SZÉCHENYI ISTVÁN EGYETEM
AUDI HUNGARIA
Faculty of Automotive Engineering

Capstone 3 Project report

Team members

Name		%
Ganbat Máté	**W2M8MM**	16.6%
Kumbalathara Arachchige Don Gaurawa Kovida	**CTB53R**	16.6%
Samarappuli Mudiyanselage Nipun Gunarathne	**XNC18C**	16.6%
Akwalu Antony Mwongela	**PNLTLX**	16.6%
Sass Bendegúz István	**HRDVNZ**	16.6%
Szabó Vilmos Benedek	**UHGGC1**	16.6%

Győr, 2026.01.20

Table of Contents

1. Abstract and goals

This report details the development of a custom measurement system designed to analyze the tightening processes of cylinder head bolts in an internal combustion engine. Operating as a simulated start-up, the team engineered a complete solution by integrating strain gauge-based hardware with a custom data acquisition software stack. The system construction involved the precise soldering of components, circuit construction using Wheatstone bridges and HX711 amplifiers, and the calibration of the transducer for accurate force detection. Experimental measurements were subsequently executed to capture real-time tightening curves and evaluate the stress and load states of the mechanical components. Ultimately, this work demonstrates the practical application of experimental analysis and professional project management in a vehicle engineering context.

1.1. Project Goals

- To gain a deeper insight into experimental analysis and professional data acquisition techniques.
- To analyze and compare the processes of tightening cylinder head bolts in an internal combustion engine.
- To acquire specific knowledge regarding the stress and load states of the bolts and the cylinder head.
- To design, build, and calibrate a functional measurement system (transducer and software) from the perspective of a start-up company adjusting to customer needs.
- To develop project management and organization skills through the separation of tasks into sub-teams (Hardware, Software, and Measurement).

2. Force Transducer

The core component of our measurement system is the custom-built force transducer, designed to convert the mechanical clamping force of the cylinder head bolts into a quantifiable electrical signal. To achieve this, the Hardware Team engineered a strain gauge-based sensor system capable of withstanding the high compressive loads typical of an internal combustion engine environment. The construction involved the precise integration of mechanical elastic elements with a sensitive electrical signal chain, comprising Wheatstone bridges, high-precision amplifiers, and a microcontroller interface.

2.1. Steps of the build

2.1.1. Soldering and its Basics

The construction of the hardware began with soldering, a fundamental process used to join electrical components by melting a filler metal (tin) into the joint. The objective was to create a strong permanent bond between the electronic components and the printed circuit boards or wires without melting the workpieces themselves. To ensure a reliable electrical connection, it was critical to heat both parts of the joint sufficiently so the solder would flow freely and wet the surfaces. We focused on achieving shiny, cone-shaped joints while avoiding cold solder joints, which occur when the solder fails to fuse properly, leading to high resistance or intermittent signal failure in the measurement chain.

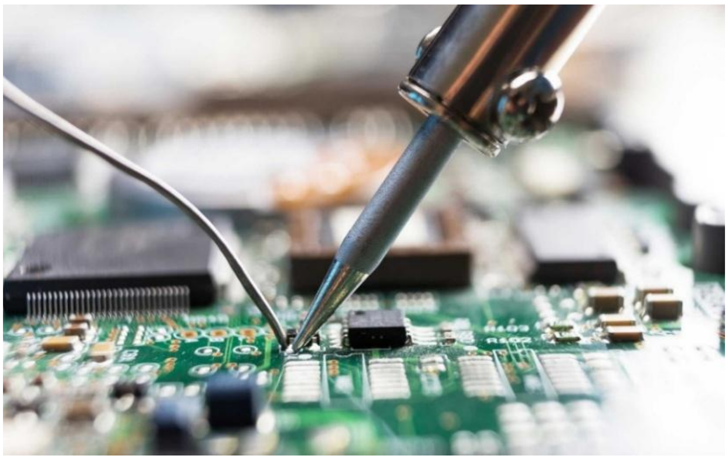


Figure 1. Soldering

2.1.2. Strain Gauges

For this project, we utilized the BX120-2BB Strain Gauge, a dual-grid sensor designed to measure deformation in two perpendicular directions.

The Elastic Element: Instead of applying gauges directly to the bolt shank, we utilized a separate elastic element: a hardened steel ring (Model: **IR 15x20x14 IS1-OF-XL**). This component serves as the transducer body. When the cylinder head bolt is tightened through this ring, the ring compresses slightly. This deformation is what we measure to calculate force.

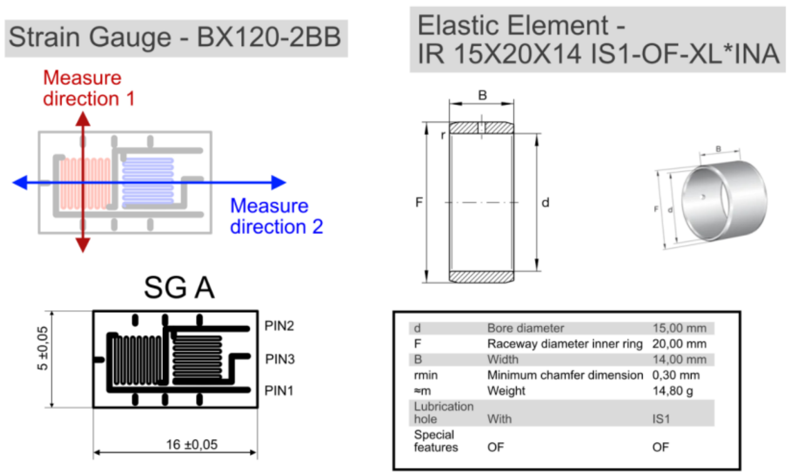


Figure 2. BX12`-2BB Strain Gauge components and its dimensions

The Sensor (BX120-2BB):

We selected this specific gauge because its dimensions $0.05mm \times 0.05mm$) fit perfectly within the 14.00 mm width of the steel ring. The gauge features two distinct measuring grids:

- **Direction 1 (Red Arrow):** Aligned to measure the primary axial strain (compression of the ring).
- **Direction 2 (Blue Arrow):** Aligned to measure the transverse strain (expansion of the ring due to the Poisson effect).

