Motor controlled system development with force-assistance using force/torque sensor for four-axis ceiling suspension system

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ABSTRACT

Multi-axis force and torque sensors are type of transducers. They can measure force and torque in three dimensions. These sensors have multiple applications in robotic systems. The majority of these type of sensors use the strain measurement in any elastic structure. There are multiple approaches for strain measurement which include resistive strain gauge, piezo-electric and capacitive technologies. The evaluation of such a system can be done on various parameters, maximizing the acceptable sensing range while minimizing measurement errors/crosstalk is the main design challenge. In future, because force and torque sensors are necessary for service machines to interact with people in different situations, they will be widely deployed. However, it is challenging to find an appropriate force/torque sensor, and the cost is very high, because of certain design concerns and needs. This paper discusses an application based on the multi-axis force/torque sensor. A force-assisted control system has been proposed with simultaneous motorized action using force as feedback. The sensor needs and machine performance are reviewed after a thorough analysis of relevant data. This thorough investigation will benefit in the interfacing of specialized force/torque sensors to reduce crosstalk and aid in broadening the scope of service machines in which they can be used.

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1. INTRODUCTION

The contribution of technology to human life and work is growing, and technologies are being created to supplement humans in their labor while attending various machines. Human-machine interface (HMI) plays an important role in proper execution of object manipulation functions, such as assisting a person's task through machines. Researchers are investigating and developing software and hardware-based HMI manipulation tools that include sensors and integrated sensor technology. HMI has undergone a lot of development [1].

In order for the machine to interact with people, it is necessary to create and use a new sensor that requires very tight control over sensing data as well as extremely accurate measurements of force and torque [2]. Sensors like gyroscopes, accelerometers, and force/torque sensors are very necessary to read and record any movement of a machine interacting in a closed or open environment. Considering the sensor technologies, the force/torque sensor is being used to adjust its functions and size according to the work in various fields like from industrial robots to medical robots and service machine systems. A force/torque sensor is utilized on a very large scale for HMI since it can measure the direct force, impulse, or torque operating at a specific spot [3].

While operating an HMI enabled system, in which a user is required to move or rotate a certain machine, the first contact point of the user (at a control handle) is the force/torque sensor. This understands the user's force/torque and the direction. Accordingly, it amplifies the force/torque using motors and other actuators that assemble the system, and moves the machine in the desired direction. Thus, providing a force assistance, the user is required to apply very minimum force to move heavy machinery.

Digital X-ray system, dental chairs, dental units, and robots are some of the representative examples of system devices that are made to interact with humans through HMI. Sensing user force to move machinery is a basic principle in very immersion technology like an exoskeleton robotic suit. The force sensors interfaced in this were made of resistive and semiconductor materials [4], [5]. Many different applications, including strain gauges, tactile sensing, temperature sensing, photo detector, and gas detecting sensors, use resistive sensors. The voltage change in the circuit is a popular way to quantify the change in resistance. An operational amplifier circuit is then used to examine this alteration in resistance. The amplifier circuit is also used for signal conditioning. Sensors like stain gauges include more than 32 interconnected variable resisters, and many sensors are multiplexed to transfer data for data acquisition [3]–[5].

When a single force sensor is employed to identify the user effort input for movement of a machine in various directions then the data recorded by the sensor corresponding to forces in multiple directions causes crosstalk. Crosstalk is the term for the mistake that results due to multiple direction force values in measured data [6]. The crosstalk is produced by the multiplexer channels' leakage currents and the pathways taken by the various strain gauge elements within the sensor. Any reading change could be seen as false due to crosstalk. In order to attain the best accuracy in force sensing, crosstalk reduction becomes crucial [7], [8]. The gain of the amplifiers determines how well the signal conditioning and amplifier circuits function overall. However, despite performing numerous operations on the signal, crosstalk cannot be eliminated. Even though the mechanical construction of the commercially available multi-axis load cells or force/torque sensors is straightforward, the signal processing and amplifier circuit boards with sensors are expensive [9], [10]. Thus, systems incorporating force and torque measurement to facilitate effort reduction while operating the machine through HMI are facing the problems related to crosstalk. There is need to address the issues related to crosstalk either by its complete elimination which is inevitable or build the system having algorithm or software/hardware to nullify effect of crosstalk.

