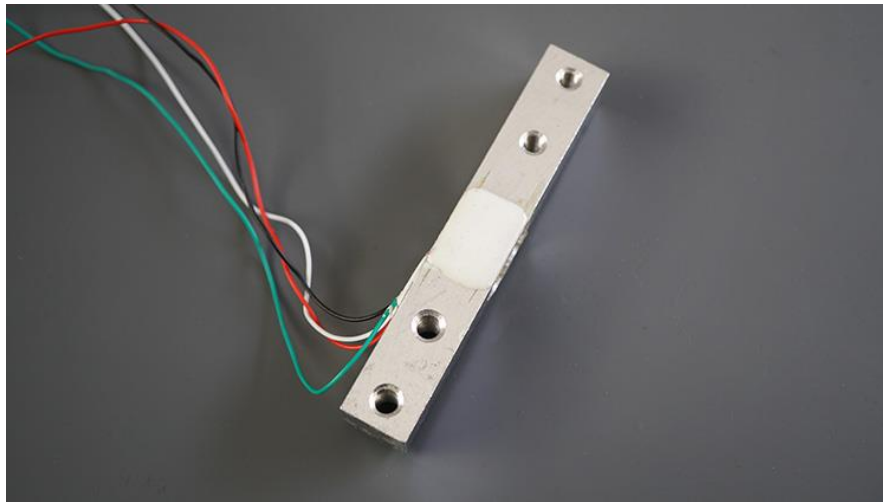
It has higher processing power, which can help us to work with the number of sensors at a time.

Difference between Arduino-UNO and Arduino-Mega

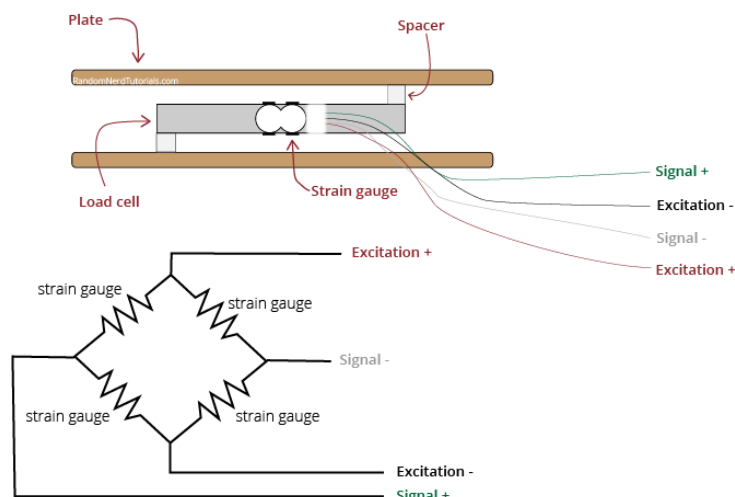
- The Arduino UNO is based on the ATmega328 Microcontroller, while Arduino Mega is based on ATmega2560 Microcontroller.
- Arduino Mega (8Kb SRAM) acquires more SRAM space than Arduino UNO (2Kb SRAM). The greater the SRAM space, the more space would the Arduino have to manipulate and create a variable when it runs.
- The Arduino UNO includes 6 analog pin inputs, 14 digital pins, a USB connector, a power jack, and an ICSP (In-Circuit Serial Programming) header. The Arduino Mega includes 54 I/O digital pins and 16 Analog Input/output (I/O), ICSP header, a reset button, 4 UART (Universal Asynchronous Receiver/Transmitter) ports, USB connection, and a power jack.
- PINS of Arduino Mega 2560 Board & Uses
- In digital side 54 pins for I/O (input output pins)
- 15 pins out of this are useful for PWM (pulse width modulation)
- In analog side 16 input pins
- Ground pins : 5
- One pin for 3.3 volts
- One reset button
- USART pins : 4 (These are hardware serial ports which produces maximum speed to setup communication)
- ISP programming pins : 6
- Crystal oscillator is added on the board having frequency of 16 MHz

Resettable Polyfuse : (to provide extra layer of protection. It prevents USB port of the computer from overheating in case of high current flowing through microcontroller board)

LOAD CELL: A load cell converts a force into an electrical signal that can be measured. The electrical signal changes proportionally to the force applied. There are different types of load cells: strain gauges, pneumatic, and hydraulic. In this tutorial, we'll cover strain gauge load cells.



Strain gauge load cells are composed of a metal bar with attached strain gauges (under the white glue in the picture above). A strain gauge is an electrical sensor that measures force or strain on an object. The resistance of the strain gauges varies when an external force is applied to an object, which results in a deformation of the object's shape (in this case, the metal bar). The strain gauge resistance is proportional to the load applied, which allows us to calculate the weight of objects. Usually, load cells have four strain gauges hooked up in a Wheatstone bridge (as shown below) that allow us to get accurate resistance measurements.



