ECE1006

Introduction to Nanoscience and Nanotechnology
Project Report

MEMS and their Applications to Smart Systems and Devices

Submitted by

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Abstract

The microelectronics industry has seen exponential growth during the last several decades. Demand for applications ranging from health, defence, security, connectivity, and entertainment have driven the development of new materials, and technologies for the fabrication of even more complex devices with feature sizes now down at the sub-micron and nanometer levels. Recent interest has arisen in employing these materials, tools and technologies for the fabrication of miniature sensors and actuators and their integration with electronic circuits to produce smart devices and systems. Given that the end-point for several applications involve mechanical sensing and movements, there has been a demand for miniaturising electro mechanical devices.

As MEMS become smaller, require less power, and are less expensive to manufacture, they are expected to play an increasingly important part in Sensory interfaces, man-machine interfaces, Health, Robotics, Automobiles, Wireless internet of things (IoT) and Industry & home automation.

In addition to carrying out a literature survey to develop a background and understanding of MEMS as a technology and its application areas, it was decided to carry out a hands-on by interfacing a real MEMS device to a microcontroller and studying its behaviour and applicability in real-life application areas. The MEMS device chosen (a Bosch BNO055 or a GY-87 module) is an Intelligent 9-axis absolute orientation sensor which is a combination of an (a) Accelerometer, (b) Gyroscope, and (c) Magnetometer.

The sensor will be interfaced with an Arduino microcontroller, and software will be developed to test the 3-axis data output by the sensor.

Data will be tabulated and plotted for study and analysis.

The report ends with a conclusion based on the literature review and observations on interfacing the MEMS sensor to a microcontroller.

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Literature Review [1] to [10]

The microelectronics industry has seen explosive growth during the last thirty years. This has been driven by the availability and demand of affordable utility and essential smart devices -- such as (to name a few) -- Smart phones, Wearables such as Fitbits & smart watches, Health related devices such as BP meters, Oximeters (due to the COVID-19 pandemic), Sugar level checkers, Automobile industry, Home automation, and other commercial applications.
This increase in demand has driven the development of new materials and technologies, for the fabrication of even more complex devices with feature sizes now down at the sub-micron and nanometer level [1]. These include the fabrication of miniature sensors and actuators and their integration with electronic circuits to produce smart devices and systems.

MEMS and NEMS Technology

These micro-miniature electromechanical devices are called Micro-electromechanical systems (MEMS) and Nano-electromechanical systems (NEMS).
NEMS typically integrate transistor-like nanoelectronics with mechanical actuators, pumps, or motors, and may thereby form physical, biological, and chemical sensors.

The name derives from the fact that typical device dimensions are in the nanometer range; leading to low mass, high mechanical resonance frequencies, potentially large quantum mechanical effects such as zero-point motion, and a high surface-to-volume ratio useful for surface-based sensing mechanisms [2].

Both the fields -- micro-electromechanical systems (MEMS) and nano-electromechanical (NEMS) are highly interdisciplinary, and rely heavily on experimental mechanics for materials selection, process validation, design development, and device characterization. These devices range from mechanical sensors and actuators, to microanalysis and chemical sensors, to micro-optical systems and bioMEMS for microscopic surgery.

Figures 1 and 2 shown below kind of mechanics that can be integrated within MEMS devices.

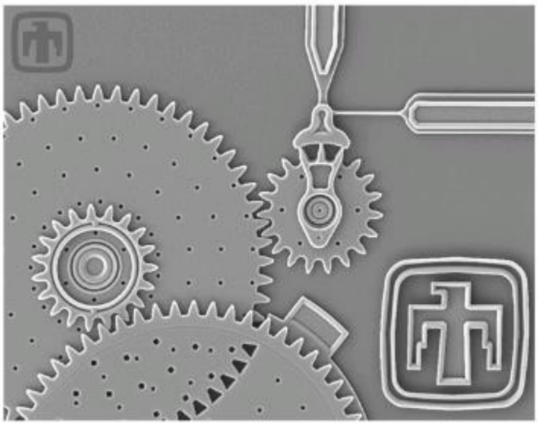


Figure 1 Multiple gear speed reduction unit (Courtesy of Sandia National Laboratories)

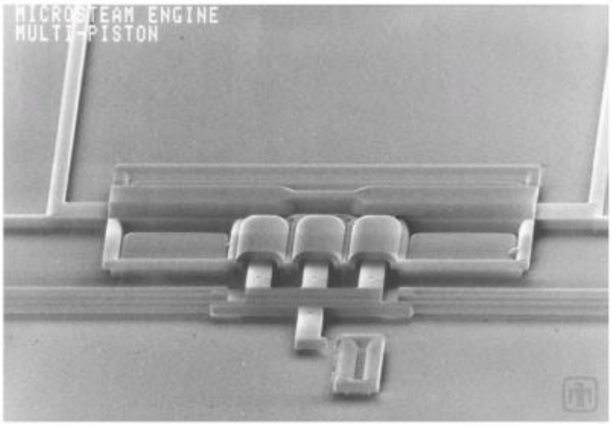
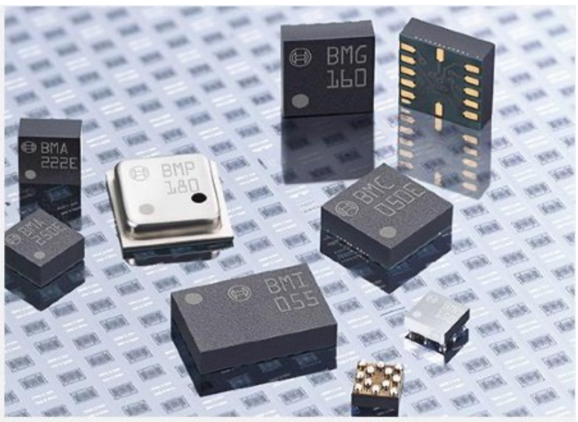


Figure 2 Triple-piston micro steam engine (Courtesy of Sandia National Laboratories)

A picture of some of the commonly used MEMS sensors manufactured by BOSCH is shown below:



A variety of MEMS sensors developed by Bosch Sensortec for use in consumer electronics, safety systems, industrial technology, and logistics. Photo courtesy of Bosch Media Service.

MEMS and NEMS Applications

Applications of NEMS and MEMS span a wide range of areas including automotive industry, communications, defence systems, national security, health care, information technology, avionics, and environmental monitoring. [3]

As MEMS become smaller, require less power, and are less expensive to manufacture, they are expected to play an increasingly important part in Sensory interfaces, man-machine interfaces, Health, Robotics, Automobiles, Wireless internet of things (IoT) and Industry & home automation.

