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Original Article

Force Control of A Motorized Multi-Axis Ceiling Suspended System with Force-Torque Sensor

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Abstract *- Devices that measure multi-dimensional force torque are suitable for various industrial equipment / machines / processes applications. Such sensors/sensing devices can read the direct physical force and convert it into digital data. In addition to resistive strain gauges, piezoelectric, capacitive, and optoelectronic methods, there are many other ways to measure the strain. Most of these rely on detecting stresses in an elastic structure as their underlying sensing principle. Force-torque sensors will be necessary because future human assistive equipment/machines will be more interactive with human beings in various unstructured circumstances. Due to criteria and design considerations, not only finding a suitable force-torque sensor is challenging, but also it incurs high costs. These sensors frequently produce data that include noise and crosstalk problems. A multi-axis force-torque sensor application is discussed in this paper. To decrease noise and crosstalk mistakes, the study presented a control system that simultaneously gives motorized action and uses force as feedback. The proposed system can be evaluated using a variety of metrics; however, the fundamental design challenge is to expand the allowed sensing range while minimizing measurement errors. After thoroughly investigating the necessary data, the requirements for sensors and machine performance are examined. The development of force-torque sensors in the machine and the expansion of their application in the various service machine industries will benefit from this in-depth examination.*

Keywords *- Crosstalk, Force-torque sensor, Load cell, Strain measurement, Torque control.*

1. Introduction

Devices are designed to work collaboratively with humans. They have interactive interfaces for humans, termed human-machine interfaces (HMI). The interface is a combination of hardware and software which generates commands for devices through various channels and gives the user the desired output [1]. Technology for HMI has been applied in various fields, including electronics, entertainment, the military, and medicine. HMI facilitates the incorporation of people into sophisticated technology systems [2].

Human-to-machine and machine-to-human interactions are the two main types of interactions in HMI. Because HMI technology is so widely used, the interfaces that it uses are sensors, force sensors**,** switches, control joystick, and screen touch using multiple sensor arrays or interactive devices. HMI technology can be used as an adapter for other technologies, despite being regarded as an independent technological field [3, 4]. Working with humans and observing and reading human behaviour is the foundation for developing HMIs. In other words, the foundation of HMIs is usability. HMIs can offer unique potential for applications, learning, and entertainment in addition to improving user experience and efficiency. In reality, HMI supports users' quick skill acquisition. A quality HMI can offer believable and organic interactions with external devices [5].

The force-torque sensor is the user's first point of interaction at a controlling handle when using an HMI-enabled system that requires them to manipulate or revolve a particular machine. This comprehends the magnitude and directions of force torque when a user applies an operating effort. As a result, it magnifies the force torque using the system's motors and other controllers to move the machine in the intended direction. As a result, the operator only needs to exert a relatively small amount of force to move large machines.

The linear and rotational forces applied to an object are monitored, detected, recorded, and controlled by an electronic device known as a force-torque sensor [6]. The force sensor is a device which converts physical variables like pressure and load into a readable and recordable data array [7]. The data or signals recorded from such sensors are convertible in a digital format with various sampling rates. This data can be monitored and converted so that different algorithm types can be applied to remove various resulting errors. Various loadcell, strain gauges, or smaller force-torque sensors with variable amplifier modules are available. Many force-torque sensors are built using semiconductor strain gauges [8].

In the multi-direction manoeuvring of the machine, if a unitary force-torque sensor is measuring the input effort from the user, crosstalk results in the sensor's data while recording forces in many directions [9,10]. The error from the multi-direction force's magnitude during data measurement is known as crosstalk. Current leakages through the multiplexer channel and the routes used by the strain gauge's different components inside the sensor result in crosstalk [11]. Crosstalk may cause any change in reading to be perceived as false. Crosstalk reduction becomes essential for obtaining the most precise force-sensing measurements [12].

The noise is a standard error induced in any form of sensor reading. As the physical variable are analogues, the recorded data can be infected with many surrounding unwanted values. Noise affects both analog and digital both types of signals. When noise is suppressed with a Gaussian filter, the signal is also distorted as the noise is smoothed out. The Gaussian filter works on edge detection by following the signal and comparing every data value with its previous value, which helps normalise the recorded data value curve [13]. A statistical noise known as "Gaussian noise" has a probability density function identical to the Gaussian normal distribution. Different filtering methods eliminate this noise while maintaining the signal's integrity. Different noise reduction techniques, like Gaussian distribution, rely on the standard deviation's pre-knowledge and several other characteristics [14].