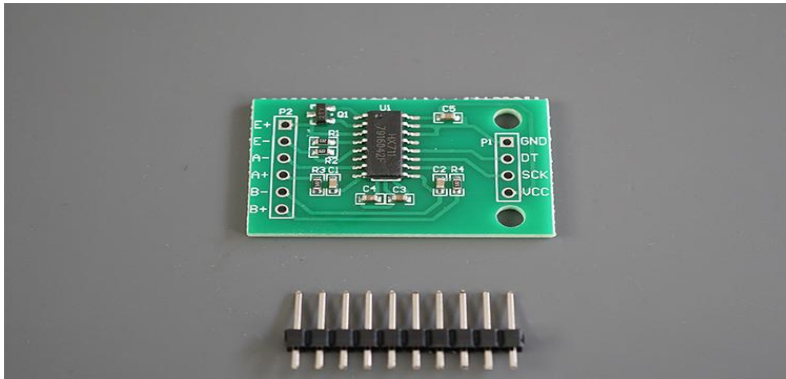
The wires coming from the load cell usually have the following colors:

- Red: VCC (E+)
- Black: GND (E-)
- White: Output – (A-)

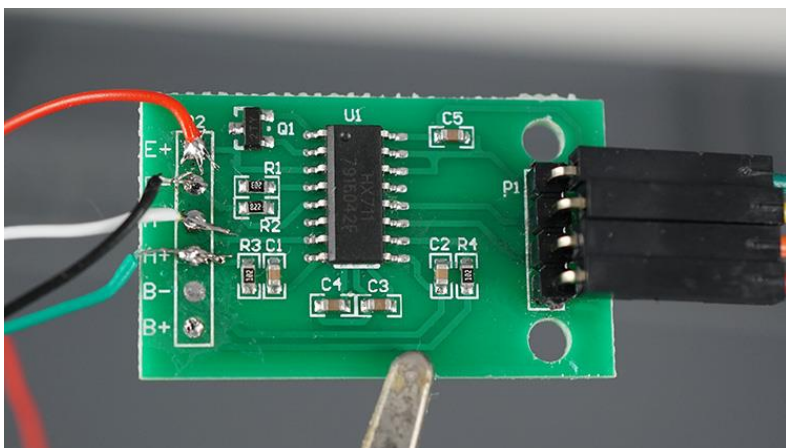
- Green: Output + (A+)

HX711 Amplifier

The HX711 amplifier is a breakout board that allows you to easily read load cells to measure weight. You wire the load cell wires on one side, and the microcontroller on the other side. The HX711 communicates with the microcontroller using two-wire interface (Clock and Data).



You need to solder header pins on the GND, DT, SCK, and VCC pins to connect to the Arduino. I soldered the load cell wires directly to the E+, E-, A-, and A+ pins. The load cell wires were very thin and fragile, be careful when soldering to not damage the wires.



For more information about the HX711 amplifier, you can consult the HX711 datasheet.

IR SENSOR:

An infrared (IR) sensor a proximity sensor, or a 'nearness' sensor that senses whether there is an object near it or not. The IR stands for Infrared sensor. Infrared is the light out of our visible spectrum.

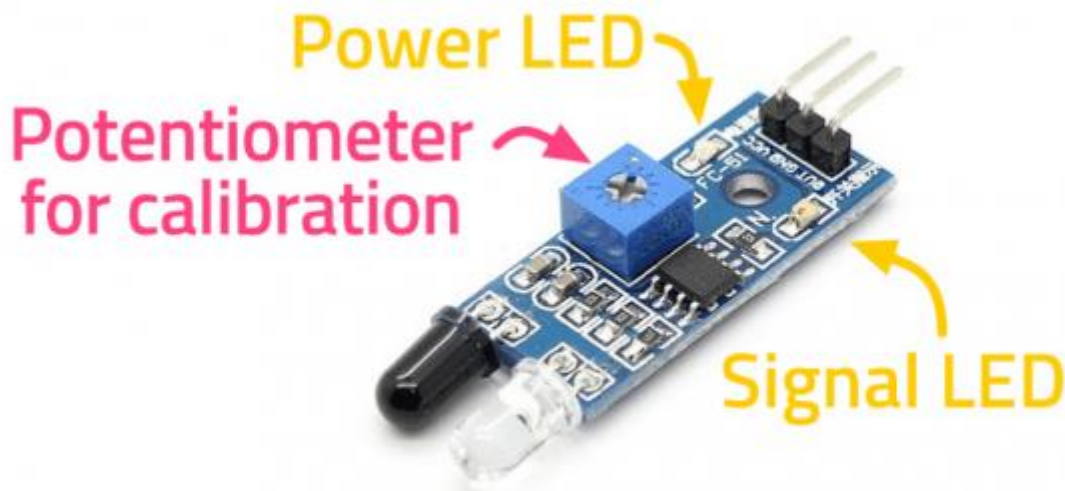
Working of an IR Sensor

The white LED here is an IR LED which works as the transmitter and the component next to the IR LED is a photodiode that works as the receiver in the IR sensor.