A few common commercial applications of MEMS include:

- **Accelerometers:** in consumer electronics devices such as game controllers (Nintendo Wii), personal media players / cell phones (virtually all smartphones, various HTC PDA models) and a number of Digital Cameras (various Canon Digital IXUS models). Also used in PCs to park the hard disk head when free-fall is detected, to prevent damage and data loss.

- **Silicon pressure sensors:** in car tire pressure sensors, and disposable blood pressure sensors

- **MEMS microphones:** in portable devices, e.g., mobile phones, head sets and laptops. The market for smart microphones includes smartphones, wearable devices, smart home and automotive applications.

- **Inkjet printers:** use piezoelectric or thermal bubble ejection to deposit ink on paper.

- **Inertial Measurement Units (IMUs):** MEMS Accelerometers and MEMS gyroscopes in remote controlled, or autonomous, helicopters, planes, drones, ships, ... used for automatically sensing and balancing movement characteristics of roll, pitch and yaw.

- **Magnetometer:** may also be incorporated in robotic and mobile devices mentioned above to provide directional heading.

- **Optical switching technology:** used for switching technology and alignment for data communications

- Bio-MEMS applications in medical and health related technologies from Lab-On-Chip to **MicroTotalAnalysis** (biosensor, chemosensor), or embedded in medical devices e.g. stents, disposable, wearable insulin pump for managing diabetes, ...

- **Interferometric modulator display (IMOD):** applications in consumer electronics (primarily displays for mobile devices), used to create interferometric modulation – reflective display technology as found in mirasol displays

- **Micromachined ultrasound transducers:** for range finding, collision avoidance, ...

- **MEMS-based loudspeakers:** focusing on applications such as in-ear headphones and hearing aids

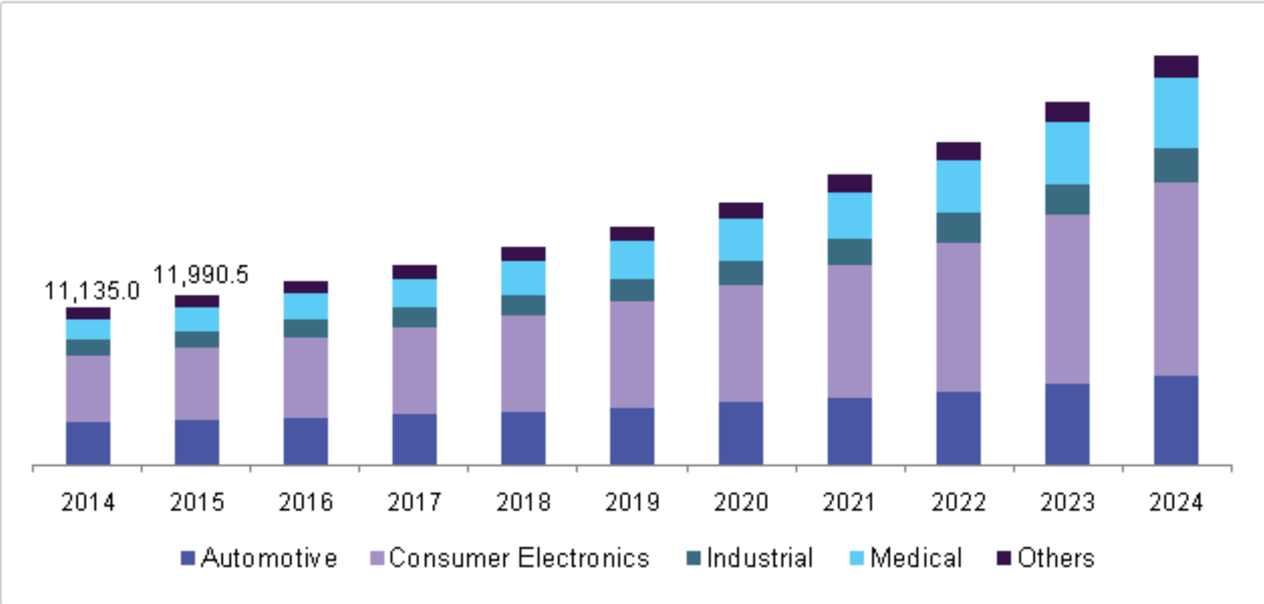
Additional common application of MEMS is tabulated below [4]:

Automotive	Electronics	Medical	Communications	Defence
Internal navigation sensors	Disk drive heads	Blood pressure sensor	Fibre-optic network components	Munitions guidance
Air conditioning compressor sensor	Inkjet printer heads	Muscle stimulators & drug delivery systems	RF Relays, switches and filters	Surveillance
Brake force sensors & suspension control accelerometers	Projection screen televisions	Implanted pressure sensors	Projection displays in portable communications devices and instrumentation	Arming systems
Fuel level and vapour pressure sensors	Earthquake sensors	Prosthetics	Voltage controlled oscillators (VCOs)	Embedded sensors
Airbag sensors	Avionics pressure sensors	Miniature analytical instruments	Splitters and couplers	Data storage
"Intelligent" tyres	Mass data storage systems	Pacemakers	Tuneable lasers	Aircraft control