The system uses a precision 24-bit analog-to-digital converter (ADC) in its initial iteration. For the HX711 IC, the HX711 module is a load cell amplifier that makes it simple to read load cells. HX711 24 bit high-precision ADC chips are used. The input circuit set with a higher gain is accurate, and is a perfect for sampling. The HX711 communicates using a two-wire interface clock and data [11]. HX711 has benefits like high integration, quick reaction, immunity, and other qualities that enhance overall performance. After reading the data and applying a number of processes, the microcontroller's algorithm removes crosstalk by mapping the data with absolute values. The real time data of 24 bits is processed and converted to absolute set of values on which the pulse width modulation required for motor driver to run the permanent magnet DC motor. The present paper has proposed a new method by which a multi-axis system can measure the direct force acting on it and, using data acquisition, assess the force's direction. Crosstalk is eliminated on two levels in the system that is being suggested. First, by updating the analog-to-digital hardware at higher bit rate and higher gain and the second, is by implementing authors' customized algorithm. Thus, authors' have proposed a unique but combined two level solution, incorporating hardware level as well as software level, to avoid the effect of crosstalk.

In this regard, this study provides the design and analysis of a mechatronic system while development of sensor integrated four-axis ceiling suspension system using a force/torque sensor. Thereby it aims to provide force assistance to the navigation task of the technical person attending that service machine. The aim of the paper is to formulate a way by which a multi-axis system will be capable of measuring the direct force acting on it and using the data acquisition it will be able to analyze the direction of the force. The use of this process will be useful in HMI. It will help in creating an environment in which the service machine will assist the human by reducing the force effort to be applied by the attendant to drive/navigate the service machine.

2. FORCE/TORQUE SENSOR AND EXISTING TECHNOLOGY

Force/torque sensor in an electronic device that is capable to sense the direct force or rotational force applied to it [12]. An electronic instrument converts the physical form of energy into electrical form using some electrical signal conditioning devices is a transducer. The applied force like compression, tension or weight on a device and the device read those changes occurs physically is force or torque transducer [13],

[14]. There is a lot of development in different sensor technologies to record the force using multiple ways and multiple materials. To make the force sensors more compact and error less technologies are developing. The major role of semiconductors to build such devices is very huge [15], [16].

The strain gauge load cell is the most used kind of force sensor or transducer and a good example of an elastic device. Once the load or force applied to any strain gauge devices because of its elastic nature it tends to change its geometric shape that leads to change in diameter, length and cross section area of the semiconductor wire attached in the object [17]. Figure 1 illustrates some of the different resistance strain gauges that are available for use in diverse applications, including the linear gauge, T-rosette, and double shear [18]–[21]. Because of change in cross section area of the wire the resistivity and the resistance of such devices changes this change can be seen using a voltage divider circuit [22]. Using polymers adhesive if such construction attached to an object which is then introduced with certain load the wire construction will able to sense the developed strain in the devices. To get the sensing data accurate multiple numbers of such small strain gauges are connected in series or in parallel configuration depending upon the range of force in Newton required, with different rated capacities typically ranging from 2 N to more than 50 MN [23]–[25]. Copper-nickel, nickel-chromium, nickel-chromium-molybdenum, and platinum-tungsten alloys are the most popular materials used to make strain gauges [26].

In force sensitive resistor (FSR) sensor, foam is used to separate the two copper sheets. This construction of strain gauge, using foam as a separating membrane, is very useful for multiple applications [27]. The FSR sensor is lightweight and has been considered for the study presented in this paper. High sensitivity and high-resolution are key features of the capacitive type of force sensors [28]. Capacitive sensors advantage from the accessibility of tiny chips for signal digitization. However, due to their frequent severe hysteresis and sensitivity to variables like temperature and humidity, capacitive sensors are infrequently employed for macro scale force/torque sensors [29]–[35]. Because viscoelastic material is used in capacitive sensors, the sensors exhibit substantial hysteresis [36]. Figure 1 shows the construction of different types of gauges available to be used for resistance-based construction of force sensor.