The IR transmitter continuously emits the IR light and the IR receiver keeps on checking for the reflected light. If the light gets reflected back by hitting any object in front it, the IR receiver receives this light. This way the object is detected in the case of the IR sensor. The blue knob here is a potentiometer. You can control the range i.e. from how far you want to detect the object by changing the value of the potentiometer.

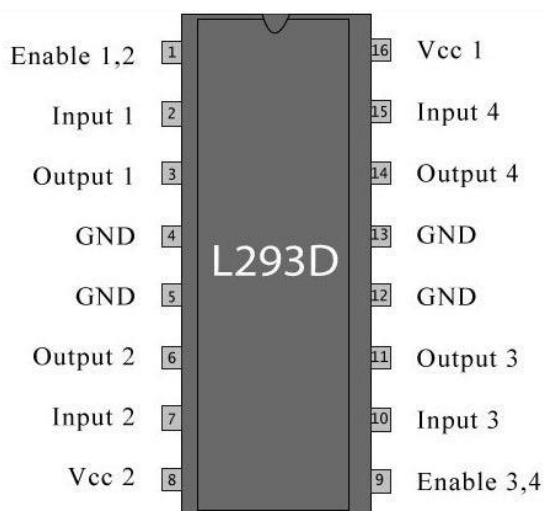
An IR sensor has two small LED indicators – one for power, which is ON the entire time the sensor is ON; the other is the Signal LED which detects the object. The signal LED has two states or situations:

- ON (Active) when it detects an object
- OFF (Inactive) when it doesn't detect any object



The IR sensor is a digital sensor, thus, the output received from it will either be **1** or **0**.

L293D DRIVER: A motor driver is an integrated circuit chip which is usually used to control motors in autonomous robots. Motor driver act as an interface between Arduino and the motors . The most commonly used motor driver IC's are from the L293 series such as L293D, L293NE, etc. These ICs are designed to control 2 DC motors simultaneously. L293D consist of two H-bridge. H-bridge is the simplest circuit for controlling a low current rated motor. We will be referring the motor driver IC as L293D only. L293D has 16 pins.



The L293D is a 16 pin IC, with eight pins, on each side, dedicated to the controlling of a motor. There are 2 INPUT pins, 2 OUTPUT pins and 1 ENABLE pin for each motor. L293D consist of two H-bridge. H-bridge is the simplest circuit for controlling a low current rated motor.

Pin No. - Pin Characteristics

- 1 - Enable 1-2, when this is HIGH the left part of the IC will work and when it is low the left part won't work.
- 2 - INPUT 1, when this pin is HIGH the current will flow through output 1
- 3 - OUTPUT 1, this pin should be connected to one of the terminal of motor
- 4,5 - GND, ground pins
- 6 - OUTPUT 2, this pin should be connected to one of the terminal of motor
- 7 - INPUT 2, when this pin is HIGH the current will flow through output 2
- 8 - VCC2, this is the voltage which will be supplied to the motor.
- 16 - VCC1, this is the power source to the IC. So, this pin should be supplied with 5 V
- 15 - INPUT 4, when this pin is HIGH the current will flow through output 4
- 14 - OUTPUT 4, this pin should be connected to one of the terminal of motor
- 13,12 - GND, ground pins
- 11 - OUTPUT 3, this pin should be connected to one of the terminal of motor
- 10 - INPUT 3, when this pin is HIGH the current will flow through output 3
- 9 - Enable 3-4, when this is HIGH the right part of the IC will work and when it is low the right part won't

GEAR MOTOR

Geared DC motors can be defined as an extension of DC motor which already had its Insight details demystified here. A geared DC Motor has a gear assembly attached to the motor. The speed of motor is counted in terms of rotations of the shaft per minute and is termed as RPM. The gear assembly helps in increasing the torque and reducing the speed. Using the correct combination of gears in a gear motor, its speed can be reduced to any desirable figure. This concept where gears reduce the speed of the vehicle but increase its torque is known as gear reduction. This Insight will explore all the minor and major details that make the gear head and hence the working of geared DC motor.