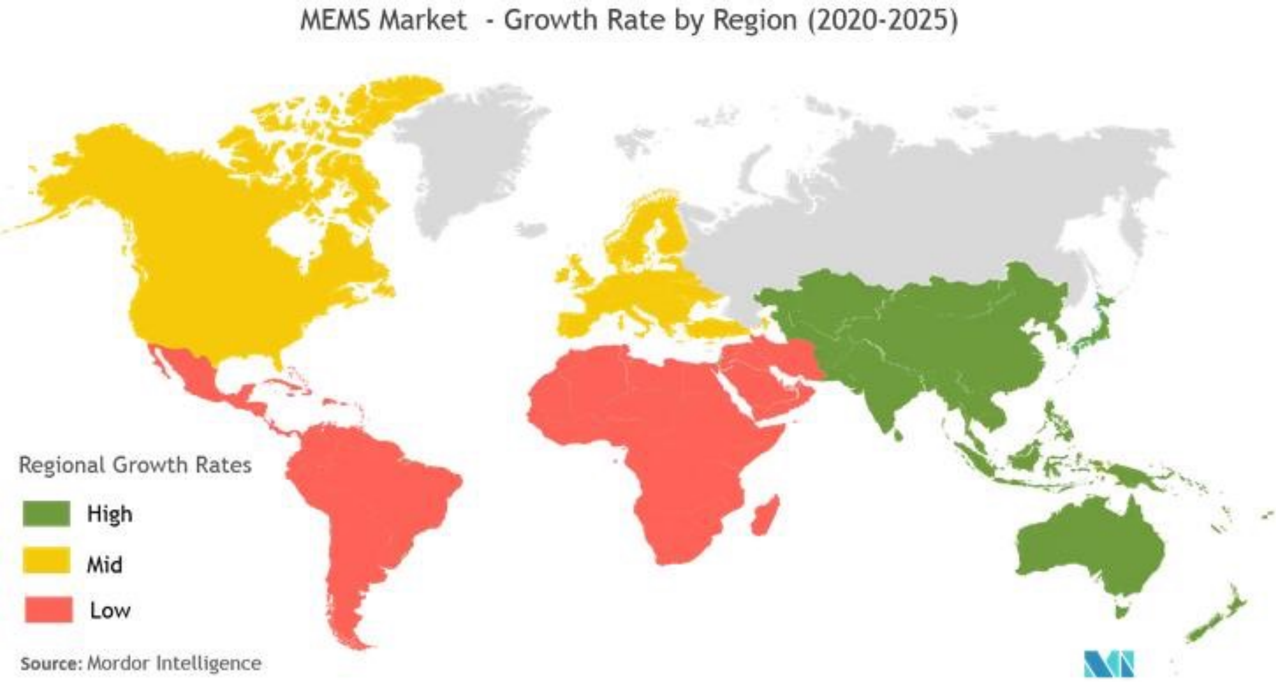
Growth trends and Forecast for MEMS and NEMS [9] and [10]

The global microelectromechanical systems (MEMS) market size was valued at USD 11.99 billion in 2015, and is expected to more than double in 2024. Presently, growth prospects for the market seem very upbeat on account of increasing adoption of this technology in consumer electronic devices such as wearable devices, tablets, and smartphones. Other verticals such as automotive, industrial, and healthcare are also expected to spur industry growth as device manufacturers and suppliers are industrializing a series of new devices including accelerometers, gyroscope, pressure sensor, inertial sensors, and others.

Global MEMS market by application, 2014 - 2024 (USD Million)



Predicted Growth and Region wise distribution of the MEMS market in the next five years is shown below.



Project Motivation and Objectives

Based on the literature survey done on NEMS and MEMS technologies, it was quite apparent that both these technologies are growing rapidly. From the survey we realised that the NEMS and MEMS technologies have very high projected growth and will be increasingly used in a large number of application areas covering a lot of Smart Systems and devices.

The MEMS technology has already matured to a significant extent and MEMS devices are being used in a wide range of application areas including Smart systems and devices.

We realised that we were already using Smart devices and appliances that incorporated MEMS devices such as accelerometers and were not aware of it.

Some of the devices we were already exposed to include: Smart Phones, Gaming devices (Nintendo Wii), Air bags in cars, and gravity sensors in laptops to prevent damage due to impact (hard disk heads are retracted to prevent damage in case of a free fall).

During the survey, and while looking up associated web sites, we came to know that some MEMS devices such as the Pressure sensor, Accelerometers, Magnetometers were readily available from online vendors at affordable prices.

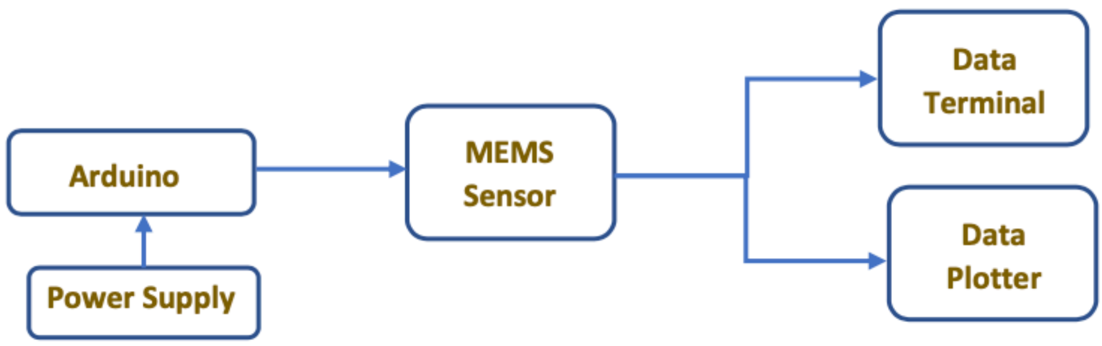
Since, as a team, we have a little experience of working with hardware – specifically, Arduino microcontrollers, we decided to include some hardware interfacing of MEMS sensors as a part of this project to try it out and learn about their operation.

The objective here is to get a better understanding the actual MEMS device, in terms of its interfacing to microcontrollers, the type of data output by these sensors, and also the complexity involved in their use.

The MEMS device chosen (a Bosch BNO055 or a GY-87 module) is an Intelligent 9-axis absolute orientation sensor which is a combination of an (a) Accelerometer, (b) Gyroscope, and (c) Magnetometer. In addition, the GY-87 also includes a sensor to measure the temperature and the barometric pressure.

Hardware and Software

We will be interconnecting the MEMS sensor to the Arduino microcontroller and writing programs to initialise and acquire data from the sensor.
The data from the sensor will be displayed on the Serial Monitor (Terminal), and also plotted on the display.