Layout and Pinout Configuration: To create a complete measurement circuit, we employed two identical gauges, designated as **SG A** and **SG B**.

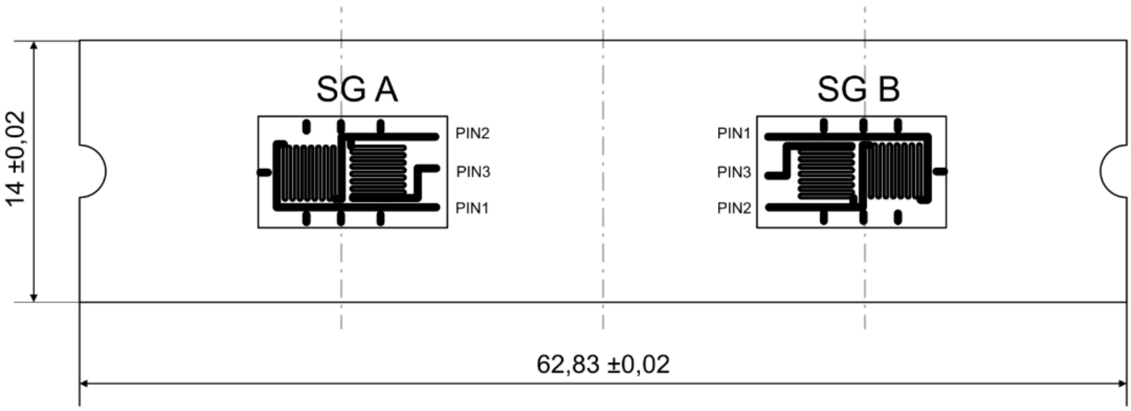


Figure 3. Layout of SG A and SG B in the Wheatstone Bridge

- Each gauge operates as a "half-bridge" internally, featuring three connection points: **PIN1**, **PIN2**, and a center tap **PIN3**.
- By combining SG A and SG B, we utilize all four grids (two per gauge) to form a Full Wheatstone Bridge. This configuration maximizes the sensitivity of the system and provides inherent temperature compensation, as temperature changes affect both grids equally and cancel out.

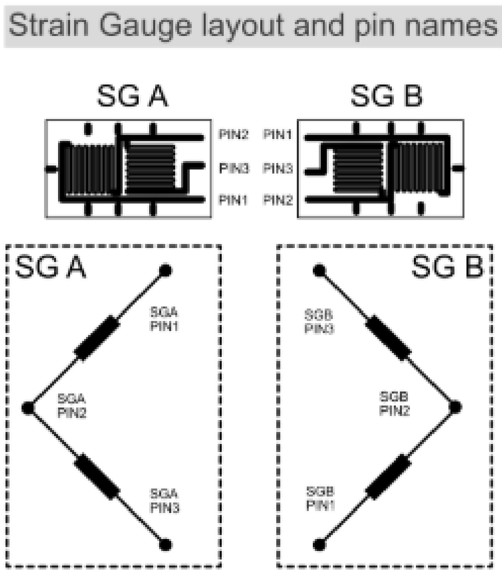


Figure 4. Visual diagram of the strain gauges and pins in the Wheatstone Bridge

2.1.3. Wheatstone Bridge Wiring

To convert the resistance changes from the strain gauges into a measurable voltage, we wired the two gauges (SG A and SG B) into a **Full Wheatstone Bridge** circuit.

- **Prototyping:** Before soldering the delicate strain gauges, we first constructed a "dummy" bridge using fixed discrete resistors. This allowed us to verify our circuit design and test the stability of the soldering connections without risking damage to the expensive sensors.

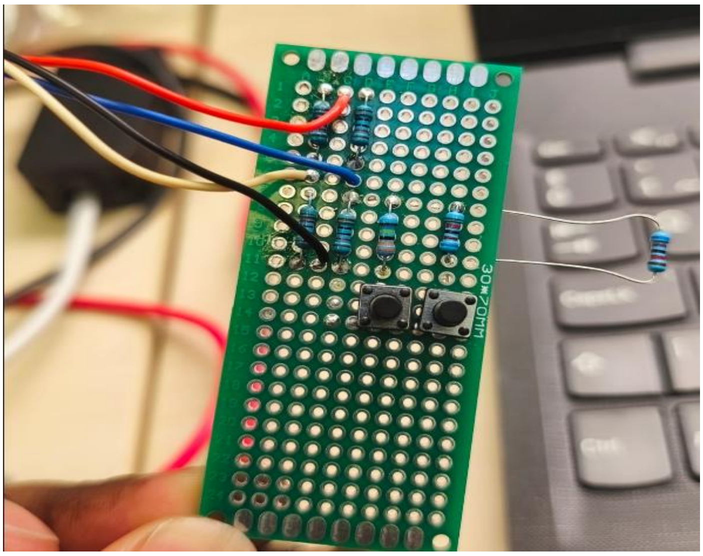


Figure 5. Prototype(dummy) of Wheatstone bridge using resistors

- **Final Assembly:** Once the prototype was verified, we wired the actual strain gauges according to the specific diagram:

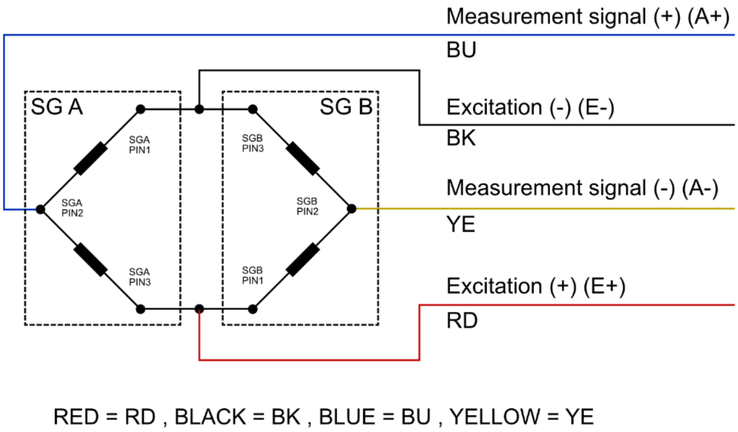


Figure 6. Wiring diagram of the Wheatstone Bridge

This configuration creates a closed loop where the differential voltage between the blue and yellow wires represents the force applied to the bolt.

2.1.4. Signal Conditioning (HX711 Integration)

The signal output from the Wheatstone bridge is an analog voltage in the millivolt range, which is too weak and noisy for the microcontroller to read directly. To solve this, we integrated the HX711 module, a 24-bit Analog-to-Digital Converter (ADC) designed for high-precision weigh scales.

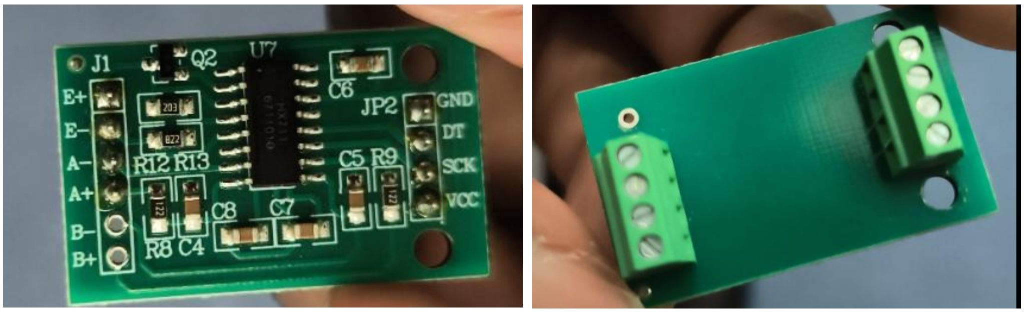


Figure 7. Back and front faces of the HX711 load cell

Function**:** HX711 performs two critical tasks:

1. Amplification: It boosts the weak differential signal from the bridge.
2. Digitization: It converts the analog voltage into a digital data stream that the ESP32 can process.

Wiring Connections**:** We connected the four colored wires from our Wheatstone bridge directly to the inputs of the HX711 module, strictly following the polarity to ensure positive force readings

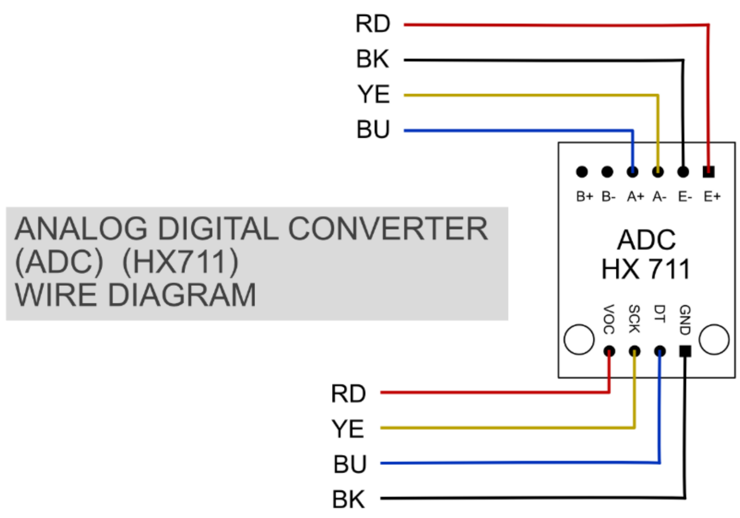


Figure 8. HX711 wiring diagram

On the output side, the module prepares the data for transmission via four pins: VCC (Power), SCK (Clock), DT (Data), and GND (Ground).

2.1.5. Microcontroller Interfacing (ESP32)

The final stage of the hardware build was connecting the digitized signals to our processing unit, the ESP32 Development Board.

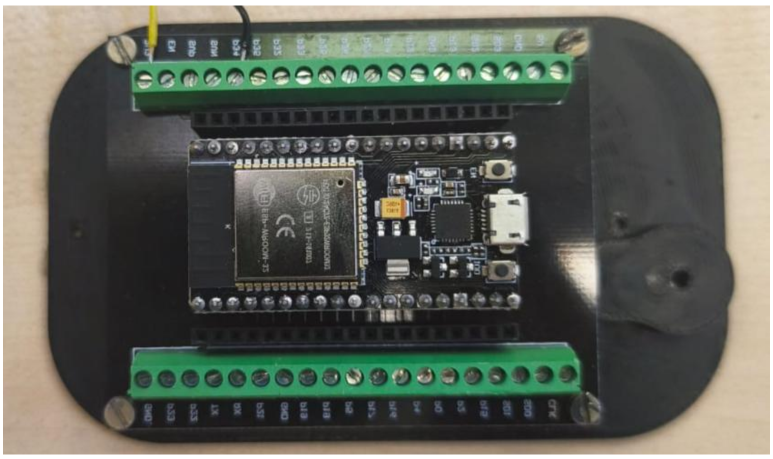


Figure 9. ESP32 Microcontroller

- Multi-Channel Architecture: Unlike a simple s

 Channels **1-8 (Bolts):** Connected directly to the cylinder head bolts to capture the clamping force distribution across the engine block.