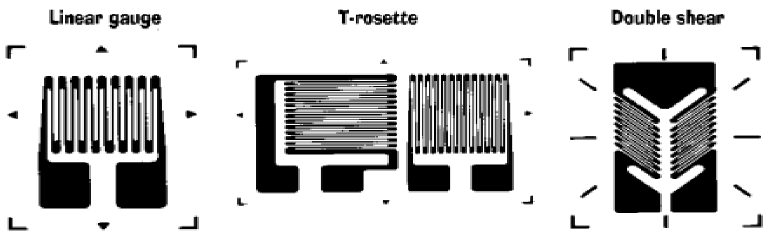


Figure 1. Type of strain gauges

On the crystal surface of some crystalline materials, electric charges are created in directly proportional to the change in force applied. In order to operate the device, a charge measuring amplifier is needed to provide a signal that is both large enough to measure and proportionate to the applied force. The early piezoelectric transducers for measuring used naturally produced quartz, however today most quartz is synthetic. Due to this, these sensors are frequently referred to as quartz force sensor, however the term "piezoelectric crystal" will be used here more frequently. The fact that these piezoelectric crystal sensors are active sensing components sets them apart from the majority of other sensing methods. The advantage of such large frequency response of the measuring system without creating geometric changes to the force measuring channel is less power supply is required and the deformation to obtain a signal is very minute. A piezoelectric sensor can still be used to measure the change in the position vector. Using a substance known as piezoelectric, energy can be transformed from mechanical to electrical or electrical to mechanical. A transition occurs because of the piezoelectric effect [37]. Manufacturing, microscopy, medicine, robotics, and defense are just a few of the industries that are using more and more piezoelectric actuators for stack-type placement. These systems are prized in real-world applications for their compact design, low energy usage, and powerful actuator dynamic performance [38].

These instruments allow measurements of high-speed scenarios, such as the direct impact on solids and press forces, which could not otherwise be possible. Piezoelectric sensors require a circuit allows a relatively small amount of current through, per unit of applied voltage at that point. Utilizing the appropriate cabling included with a transducer is crucial [39]–[41]. Table 1 provides a comparison of different device types that can be used for force sensor construction and thereby can be further modified to be used as force/torque sensor.

Table 1. Comparison of different device types that can be used for force sensor construction

Device type	Subcategory	Range of capacities	Uncertainty % of reading	Temperature Sensitivity and Operating range of reading per °C
Strain gauge or load cells	Semiconductor	0.01 N to 10 kN	0.2 to 1	-40 ºC to +80 ºC
	Thin film	0.1 N to 1 MN	0.02 to 1	-40 ºC to +80 ºC
	Foil	5 N to 50 MN	0.02 to 1	-40 ºC to +80 ºC
Piezoelectric crystal		1.5 mN to 120 MN	0.3 to 1	-40 ºC to +80 ºC
Capacitive, linear variable differential transformer vibrating wire		10 mN to 1 MN	0.02 to 2	-40 ºC to +80 ºC

3. METHOD

The experimental hardware contraction consists of a strain gauge-based force/torque sensor connected with the ADC HX711. ADC consists of an operational amplifier which is used for comparing and reading the change in resistance within the strain gauge. To measure small changes in resistance, strain gauge configurations are based on the concept of a Wheatstone bridge. The general Wheatstone bridge, illustrated in Figure 2 is a network of four resistive arms with an excitation voltage, V_{EX}, that is applied across the bridge. The block diagram of data acquisition is shown in Figure 3. Force sensor gives the differential voltage which is measured by the ADC HX711 and the data through serial communication is given to the microcontroller, the microcontroller has the code to evaluate and to generate the required pulse with modulation (PWM) and duty cycle for the motor driver to run the motor in desired position.

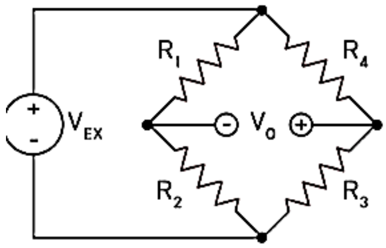


Figure 2. Wheatstone bridge circuit configuration in rhombus style

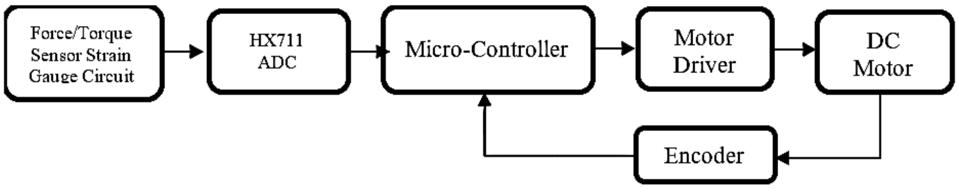


Figure 3. Block diagram of data acquisition

4. RESULTS AND DISCUSSION

The current results are the consequence of a multidisciplinary approach and include issues of equipment design, algorithm for data processing, mounting the sensor, data measuring and recording, and a build of a prototype for qualitative evaluation.