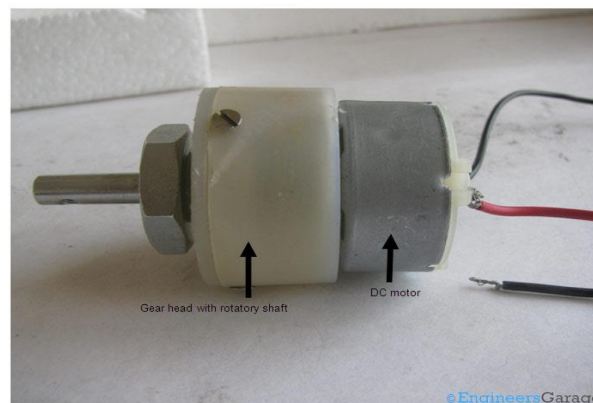


Fig. 6: External Structure of DC Geared Motor

BUZZER The two most common technologies used in buzzer designs are magnetic and piezo. Many applications use either a magnetic or a piezo buzzer, but the decision regarding which of the two technologies to use is based upon many different constraints. Magnetic buzzers operate at lower voltages and higher currents (1.5~12 V, > 20 mA) compared to piezo buzzers (12~220 V, < 20 mA), while piezo buzzers often have greater maximum sound pressure

level (SPL) capability than magnetic buzzers. However, it should be noted that the greater SPL available from piezo buzzers requires larger footprints.

ADVANTAGES:

1. High Load Density Measurement

The sensor can accurately measure high force values within a compact structure, making it suitable for robotic foot applications.

2. Miniature Size

Its small size allows easy integration into robot legs and compact robotic systems without increasing weight significantly.

3. Improved Stability and Balance

The sensor helps robots maintain balance during walking, climbing, and uneven surface movement by providing accurate force feedback.

4. High Sensitivity

It can detect small variations in pressure and contact force, improving robotic motion control.

5. Real-Time Monitoring

The sensor provides continuous force data for fast decision-making in robotic control systems.

6. Low Power Consumption

The miniature design consumes less power, which is beneficial for battery-operated robots.

7. Enhanced Safety

Accurate force sensing prevents excessive pressure on surfaces and reduces the risk of robotic damage.

8. Durability and Reliability

The sensor is designed to withstand repeated loading conditions during robotic locomotion.

9. Supports Intelligent Navigation

Force information helps robots detect terrain conditions and adapt their movement accordingly.

10. Easy Integration With IoT Systems

The sensor data can be transmitted to cloud or monitoring systems for remote analysis and control.

Applications

1. Humanoid Robots

Used in robotic feet to improve walking, running, and balancing capabilities.

2. Industrial Robotics

Helps robots perform precision tasks involving contact force monitoring.

3. Medical Rehabilitation Robots

Used in assistive robotic devices and prosthetic legs for pressure monitoring.

4. Search and Rescue Robots

Enables robots to move safely on rough and unstable terrains.

5. Military Robots

Useful in autonomous robotic systems operating in difficult environments.

6. Service Robots

Helps domestic and service robots detect floor conditions and obstacles.

7. Biomechanical Research

Used for studying foot pressure distribution and gait analysis.

8. Smart Prosthetics

Assists artificial limbs in providing realistic force feedback.

9. Agricultural Robots

Helps robots move effectively across uneven farming surfaces.

10. IoT-Based Monitoring Systems

Sensor data can be monitored remotely for analysis and predictive maintenance.

Conclusion

The high load density miniature force sensor provides an effective solution for accurate force measurement in robotic foot applications. Its compact size, high sensitivity, and reliable performance improve robotic balance, stability, and motion control. The sensor enables robots to operate efficiently on different terrains while ensuring safety and precision. Integration with IoT technology and additional sensors such as IR sensors further enhances obstacle detection and intelligent movement control. Overall, the proposed system offers improved robotic performance, reduced power consumption, and better adaptability for modern robotic applications.

Future Scope**1. Integration With Artificial Intelligence**

AI algorithms can be used for intelligent terrain analysis and adaptive walking control.

2. Wireless Communication Enhancement

Future systems can use advanced wireless technologies for faster remote monitoring.

3. Multi-Sensor Fusion

Additional sensors such as temperature, gyroscope, and accelerometer sensors can be integrated for improved environmental awareness.

4. Cloud-Based Data Analytics

Sensor data can be stored and analyzed in cloud platforms for predictive maintenance and performance optimization.

5. Energy-Efficient Design

Future improvements can focus on ultra-low-power sensor architectures for longer battery life.

6. Miniaturization Using MEMS Technology

Advanced MEMS fabrication can further reduce sensor size while increasing accuracy.

7. Autonomous Navigation

The sensor can support fully autonomous robots capable of self-balancing and obstacle avoidance.

8. Improved Load Handling Capability

Future designs may support higher force ranges for heavy-duty robotic applications.

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