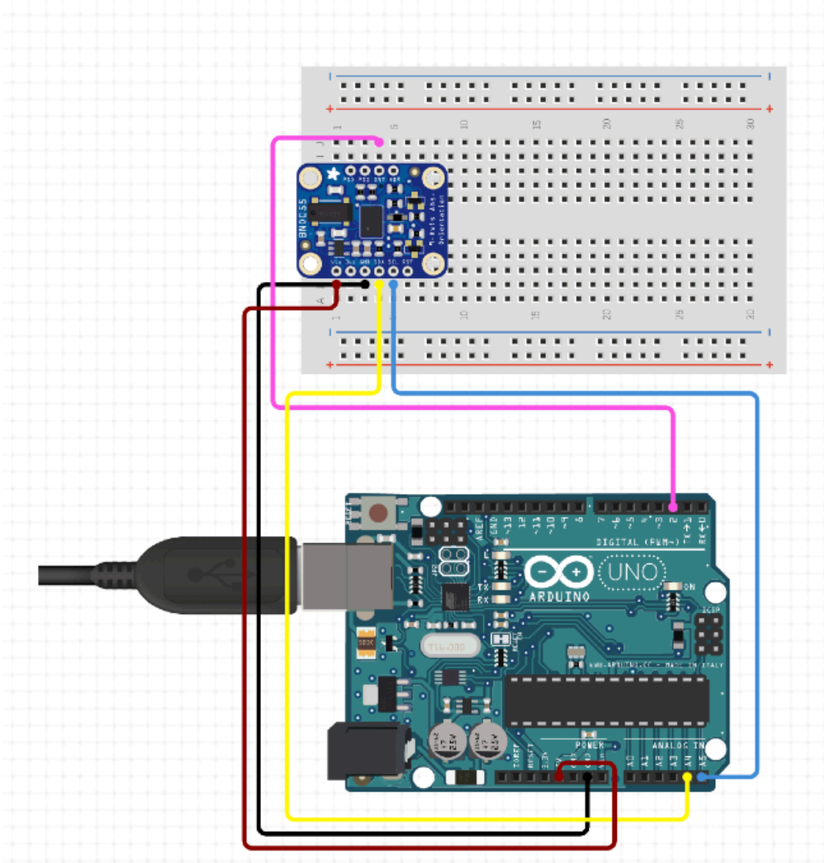


The sensor boards have two ways for interfacing them to the Arduino, (1) standard serial, and (2) Inter-Integrated Circuit (I2C).