 Channel **9 (Wrench):** Connected to the instrumented torque wrench. This channel allows us to correlate the applied torque (input) with the resulting clamping force (output) on the bolts.

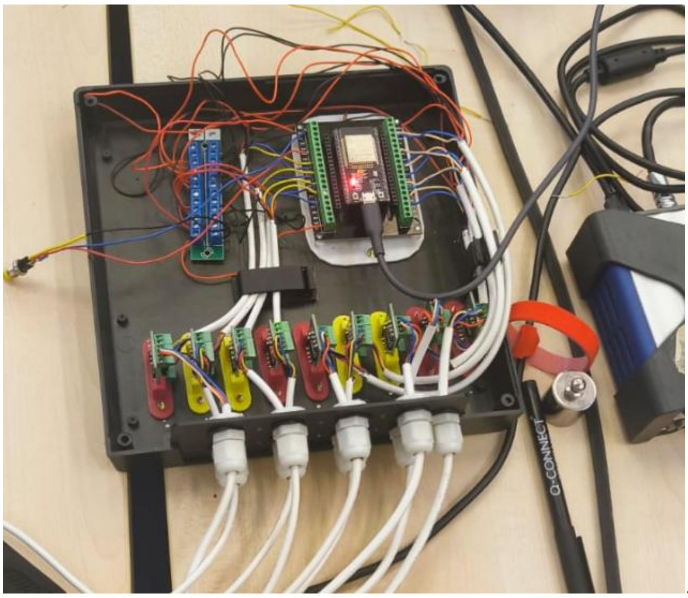


Figure 10. Wiring of the channel 1-9 to the ESP32

Pin Mapping and Wiring: To manage this high density of connections, we used a breakout board with screw terminals to wire the HX711 modules securely. We followed a specific pin mapping protocol to ensure the software could distinguish between the bolts and the wrench.

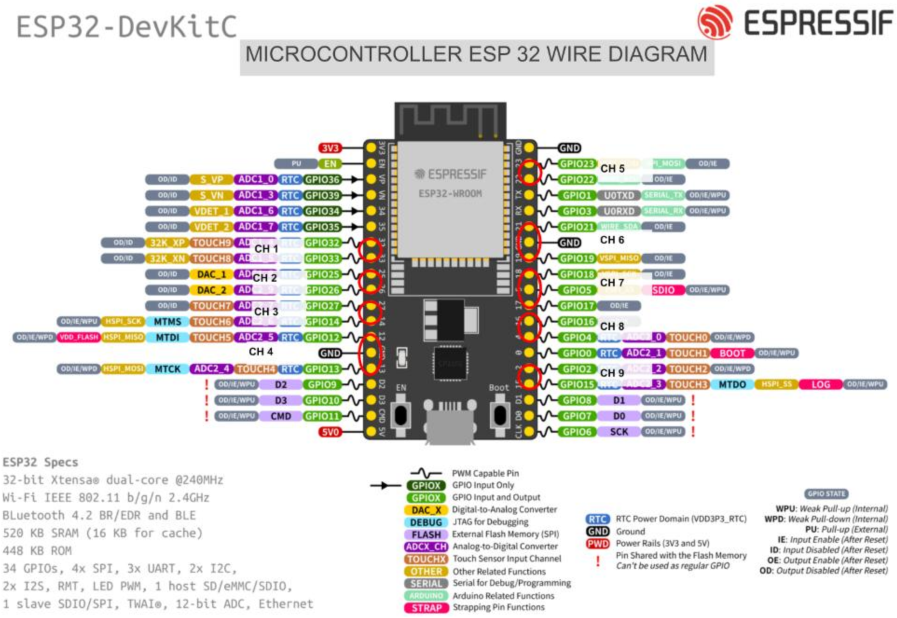


Figure 11. ESP32 pin naming

This configuration enables Team Software to record a synchronized dataset, linking the force applied by the operator directly to the stress measured in the bolts.

3. 1. DAQ System and C++ Code

3.1. Structure of DAQ System

The Data Acquisition system (DAQ) serves as the bridge between the physical world and digital analysis. The main aspects of the system are identified as follows:

- **Processor:** The system is built on the **ESP32 microcontroller**, chosen for its high clock speed, allowing it to manage multiple sensors without lag.
- **Sensor Interface:** Nine **HX711 24-bit Analog-to-Digital Converters** are used to detect minute changes in voltage from the load cell strain gauges.
- **Wiring Strategy (Direct Parallel Interface):** To ensure maximum signal fidelity and eliminate crosstalk, a **Direct Parallel Interface** was utilized. This required allocating **18 GPIO pins** (9 Clock + 9 Data) to drive the sensors individually, ensuring stable communication and faster rise times compared to multiplexed matrix systems.
- **Communication:** Data is streamed to the PC via **Serial Communication** over USB at 9600 baud.
- **User Interface:** The primary interface for trials is a **PC-linked Excel dashboard** using the **Data Streamer add-in**.
- **Calibration Control:** A physical button is connected to GPIO 34 to trigger the **Tare (zeroing) function**, which calculates the zero level for all sensors simultaneously to ensure measurement accuracy.