4.1. Experimental setup

The setup consists of the major components as force/torque sensor, ADC HX711, micro-controller (ATMEGA2560), DC motor driver board (Cytron enhanced 13 Amp), power supply and DC motor. The force/torque sensor has a construction of multiple strain gauges which is connected in rhombus Wheatstone bridge construction with each HX711. To collect the data from four strain gauges, four number of HX711 are required. HX711 communicates with microcontroller using two-wire interface (clock and data), which is connected on SCK and DT pins. The force values get stored and processed in the microcontroller and mapped over the PWM. The ATMEGA gives 2^8 bytes of PWM means it gives the range of PWM pulses from 0 to 255. Using the PWM values the motor driver controls the DC motor. Figure 4 shows the interfacing of the force/torque sensor with the ADC and microcontroller.

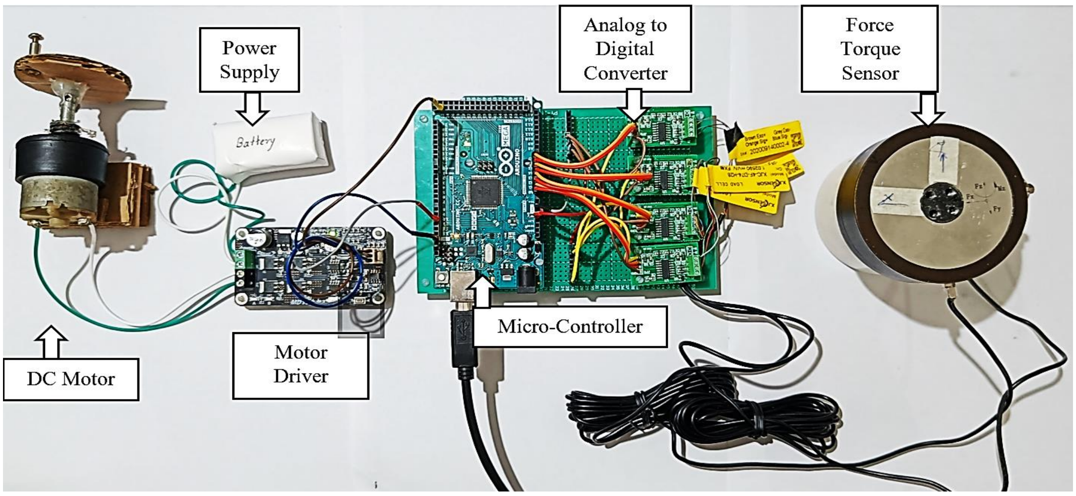


Figure 4. Experimental setup

4.2. Data measuring/recording

The communication results between the hardware and the software are shown in Figure 5 and Figure 6. The analog input signal from the force/torque sensors received by ADC HX711 is given to microcontroller and the data is processed and recorded. Graph of Figure 5 shows the data collected through microcontroller through ADC HX711, the calibration is not done in the code script and the raw data is stored. In Figure 6 the data shown is properly calibrated by generating an offset for every force value. The offset is then subtracted from the sensing values and gives the calibrated results.