The gain of the amplifiers governs the overall performance of the signal conditioning and amplifier circuits. Crosstalk, however, cannot be removed after applying several operations to the signal. The sensors integrated with data processing and amplifier circuit boards come with a hefty price tag [15, 16], despite the commercial multi-axis load cells or force-torque sensors having a straightforward mechanical design. As a result, crosstalk issues arise in systems that use force-torque monitoring to assist with machine operation via HMI. It is necessary to handle the problems caused by crosstalk, either by eliminating it, which is unavoidable, or by developing a system with an algorithm or software/hardware to counteract its effects [17].

This study presents a novel approach to measuring the direct force operating on a multi-axis system and determining its direction through data capture. The recommended approach eliminates crosstalk on two different levels. The system can be enhanced in two steps:

(i) By upgrading the analogue-to-digital gear to have more excellent bit rates and gains, and
(ii) By putting the different unusual algorithms into practice.

In order to prevent the impact of crosstalk, the authors put forth a unique yet coupled two-level method, which considers the hardware and software levels. The paper explores a mechatronic system’s creation and evaluation in developing a four-axis ceiling suspension system with integrated force-torque sensors. By doing this, it tries to explain to the technical worker operating that service equipment can offer some help with navigation. This work aims to establish a technique that enables a multi-axis system to calculate the actual force exerted on it and, through data acquisition, ascertain the orientation of the force. This work aims to establish a technique that enables a multi-axis system to gauge the magnitude of the force applied to it and, through data acquisition, ascertain the orientation of the force. This procedure will be helpful in HMI. Decreasing the force required of the machine operator to operate/manoeuvre the equipment/service machine will aid in the creation of an atmosphere where the equipment/service machine can support the operator.

Strain Gauge load cells are perfect elastic devices that are very efficient in showing small changes like compression and expansion [18]. In forming new load cell construction, multiple strain gauge cells are incorporated into a single device. The constructed shape of any strain gauge helps decide the average range of reading force [19]. This article discusses a handful of the resistance strain gauges that can be used for various tasks. Various strain gauges on the device are aligned to measure the direct force of the object [20]. Electrical resistance strain gauges: The conductive wire is coiled on an elastic surface to measure the load directly acting on it [21]. A change in the dimension of the wire produces a change in the resistance of the wire [22].