3.2. Structure of the Code

The code is written in C++ within the Arduino environment. It is designed to ensure concurrency and reliability in data acquisition, handling potential errors and bugs. The code structure is as follows:

1. **Initialization and Configuration (setup):**

- **Iterative Initialization:** The code initializes an array of 9 HX711 objects

($LoadCell[9]$). It iterates through this array to configure the dedicated Data and Clock pins and apply pre-set Gain values immediately upon startup.

- **Hard-Coded Calibration:** Specific sensitivity coefficients (Slopes) determined during calibration are hard-coded into firmware arrays to ensure processing efficiency and eliminate the need for run-time calculation.

2. Signal Processing and Calibration (loop):

- **Non-Blocking Timing:** The system uses $millis()$ to maintain a consistent **10 Hz sampling frequency**, ensuring data points are captured exactly every 100ms for accurate trial analysis.
- **Tare Functionality:** Upon a button press, the code averages 10 readings to establish a zero-baseline (Constant), effectively removing environmental noise and the weight of the testing setup.
- **Linear Scaling:** Raw sensor data is converted into engineering units (Force/Torque) by applying individual **Slope** and **Constant** parameters to each data stream.

3. Data Output Layer:

- **CSV Stream Construction:** For every sampling cycle, the code concatenates the time stamp and all nine calibrated values into a single **Comma Separated Value (CSV)** string.
- **Serial Transmission:** This string is transmitted via USB at 9600 baud. This format is specifically chosen for direct compatibility with the **Excel Data Streamer**, enabling the live "Database" view and torque monitoring used during the trials.

3.3. System Operation

1. Starting Sequence

- System powers on, initializes the ESP32, and runs the setup code.
- All 9 HX711 modules are configured with their respective pins and gains.
- Serial communication is established at 9600 baud.
- **Idle State:** The system enters the main loop, waiting for the 100ms timer trigger or user input.

2. Normal Operation Cycle

The code repeats the following cycle continuously:

- **Continuous Monitoring:** The system constantly polls the status of the **Tare Button** (GPIO 34).
- **Measurement Event (Every 100ms):**
  - **Acquisition:** Reads raw data from all 9 sensors.
  - **Processing:** Applies calibration formulas to convert raw data to Force/Torque.
  - **Transmission:** Sends the CSV string to the Excel interface.

3. Tare Operation

- **Trigger:** Detects a button press on GPIO 34 (Debounced).
- **Measurement:** Takes the average of **10 sequential readings** from all sensors.
- **Calculation:** Updates the Constant array with the new zero values.
- **Feedback:** Transmits the current **Gain** and **Slope** values to the Serial Monitor for verification before returning to the main loop.

4. Calibration and System Verification

The calibration process was a critical phase designed to establish a precise linear relationship between the electrical signals generated by the strain gauges and the physical axial force acting on the cylinder head bolts.

4.1. Main Calibration Methodology

The measuring system was calibrated using known reference loads to ensure high fidelity in the data acquisition. During the tightening process of the cylinder head, defined loads were applied to the bolts while the output signals from the strain gauges were continuously recorded.

- **Linear Regression Model:** The measured voltage values were plotted as a function of the applied loads. The software implements the following linear equation to convert the raw 24-bit digital signal (Reading) into physical engineering units (Value) for each channel i:

$$Value = \frac{Reading - Constant}{Slope}$$

Where:

- $\boldsymbol{Reading}$: The raw digital output from the HX711 amplifier.
- $\boldsymbol{Constant}$: The zero-offset determined during the Tare procedure.
- $\boldsymbol{Slope}$**:** The sensitivity coefficient derived from the calibration curve.

- **Individual Channel Evaluation:** Due to mechanical and geometrical variations in the bolt structures and strain gauge applications, the sensitivity of each measuring point was non-identical. Therefore, each of the nine measuring channels was evaluated separately. The specific sensitivity coefficients (**Slopes**) determined during calibration were hard coded into the firmware to ensure processing efficiency:

Channel / Bolt	Slope Coefficient
Bolt A (Sensor 0)	52.531
Bolt B (Sensor 1)	48.739
Bolt C (Sensor 2)	52.566
Bolt D (Sensor 3)	49.768
Bolt E (Sensor 4)	-45.207
Bolt F (Sensor 5)	-48.264
Bolt G (Sensor 6)	-51.854
Bolt H (Sensor 7)	-49.271
Torque Sensor	25911.0

- **Suitability for Comparative Analysis:**

Based on the observed linearity and repeatability of these calibration curves, the system was confirmed to be suitable for the comparative analysis of force distribution required for this measurement exercise.

4.2. Calibration Verification (System Check)

Following the main calibration, a secondary verification procedure was conducted to confirm the signal integrity of the DAQ electronics (HX711 amplifiers and ESP32 controller).

- **Reference Mass Test:**

A standard load cell structure (harvested from a commercial kitchen scale) was interfaced with the system. A known reference mass of **100g** was applied to the platform to test the system's responsiveness.

- **Span Verification:**

The system was "Tared" under load and then unloaded to observe the signal response. The resulting negative output (confirming the removal of 100g) verified that the communication between the amplifiers and the microcontroller was stable and that the software correctly processed the change in mass (Delta).