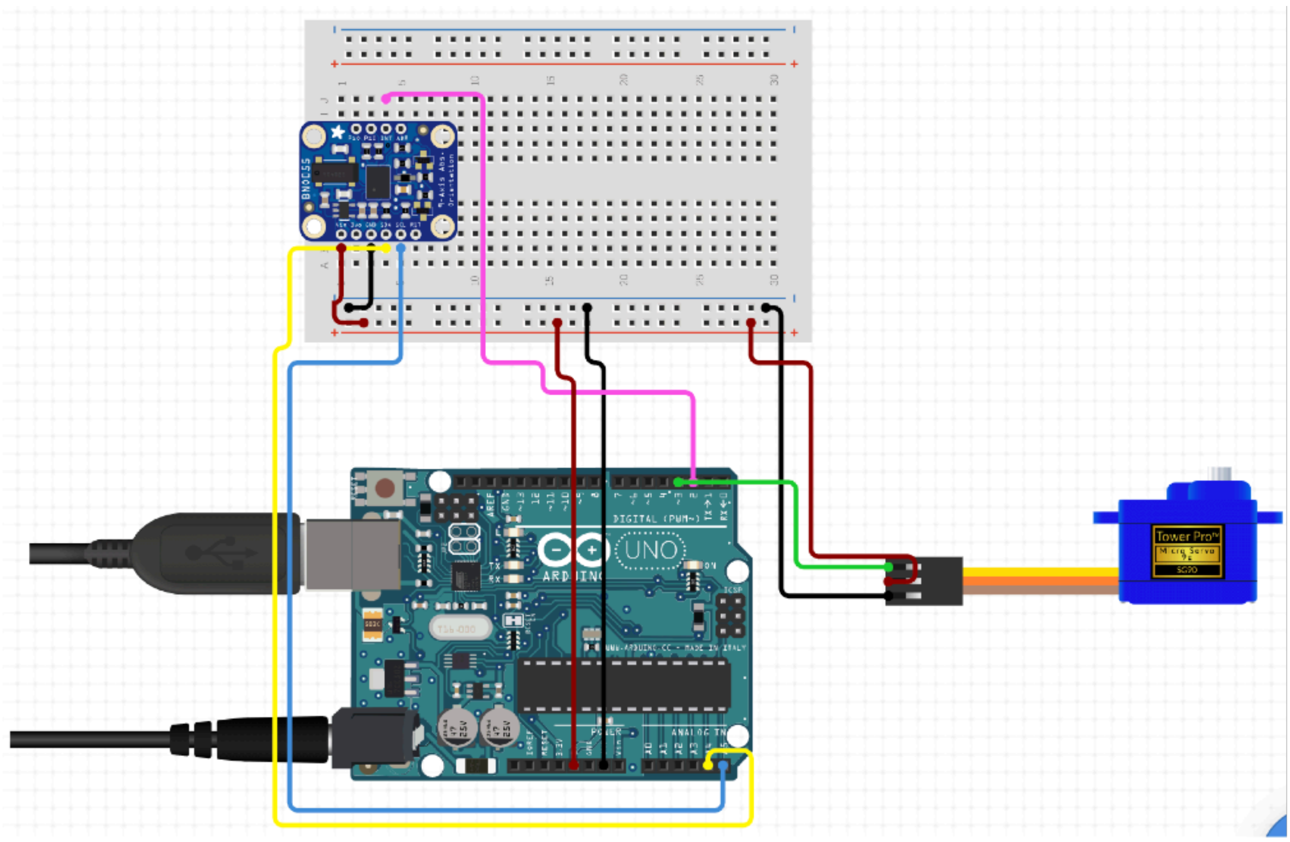
Components

1. Arduino UNO
2. MEMS Sensor
   Bosch BNO055
3. Resistors
4. Capacitors
5. Wires
6. Breadboard

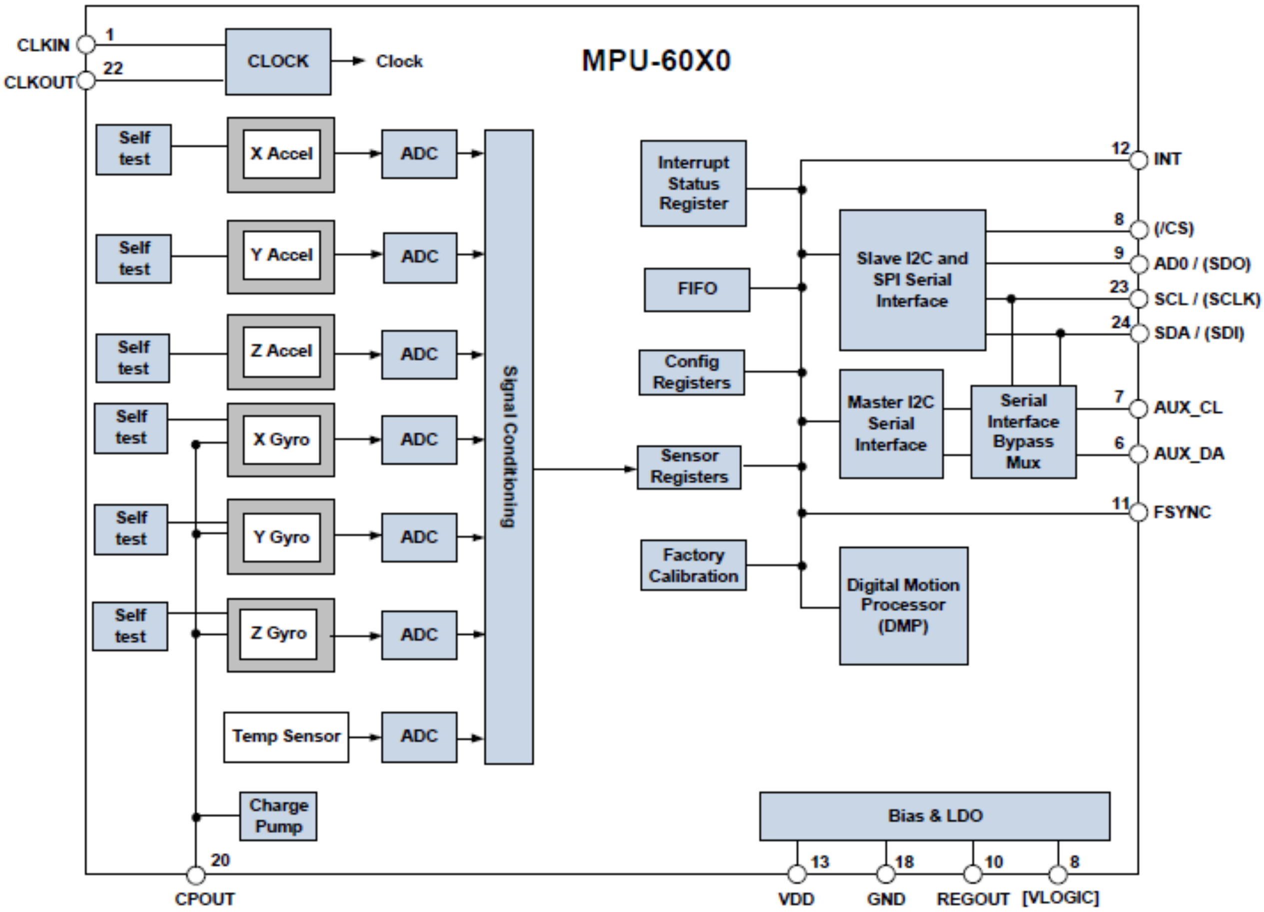
Circuit Diagrams