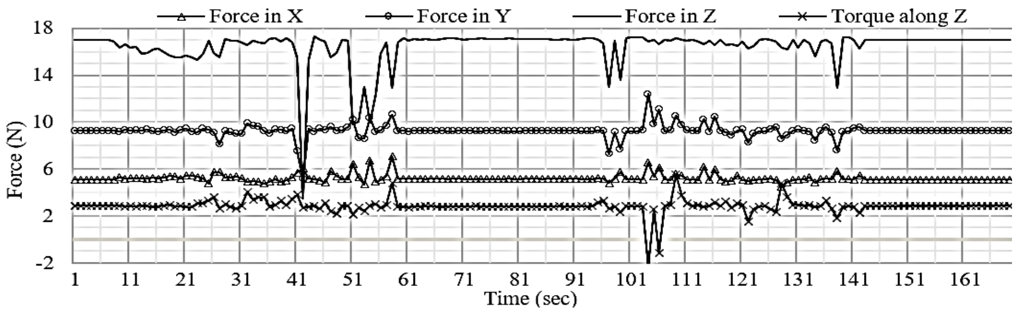


Figure 5. Data collected before calibration

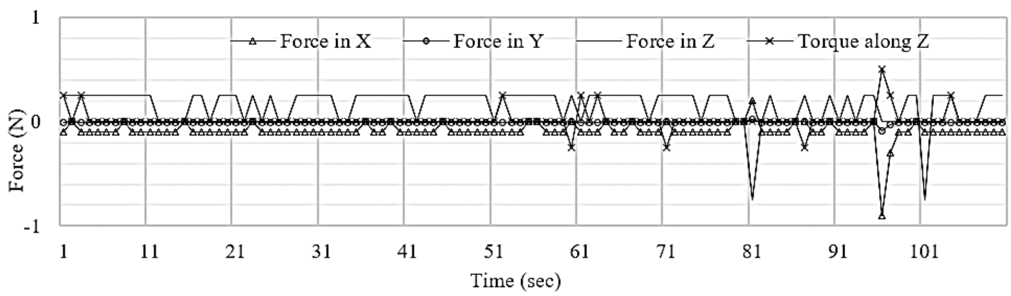


Figure 6. Data collected after calibration

Any effect can be described as "crosstalk" occurs when a signal sent through singular circuit or the same channel of a transmission used in system has an unintended impact on a different circuit or on different channel. Crosstalk is typically brought on by undesirable change in capacitance, change in inductance or heavy disturbance of error in collecting data between channels or circuits. Here the crosstalk is of four signals because the control system is reading the sensor data in all four directions at a time. There is a need to minimize the crosstalk. Figure 7 highlights the algorithm used to minimize the cross talk. After applying the algorithm, as shown in Figure 7, the absolute value is represented and the PWM is mapped along with the maximum absolute value which is calculated from the recorded values.

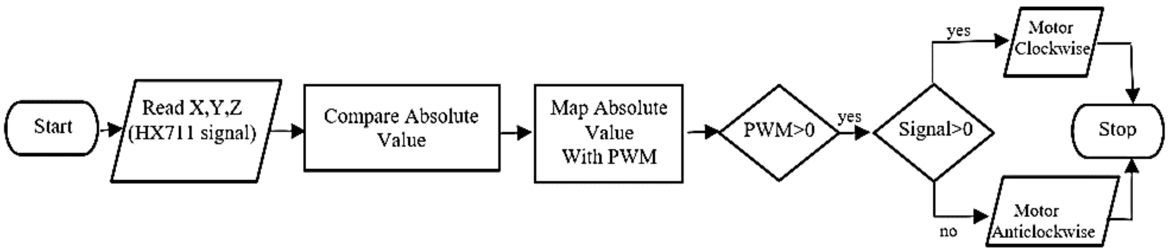
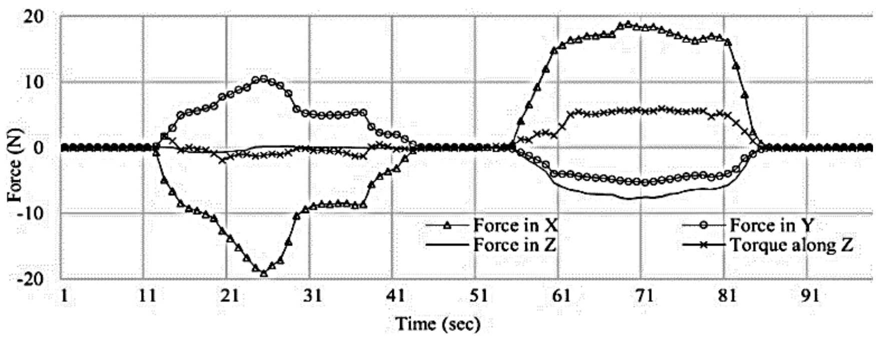
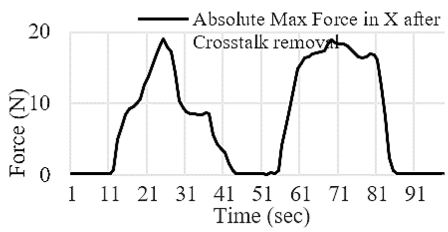


Figure 7. Algorithm used to reduce crosstalk

Figure 8 represents the data after applying the algorithm to get the mapped PWM to be provided to the motor driver to move the motor. This PWM is given as input to the motor driver circuit and the motor speed is controlled to obtain the desired position. To control the direction of rotation of the motor the negative and positive values are considered. The motor will rotate in a clockwise direction if the applied force values are positive and vice versa. Figure 9 shows data gathered from all four axes.