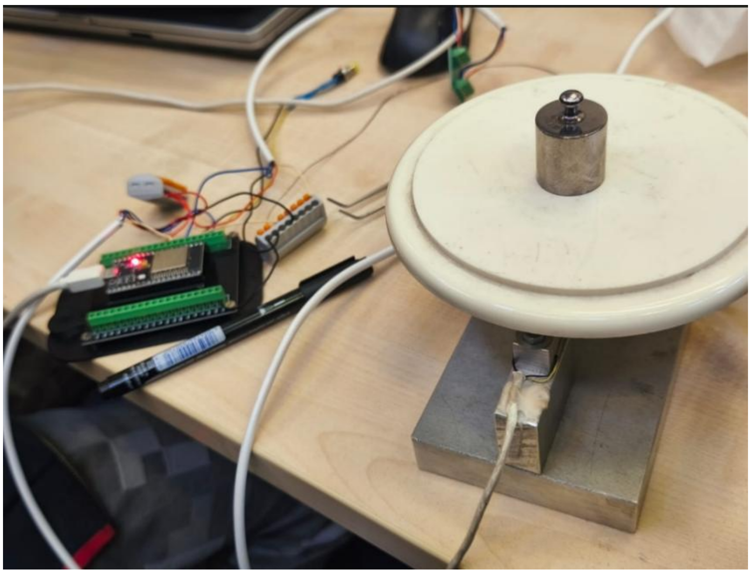


Figure 12. Connection of the signal response verification using a kitchen scale

5. Measurement Setup and Debug Process

The physical setup of the measurement system required strict adherence to signal integrity protocols to minimize electromagnetic interference (EMI). Since the output voltage from the strain gauges is in the microvolt range, proper cable routing and shielding were essential to ensure high fidelity, noise-free data acquisition.

The system underwent a rigorous three-stage debugging process before the final trials:

- **Mechanical Verification:** The primary inspection focused on the strain gauge mountings to ensure rigid attachment. We verified that the sensors remained stationary under high pressure to prevent mechanical hysteresis or drift.
- **Electrical Verification:** Continuity checks were performed on all channels to rule out loose contacts, cold solder joints, or broken conductors that could introduce signal artifacts.
- **Software & Data Logging Verification:** The final stage involved end-to-end testing of the DAQ software. We verified the stability of the Serial stream and the integrity of the Excel data logging to ensure zero data loss during the measurement window.

6. Flow of Measurement

The measurement workflow was strictly controlled to ensure repeatability and minimize the non-linear effects of gasket compression. The core of the process involved PC-linked data collection via Excel, capturing strain gauge signals (Force) and the Torque sensor input at a sampling rate of **~10 Hz (101 ms)**.

6.1. Measurement Protocol

To analyze the interaction between the bolt tension and gasket compression, a multi-stage tightening and loosening procedure was implemented for every trial:

- **Tightening Phase (3 Steps):** The bolts were not tightened to the final torque immediately. Instead, a stepped approach was used to gradually seat the cylinder head and allow for stress redistribution:
    1. **Stage 1 (Pre-load):** All bolts were tightened to **35 Nm**.
    2. **Stage 2 (Intermediate):** Torque was increased to **50 Nm** for all bolts.
    3. **Stage 3 (Final):** All bolts were brought to the target torque of **70 Nm**.

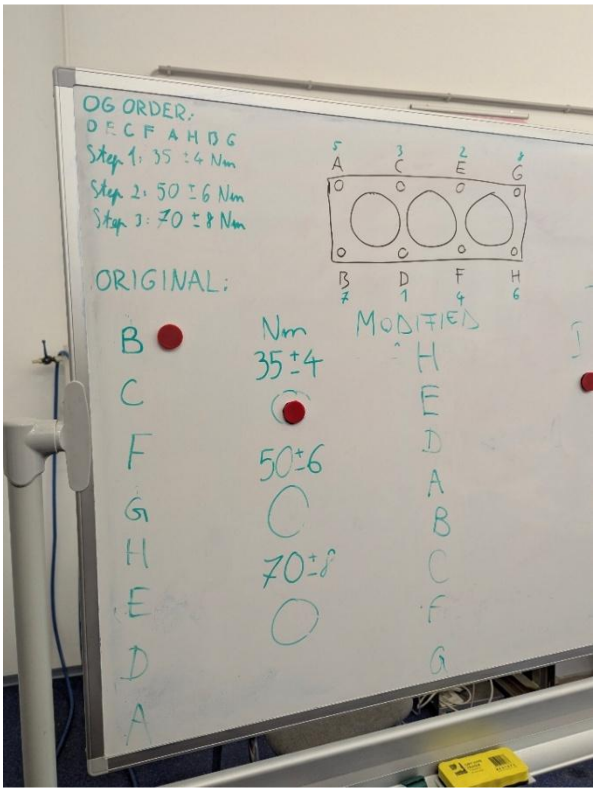


Figure 13. Tightening sequence

- **Loosening Phase (2 Steps):** To analyze mechanical hysteresis and permanent deformation, the bolts were loosened in **two distinct stages** (dropping to ~35 Nm before full release) rather than being fully removed instantly.

6.2. Applied Sequences

Two distinct tightening patterns were tested to evaluate their impact on load distribution:

Sequence A (BCFGHEDA)

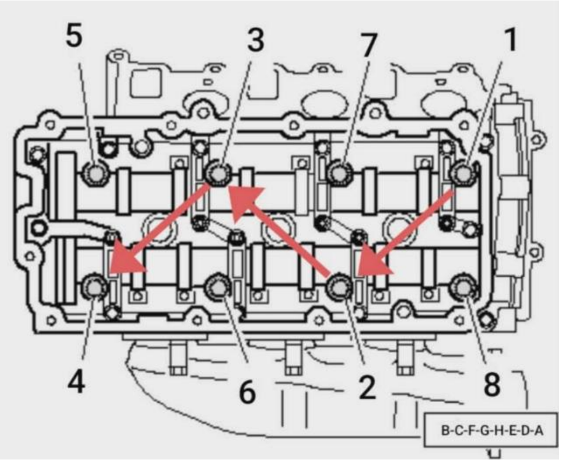


Figure 14. Diagrammatic representation of sequence A

Sequence B (HEDABCFG)