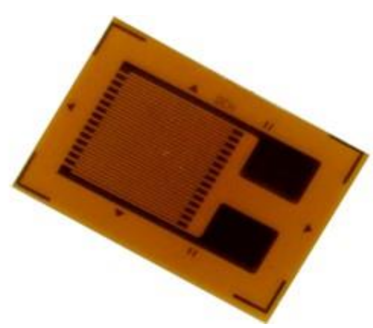

Fig. 1 Strain gauges

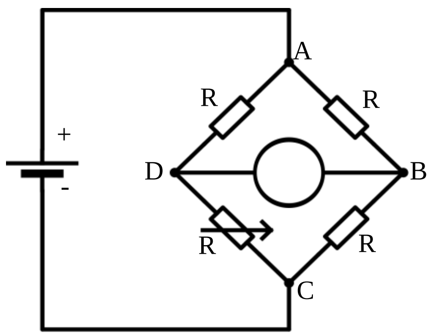

Fig. 2 Wheatstone construction

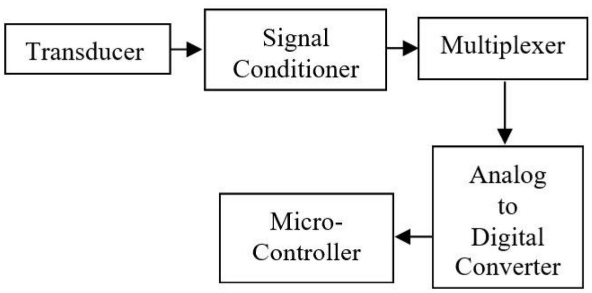

Fig. 3 Data acquisition

Several strain gauges are attached to read the specific direct force simultaneously on a device. Comparing and differentiating such multiple forces, the collective data is recorded of force. The strain gauges are very popular for measuring forces, providing voltage change with very small to very high ranges like 2N to more than 50 MN [23]. Change in resistance is measured by measuring force or load in any strain gauge-equipped device, primarily using a voltage divider circuit construction. The change in resistance leads to a change in voltage. Nickel-chromium, copper-nickel and platinum-tungsten are popularly used alloys for constructing strain gauges [24]. There are various ways of strain gauge construction, such as linear gauges, T-rosettes, double shear etc. Figure. 1 shows a strain gauge constructed with the linear gauge method. Capacitive sensors are those with good sensitivity and resolution [25]. The availability of small processors for signal digitalization benefits capacitive sensors. Capacitive sensors are rarely used for macro-size force-torque sensors because they frequently experience severe hysteresis and their susceptibility to heat and moisture [26–28]. Capacitive sensors have substantial system hysteresis due to the viscoelastic material used in the sensors' construction [29].

Certain crystalline substances produce electric charges varying proportionally per the changing applied force on their crystal surfaces. Most of the quartz used now is synthetic, compared to measurement by primary piezoelectric transducers, which incorporate naturally generated quartz. As a result, these devices are frequently called "quartz force transducers," though the wording "piezoelectric crystal" will be employed more frequently in this manuscript. In direct proportion to the change in applied force, certain crystalline materials produce electric charges on their crystal surfaces. A charge amplifier is required to power the device to deliver a signal proportional to the applied force and large enough to measure. Most quartz used now is synthetic, unlike the piezoelectric transducers for measurement. As a result, these gadgets are typically referred to as "quartz force transducers," albeit "piezoelectric crystal" will be used more commonly here [30].

2. Method

The analog-to-digital converter (ADC) HX711 is connected to a force-torque sensor based on strain gauges as the experimental hardware contraction. An operational amplifier is a component of an ADC that compares and reads changes in resistance in strain gauges.

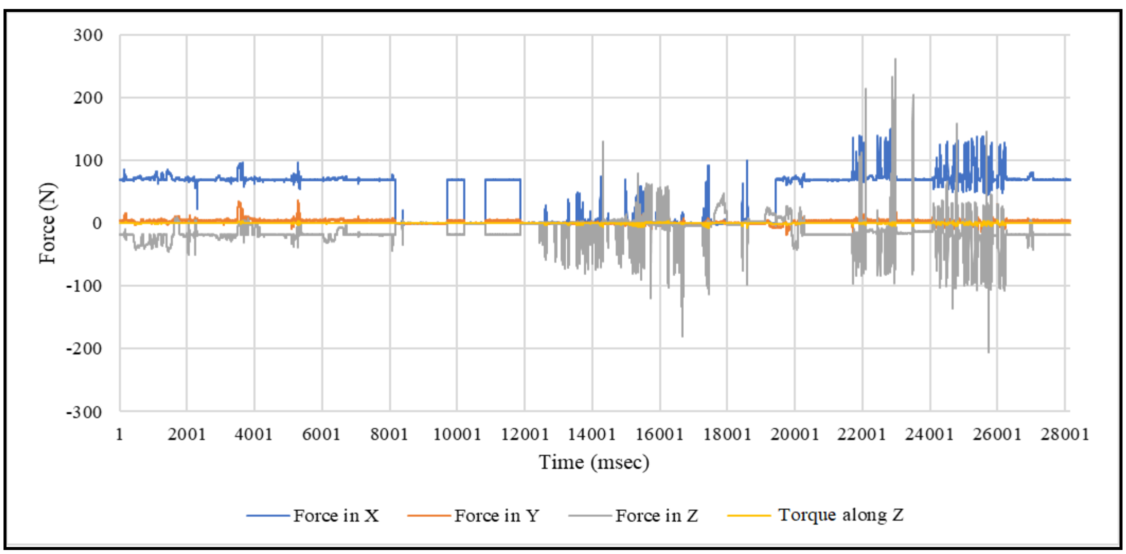

Fig. 4 Data recorded

The Wheatstone bridge concept inspires strain gauge data recording to measure differential changes in resistance. As depicted in Figure 2, a Wheatstone bridge is used to measure unidentified resistance values. It has four resistive legs, two of which have a voltage source (excitation voltage) applied across them, and one has an unknown resistance. You can figure out the value of the unknown resistance by adjusting the resistance in the other two legs until the voltage across the bridge is zero. Figure 3 displays the data acquisition block diagram. ADC-HX711 measures the differential voltage from the force sensor and sends it to the microcontroller via serial communication. The microcontroller is programmed to analyze the data and produce the necessary duty cycle and pulse with modulation (PWM) [31]. This enabled the motor driver to move the motor in desired direction.