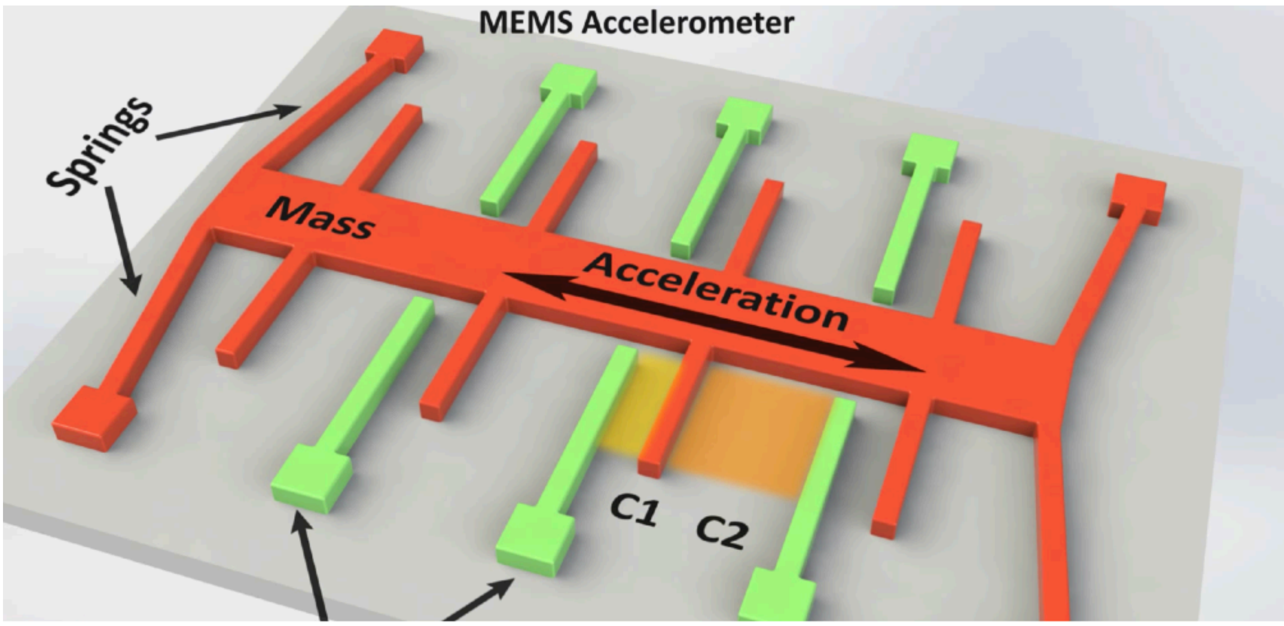
Circuit Diagram without Motor



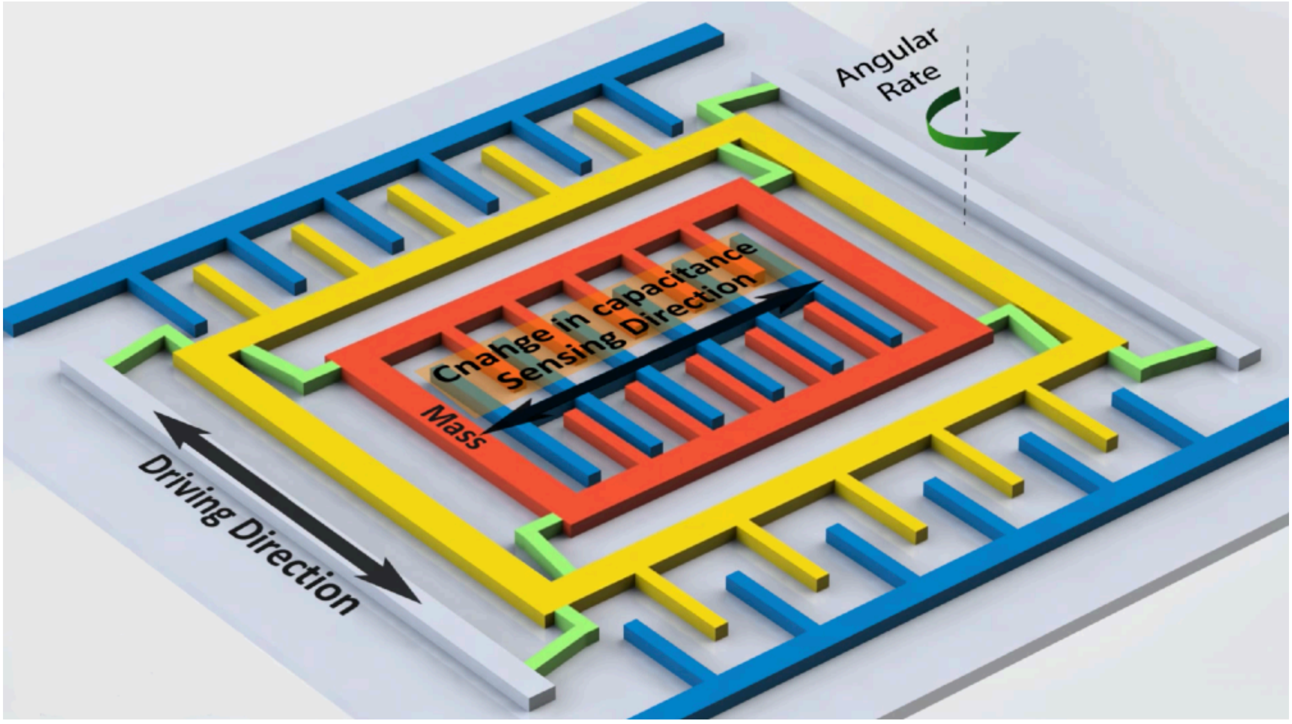
Circuit Diagram with Motor



An internal block schematic of the MPU 6050 is shown below:



Internal Structure of a MEMs Accelerometer



Internal Structure of MEMs Gyroscope

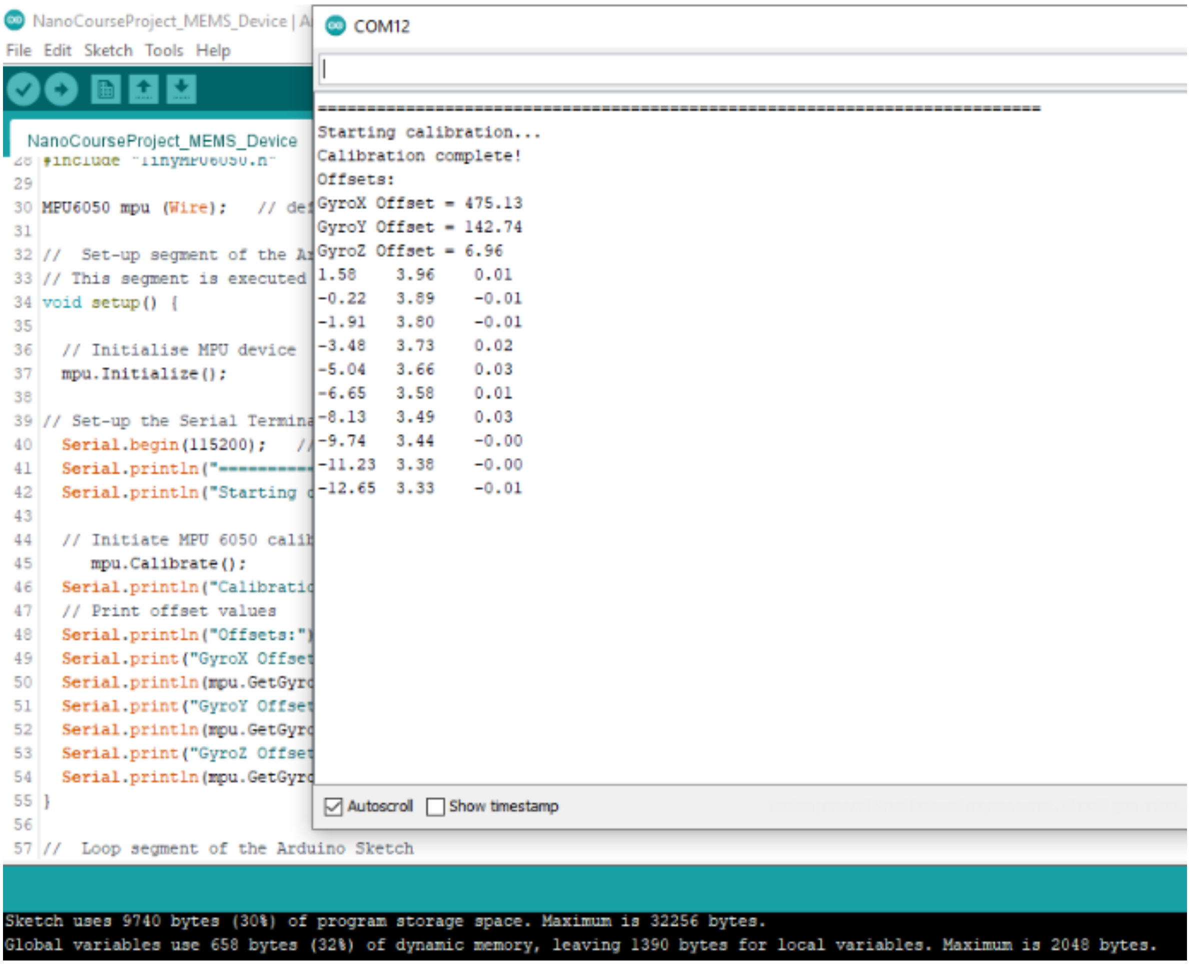
Software Description

Detailed listing is included in Appendix A

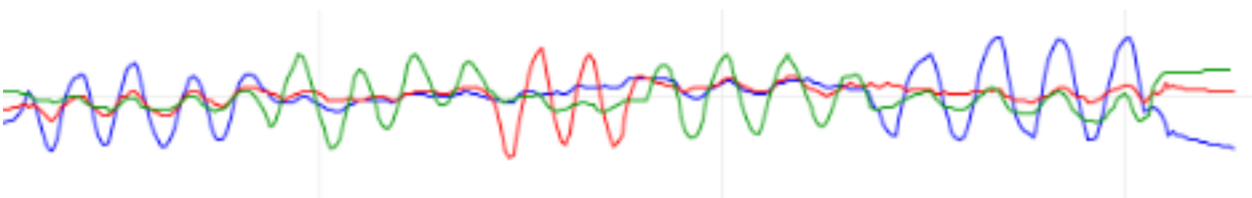
Results and Discussion

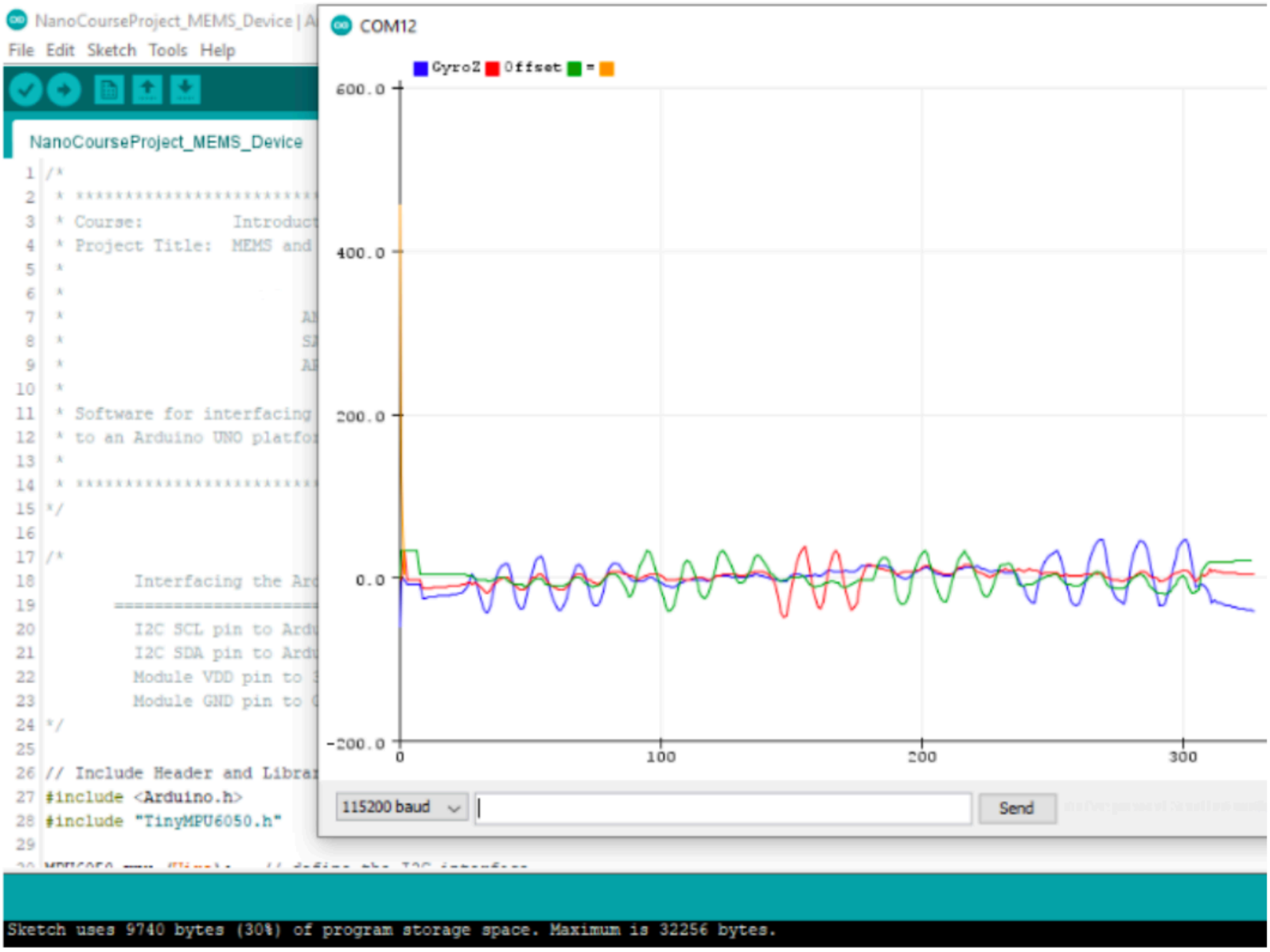
Output Data Table

The following figure shows the display on the Serial monitor as the program is executed.



Output Data plots





The three axes (X, Y and Z) are displayed in red, blue and green respectively. The plot shows the variations in the values of the three axes as the sensor is partially rotated (clockwise & anti clockwise) along the specified axis.

Conclusion

The NEMS and MEMS technologies have matured significantly over the past several years. Coupled with miniaturisation, sensors based on MEM and NEMS technologies now have enhanced functionality.
The global microelectromechanical systems (MEMS) market size was valued at USD 11.99 billion in 2015, and is expected to more than double in 2024. Presently, growth prospects for the market seem very upbeat on account of increasing adoption of this technology in consumer electronic devices such as wearable devices, tablets, and smartphones.

Other verticals such as automotive, industrial, and healthcare are also expected to spur industry growth as device manufacturers and suppliers are industrialising a series of new devices including accelerometers, gyroscope, pressure sensor, inertial sensors, and others.

Some of the devices already incorporating NEMS and MEMS devises include: Smart Phones, Gaming devices (Nintendo Wii), Air bags in cars, and gravity sensors in laptops to prevent damage due to impact (hard disk heads are retracted to prevent damage in case of a free fall). One of the impacts of proliferation of MEMS devices is that devices such as the Pressure sensor, Accelerometers, Magnetometers were readily available from online vendors at affordable prices. Leveraging our exposure to working with microcontrollers embedded in Arduino boards, we decided implement and test hardware interfacing of MEMS sensors as a part of this project.

The objective was to get a better understanding an actual MEMS device, in terms of its interfacing to microcontrollers, the type of data output by these sensors, and also the complexity involved in their use. We used a HW-290/GY-87 MEMS module, which is an Intelligent 9-axis absolute orientation sensor which is a combination of an (a) Accelerometer, (b) Gyroscope, and (c) Magnetometer.
Post interfacing the sensor and developing sofware on the Arduino, we were able to test the MPU 6050 sensor by moving it around the X, Y and Z axes to obser changes in the value of the Roll, Pitch and Yaw. These values, as we activated the sensor was tabulated and also displayed as a plot.