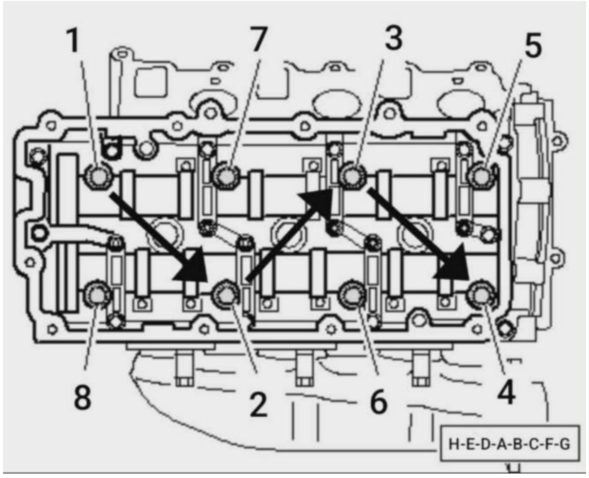


Figure 15. Diagrammatic representation of sequence A

Both shared the same crisscross pattern but one is the other ones reversed order.

7. Data Analysis

The dataset was analyzed to compare the efficacy of the two tightening sequences in achieving uniform clamping force at the final **70 Nm** target. The analysis utilized the raw data from four trials (two per sequence).

7.1. Torque-to-Force Correlation

The 3-stage tightening process (35→50→70 Nm) revealed significant non-linearity.

- **Force Divergence:** As the torque increased to the final 70 Nm stage, the divergence between bolts increased significantly. In Sequence A, the variation between the highest and lowest clamping forces reached over **27,000 units**, indicating that friction variances became dominant at higher loads.
- **Hysteresis:** The 2-stage loosening process showed that the strain values did not return to the exact levels observed during tightening at the same torque (e.g., at ~35 Nm), confirming plastic deformation in the gasket or thread friction changes.

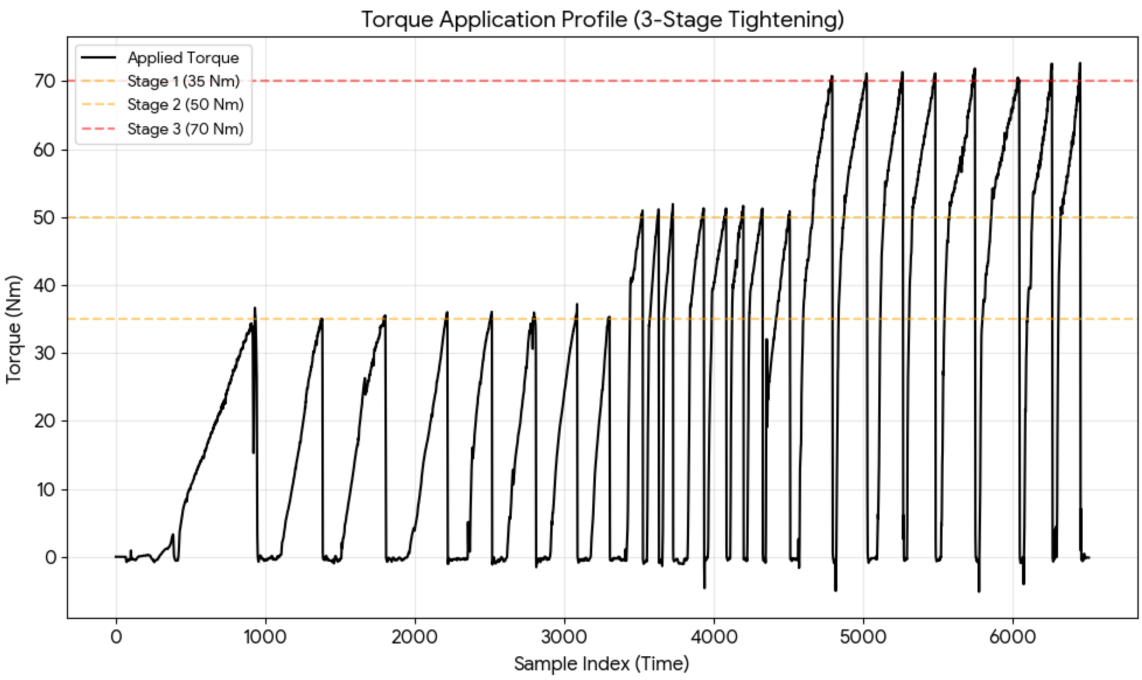


Figure 16. Graphical representation of applied torque over 3 stages.