2.1. Crosstalk Minimization

Figure 4 and Figure 5 illustrates the results of the hardware-software interactions. Through ADC-HX711, the microcontroller receives the force-torque sensors' analog input signal and processes and records the data. The graph in Figure 4 displays the data gathered using an ADC-HX711 and a microcontroller; the scripted code did not perform any calibration, and the essential information was saved. Creating an offset for each force value allows the data in Figure 5 to calibrate correctly. The results are calibrated after the offset is subtracted from the sensor measurements. The proposed system eliminates crosstalk on two different levels.

2.1.1. Crosstalk Minimization at Hardware Level

In its initial development, the system employs a precise 24-bit ADC-HX711. The HX711 and a strain gauge amplifier for the HX711 IC make reading the load cells straightforward. Figure 6 shows the load cell interfacing using HX711. The precise input circuit may be tuned for more significant gain and is ideal for sampling. The HX711 uses the two-wire clock and data interface to communicate. High integration, fast thinking, immunity, and other characteristics of HX711 are advantages that improve overall performance. Figure 7 shows the interfacing of the microcontroller Arduino mega with multiple high-precision ADC-HX711 for force values in multiple directions.

2.1.2. Crosstalk Minimization at the Software Level

The algorithm used by the microcontroller eliminates crosstalk, having analyzed the information and put it through several processing steps using absolute values to map the data. The PWM for the motor driver to operate the permanent magnet DC motor is determined using real-time data of 24 bits that have been processed and converted to an absolute set of values. The algorithm applied to read, record, and process data is shown in Figure 8. The script is written in C language in Arduino IDE. The operational flow of the recorded data is a new and composite structure. The control system records the data using ADC-HX711. The ADC record the change in voltage in the range of 0 V to 5 V. The values are stored in a temporary variable, and complete conversion is done on recorded data. It is easy to work and modulate the positive spectrum value. PWM signals are generated and given to the motor driver.

2.2. Noise Minimization

Minimizing noise error in any signal, analog or digital, is termed Noise Minimization. There is an availability of specific algorithms which can reduce the noise at a certain level. Using an algorithm will not eliminate the recorded noise.