References

Nanotechnology, NEMS and MEMS

[1] Vijay K. Vardhan, Nanotechnology: MEMS and NEMS and their applications to smart systems and devices, Oct 2003. https://www.spiedigitallibrary.org/conference- proceedings-of-spie/5062/0000/Nanotechnology--MEMS-and-NEMS-and-their- applications-to-smart/10.1117/12.514830.short?SSO=1

[2] Wikipedia.org, Nanoelectromechanical systems, https://en.wikipedia.org/wiki/Microelectromechanical_systems

[3] Wendy C. Crone, A Brief Introduction to MEMS and NEMS, Springer Handbook of Experimental Solid Mechanics pp 203-228, https://link.springer.com/referenceworkentry/10.1007%2F978-0-387-30877-7_9

[4] An Introduction to MEMS (Micro-electromechanical Systems), Jan 2002, https://www.lboro.ac.uk/microsites/mechman/research/ipm- ktn/pdf/Technology_review/an-introduction-to-mems.pdf

[5] MEMS - Recent developments and Future Directions, Technology Watch Report, 2007, https://www.lboro.ac.uk/microsites/mechman/research/ipm-ktn/pdf/Technology_review/mems-recent-developments-future-directions.pdf

[6] MEMS Overview: MEMS Devices & Uses in IoT, Arrow.com, Feb 2019, https://www.arrow.com/en/research-and-events/articles/mems-and-iot-applications

[7] Centre for Nano Science and Engineering (CeNSE), Indian Institute of Science,
http://www.cense.iisc.ac.in/research/mems-and-nems-sensors

[8] Richard Lee, MEMS to NEMS, The Institution of Engineering and Technology, 2011, https://www.theiet.org/publishing/inspec/researching-hot-topics/mems-to-nems/

Growth Forecast for NEMS and MEMS

[9] https://www.grandviewresearch.com/industry-analysis/microeletromechanical-systems-

market

[10] https://www.mordorintelligence.com/industry-reports/mems-market

Hardware and Implementation

[11] BNO055 sensor data sheet

[12] Arduino UNO specifications

[13] I2C/ Serial interfacing

Report Formatting Guidelines

[14] https://style.mla.org/formatting-papers/

[15] https://open.lib.umn.edu/writingforsuccess/chapter/13-1-formatting-a-research-paper/

Appendices

Appendix A: Code Listing

```
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BNO055.h>
#include <utility/imumaths.h>
#include <Custom_PID.h>
#include <Servo.h>

/*
 * Requires Installation of Adafruit BNO055 and Adafruit Unified Sensor Library
 */

/* Set the delay between fresh samples */
#define BNO055_SAMPLERATE_DELAY_MS (100)

// Check I2C device address and correct line below (by default address is 0x29 or 0x28)
//                                   id, address
Adafruit_BNO055 bno = Adafruit_BNO055(55, 0x28);

Servo servoRight;
Servo servoLeft;

PID pidRoll(1, 0, 0);
PID pidPitch(1, 0, 0);


void displaySensorDetails(void)
{
  sensor_t sensor;
  bno.getSensor(&sensor);
  Serial.println("------------------------------------");
```

```
  Serial.print  ("Sensor:       "); Serial.println(sensor.name);
  Serial.print  ("Driver Ver:   "); Serial.println(sensor.version);
  Serial.print  ("Unique ID:    "); Serial.println(sensor.sensor_id);
  Serial.print  ("Max Value:    "); Serial.print(sensor.max_value); Serial.println(" xxx");
  Serial.print  ("Min Value:    "); Serial.print(sensor.min_value); Serial.println(" xxx");
  Serial.print  ("Resolution:   "); Serial.print(sensor.resolution); Serial.println(" xxx");
  Serial.println("------------------------------------");
  Serial.println("");
  delay(500);
}

void setup(void)
{
  Serial.begin(9600);
  Serial.println("WebSerial 3D Firmware"); Serial.println("");

  /* Initialise the sensor */
  if(!bno.begin())
  {
    /* There was a problem detecting the BNO055 ... check your connections */
    Serial.print("Ooops, no BNO055 detected ... Check your wiring or I2C ADDR!");
    while(1);
  }

  delay(1000);

  /* Use external crystal for better accuracy */
  bno.setExtCrystalUse(false);

  /* Display some basic information on this sensor */
  displaySensorDetails();

  servoRight.attach(9);
```

```
  servoLeft.attach(10);

  servoRight.write(90);
  servoLeft.write(90);

  pidRoll.Initialize();
  pidPitch.Initialize();
}

void loop(void)
{
  /* Get a new sensor event */
  sensors_event_t event;
  bno.getEvent(&event);

  /* Board layout:
         +----------+
         |*         |  PITCH  ROLL  HEADING
     ADR |*         |
     INT |*         |    ^           /->
     PS1 |*         |    |           |
     PS0 |*         |    Y    X-->    \-Z
         |*         |
         +----------+
  */

  /* heading, pitch, roll by Eulers Angle*/
  float yaw = 360 - (float)event.orientation.x, pitch = (float)event.orientation.y, roll =
(float)event.orientation.z;
  Serial.print(F("Orientation: "));
  Serial.print(yaw);
  Serial.print(F(", "));
  Serial.print(pitch);
```

```
  Serial.print(F(", "));
  Serial.print(roll);
  Serial.println(F(""));

  /* PID */
  float updateAngleRoll = pidRoll.Update(roll, 10);
  float updateAnglePitch = pidPitch.Update(pitch, 10);
  servoRight.write(int(90 - updateAngleRoll - updateAnglePitch));
  servoLeft.write(int(90 - updateAngleRoll + updateAnglePitch));

  /* Also send calibration data for each sensor. */
  uint8_t sys, gyro, accel, mag = 0;
  bno.getCalibration(&sys, &gyro, &accel, &mag);
  Serial.print(F("Calibration: "));
  Serial.print(sys, DEC);
  Serial.print(F(", "));
  Serial.print(gyro, DEC);
  Serial.print(F(", "));
  Serial.print(accel, DEC);
  Serial.print(F(", "));
  Serial.print(mag, DEC);
  Serial.println(F(""));

  delay(BNO055_SAMPLERATE_DELAY_MS);
}
```

Appendix B: Partial list of MEMS Manufacturers

- ST Microelectronics: pressure sensors, single & multi-axis accelerometers, 6-axis inertial modules, magnetometers, microphones, scalable modules with up to 6 axes

- NXP Semiconductors: pressure sensors, single & multi-axis accelerometers, gyroscopes

- Bosch: multi-axis accelerometers, gyroscopes, pressure sensors, microphones, inertial modules.

- Analog Devices: single & multi-axis accelerometers, gyroscopes, RF-switches, magnetometers, inertial modules

- Texas Instruments: MEMS micromirror arrays