(a)



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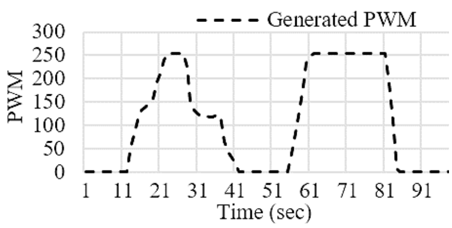
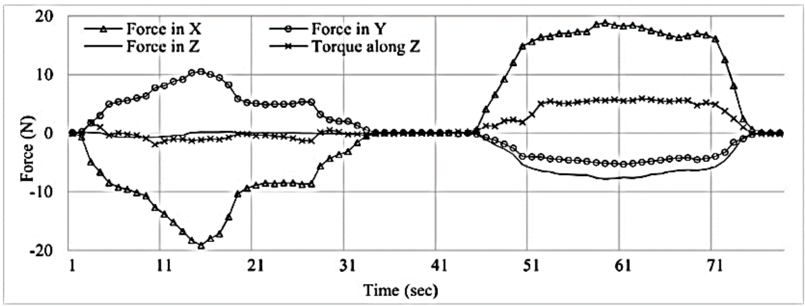


(c)

Figure 8. Crosstalk removal (a) data collected, (b) mapped absolute value, and (c) generated PWM



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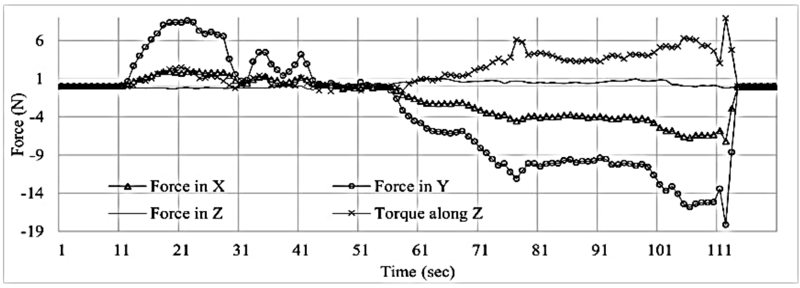

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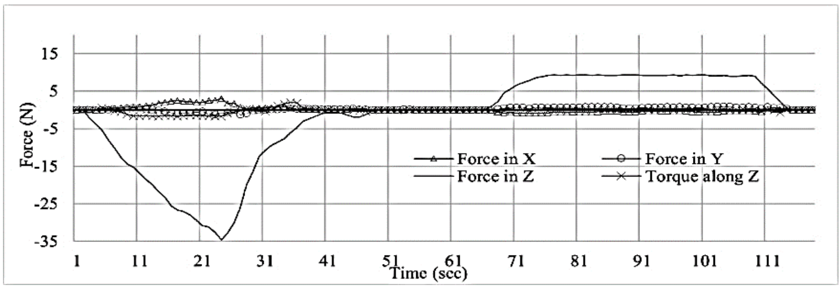

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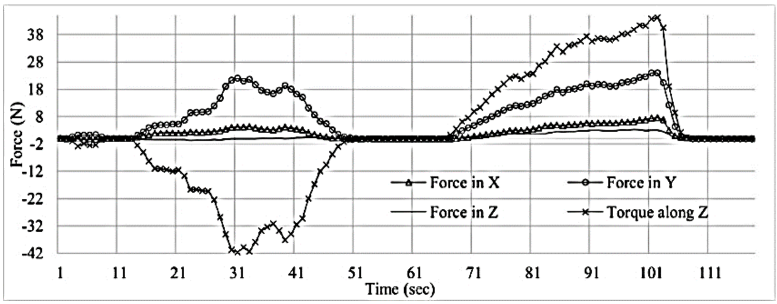

(d)

Figure 9. Data gathered from all four axes (a) force in X direction, (b) force in Y direction, (c) force in Z direction, and (d) torque along Z direction

5. CONCLUSION

The input force in the form of the analog signal is recorded using force/torque sensor and an external ADC is used to read the signal. The experimental setup has defined that a force/torque sensor contracted using strain gauges is very efficient and useful in real-time applications. A new system with a force/torque sensor has been designed with the help of discussions on special needs, range choice, and sensor structure type. The analysis and discussion in this paper are helpful for the design of a different system with various configurations and minimal measurement errors/crosstalk where there is a hard contact force between the system and the outside environment, in addition to the development of the specific force-assistance system. By applying unique two-level solution, incorporating hardware level as well as software level, the effect of crosstalk has been successfully overruled.

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