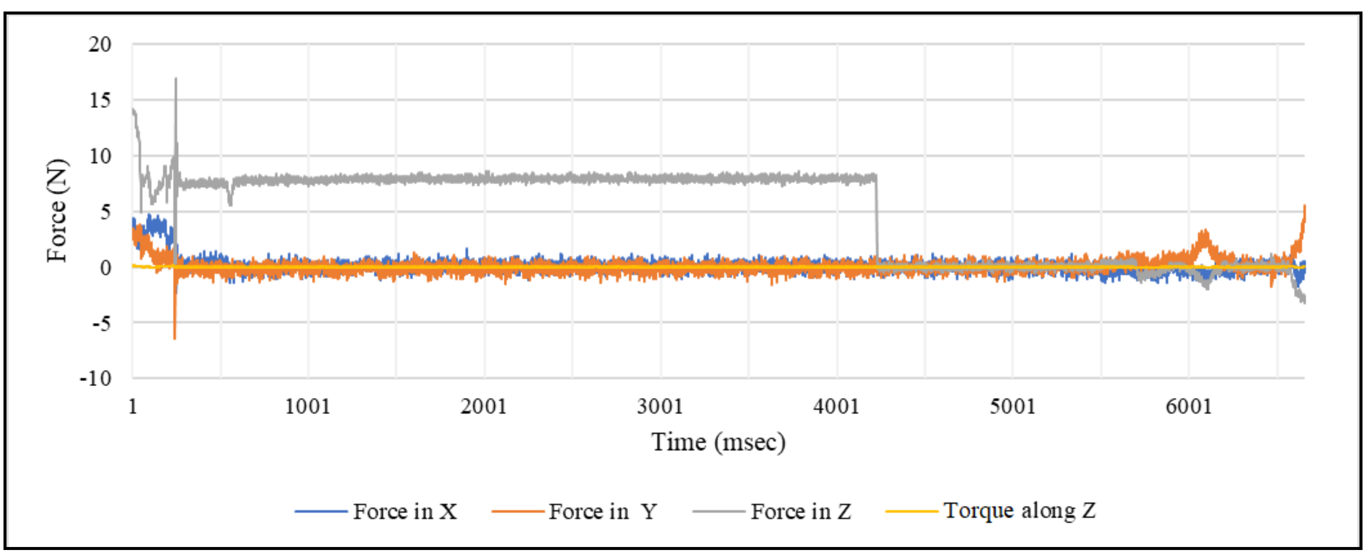

Fig. 5 Data recorded and calibrated

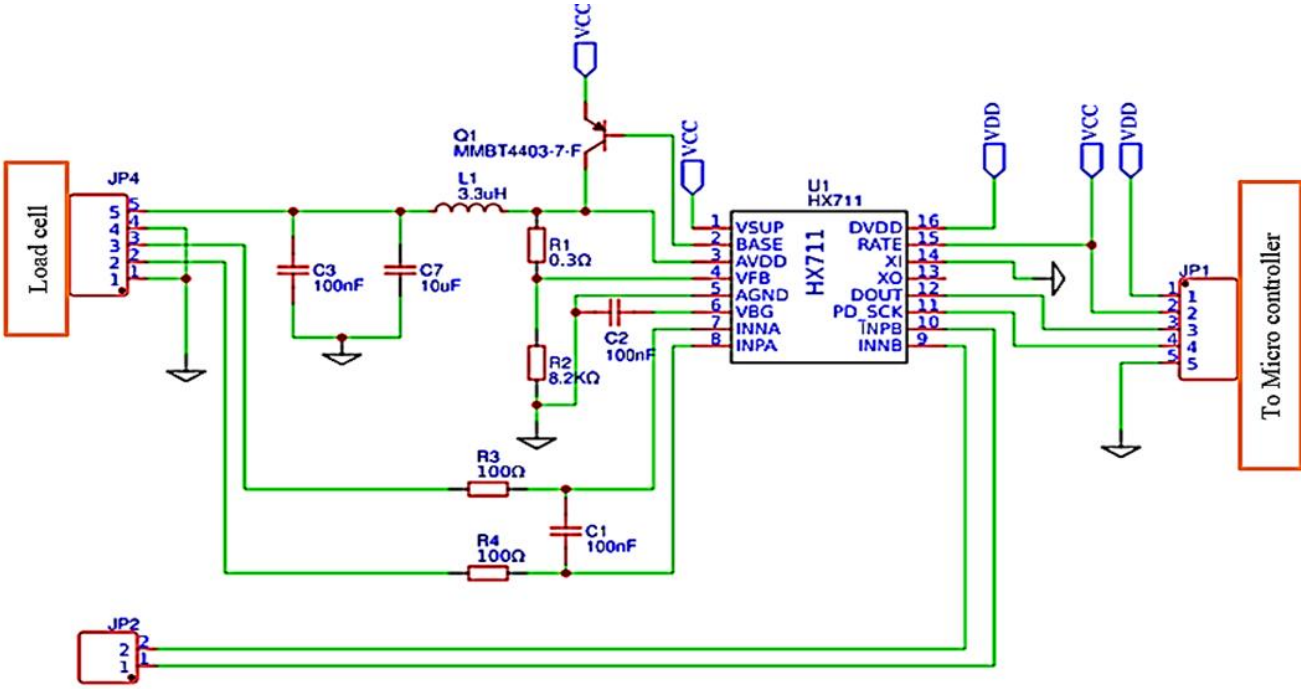

Fig. 6 Load cell interfacing using HX711

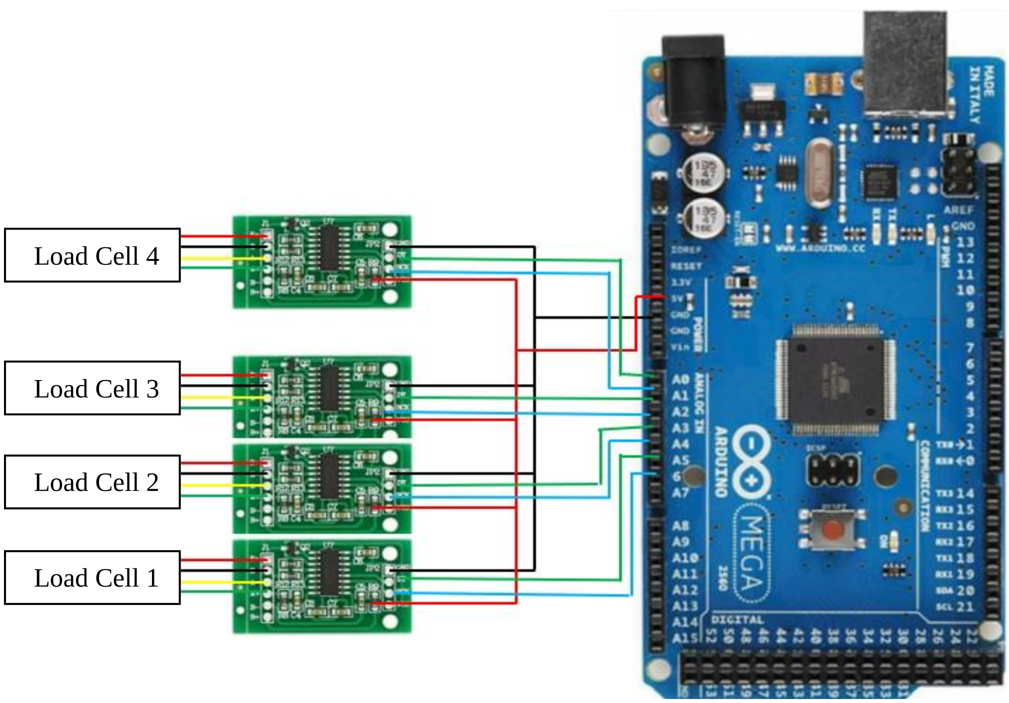

Fig. 7 Load cell interfacing using HX711 with Arduino Mega

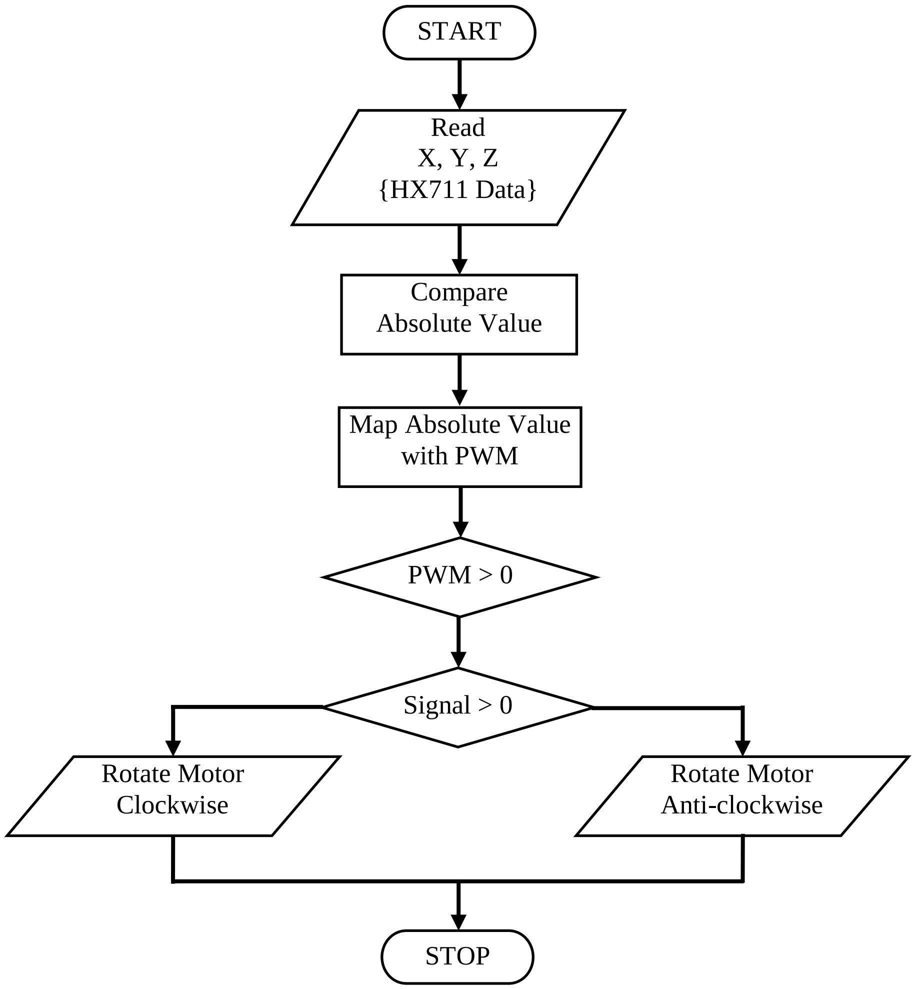

Fig. 8 Software-level algorithm

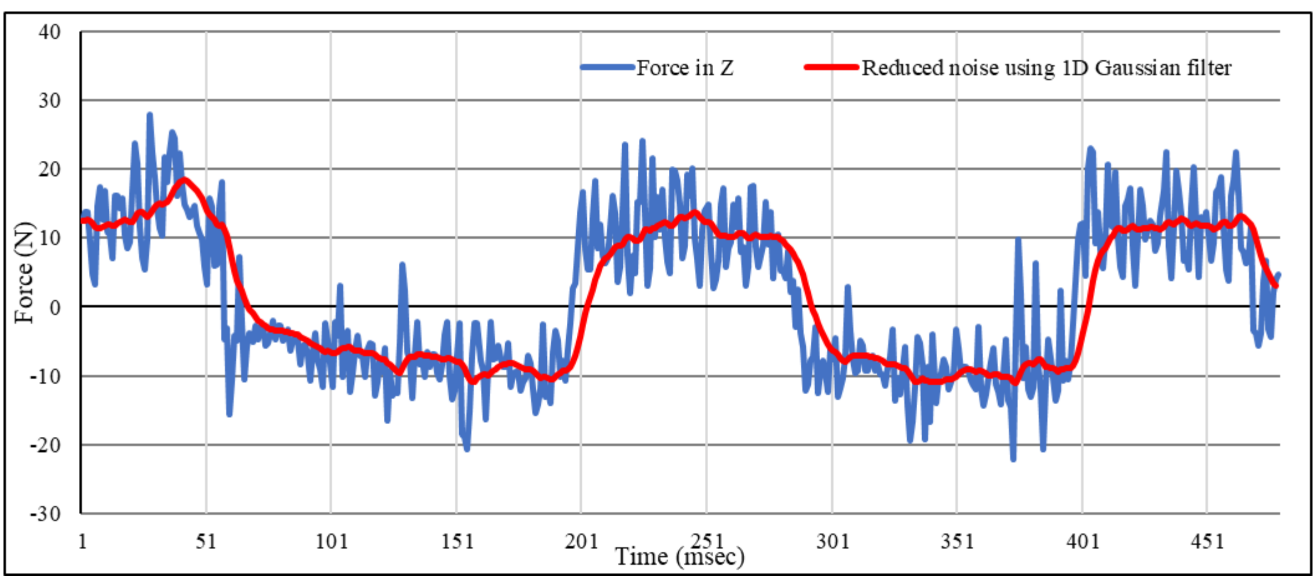

Fig. 9 Minimizing noise using Gaussian filter

Constructing such a circuit capable of removing noise during data gathering is required. Such constructions are very much accurate to minimize the addition of noise in the original signal. Figure 9 depicts the minimization of noise using the ID Gaussian filter. A Gaussian function is applied to the pixel values of an image by an image filter known as an ID Gaussian filter to reduce noise in the image.

3. Results and Discussion

The present findings from an integrated methodology cover various topics, including device design, a data processing algorithm, mounting the sensor, data measurement and recording, and the construction of a prototype for qualitative assessment. The algorithm employed to reduce crosstalk is highlighted in Figure 8. Following the algorithm, as highlighted in Figure 8, it derives the absolute value, and the PWM mapping is done with the highest absolute value derived from the observed values.

4. Conclusion

Force-torque sensors record the input force as an analog signal read using a third-party ADC. Thanks to the experimental setup, a force-torque sensor constructed utilizing strain gauges has proven highly effective and beneficial in real-time applications. Helped by discussions of unique requirements, range selection, and sensor structure, a different system with a force-torque sensor has been created. Along with creating the particular force-assistance system, this paper's analysis and discussion help create a new system with different configurations with minimal crosstalk or measurement errors when the system and the environment outside come into a strong force of contact. The impact of crosstalk and noise has been successfully countered using a novel two-level solution that includes hardware and software.

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