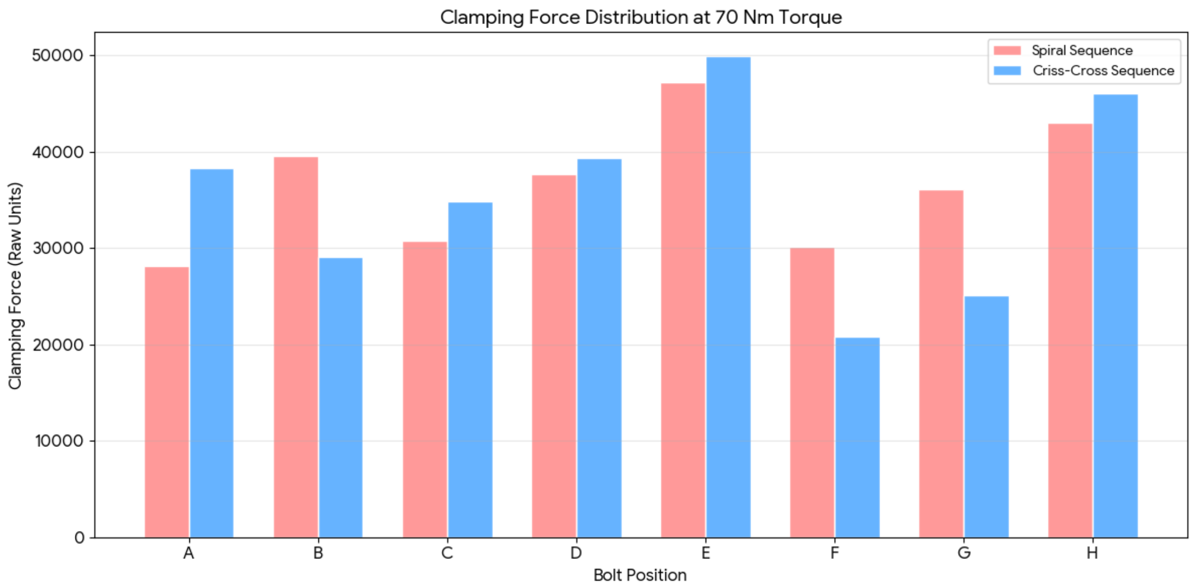
7.2. Sequence Comparison

The experiment compared two variations of the crisscross pattern to determine if the

tightening direction influenced the final load distribution:

- **Sequence A (Standard - BCFGHEDA):** This sequence exhibited a higher degree of load relaxation. The data shows that the final bolts in this order failed to achieve the same tension as the starting bolts, resulting in a total force variation of ~27,800 units.

- **Sequence B (Reversed - HEDABCFG):** By reversing the order, the system achieved a significantly more stable distribution. The force variation was reduced to ~22,350 units (a **~20% improvement**). This suggests that the "Reversed" order better counteracts the tipping moment of the cylinder head during the initial



compression phases.

Figure 17. Graphical analysis of clamping force distribution.

8. Conclusions and Development

8.1. Conclusions

The Capstone 3 project successfully demonstrated the complexity of bolt tensioning through a custom-built DAQ system. The comparative analysis of the two tightening sequences yielded the following key conclusions:

- **Torque ≠ Tension**: Despite with applied 70Nm torque equally all across the 8 bolts, the final clamping force experienced by each bolt varies within a range of 27000 N. It emphasizes that friction and mechanics dominate in the results.
- **External factors**: Usage of lubricant resulted in improved results in the second sequence hinting that even with perfect tightening sequence, factors like uniform lubrication plays a key role.

8.2. Future Development

To further improve the accuracy and utility of this measurement system, the following developments are proposed:

- **Contrasting sequences**: Even though we could identify marginal improvements in sequence B compared to sequence A, it is safe to say that these improvements were caused by lubrication of bolts and other external factors. So, for a future analysis it is recommended the analysis of entirely different sequences or better yet comparing the factory recommended sequence to some other random sequence.
- **Angle-Controlled Measurement:** Integrating a gyroscope to measure the **rotation angle** of the wrench would allow for "Torque-plus-Angle" analysis. This method is the industry standard for high-precision engine assembly as it allows the system to ignore friction variables after the yield point.
- **Higher Sampling Frequency:** Upgrading the firmware to utilize interrupt-based sampling could increase the data rate from 10 Hz to **50+ Hz**. This would allow for a more detailed analysis of the transient "click" moment of the torque wrench and the immediate relaxation phase.

- **Automated Guidance GUI:** The software could be upgraded to include a "Step-by-Step" wizard on the PC or OLED screen. This would actively guide the user through the specific 3-stage tightening sequence (e.g., "Tighten Bolt 3 to 50 Nm Now"), reducing procedural errors during complex patterns.
- **Wireless Connectivity:** Utilizing the ESP32's built-in **Wi-Fi or Bluetooth** capabilities would eliminate physical cabling. This would reduce the risk of electromagnetic interference (EMI) and make the setup easier to deploy on a real vehicle chassis.

9. References

[1] Széchenyi István University, "Capstone Project 3: Course Requirements and Project Overview," Department of Automotive Engineering, Győr, Hungary, 2025.

[2] Espressif Systems, "ESP32 Series Datasheet," Version 3.4, 2021

[3] Avia Semiconductor, "HX711: 24-Bit Analog-to-Digital Converter (ADC) for Weigh Scales," Datasheet, v2.0, 2012.

[4] Microsoft Corporation, "Data Streamer Add-in for Excel," [Online]. Available: https://support.microsoft.com.

[5] Arduino, "Arduino IDE 2.0: Integrated Development Environment," [Online]. Available: https://www.arduino.cc/en/software.

[6] L. Boros and B. Dombi, "Load Cell Measuring Firmware v2.1," Custom C++ Implementation, Széchenyi István University, 2026.

[7] J. H. Bickford, *An Introduction to the Design and Behavior of Bolted Joints*, 4th ed., CRC Press, 2008

10. Performance evaluation

Chapter Number & Name	**Máté**	**Kovida**	**Nipun**	**Antony**	**Bendegúz**	**Vilmos**
1.Abstract and goals	16.6%	16.6%	16.6%	16.6%	16.6%	16.6%
2. Force Transducer			50%	50%		
3. DAQ System & C++	50%	50%				
4. Calibration	50%			50%		
5. Meas. Setup & Debug		50%			50%	
6. Flow of Measurement					50%	50%
7. Data Analysis			50%			50%
8. Conclusions	16.6%	16.6%	16.6%	16.6%	16.6%	16.6%