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par: Bouabdallah Zinedine

Titre:

Development and implementation of a device for measuring cutting force on workpieces during machining.

Dr. SAIB Cherif	**MCA**	**Président**
Pr. MAKRI Hocine	**Pr**	**Examinateur**
Dr. ARSLANE Mustapha	**MCB**	**Encadrant**

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Abstract::

This project developed a low-cost, functional device to measure cutting forces during drilling operations. It integrates mechanical design, sensor installation, electronics, and software to provide accurate, real-time signal force feedback. Aluminum was chosen for the structure due to its mechanical advantages, and four strain-gauge load cells arranged in an X-pattern ensure balanced force detection. The system uses an HX711 amplifier and Arduino Uno microcontroller, with a 16×2 LCD for live force display. Calibration with reference weights confirmed measurement reliability under various machining conditions. This approach offers a simple yet effective solution for monitoring cutting dynamics, essential for optimizing machining processes. Future enhancements may include vibration measurement and wireless data logging.

Keywords : Cutting force measurement- Low-cost device- Strain-gauge load cells- Arduino Uno -HX711 amplifier- Real-time monitoring- Mechanical design.

Résumé:

Ce projet présente le développement d’un dispositif fonctionnel et économique pour mesurer les forces de coupe lors d’opérations de perçage. Il intègre la conception mécanique, l’intégration des capteurs, l’assemblage électronique, l’acquisition des signaux et la programmation logicielle afin de fournir un retour précis et en temps réel sur les efforts appliqués. La structure en aluminium a été choisie pour ses propriétés mécaniques, tandis que quatre capteurs à jauges de contrainte, disposés en configuration « X », assurent une détection équilibrée des forces. Le système utilise un amplificateur HX711 et une carte Arduino Uno, avec un affichage sur écran LCD 16×2. Calibré avec des poids de référence, il a démontré stabilité, précision et reproductibilité grâce à des composants standards. Ce dispositif simple et efficace facilite le suivi des efforts de coupe, paramètre clé pour optimiser les procédés d’usinage. Des améliorations futures envisagent la mesure des vibrations et l’enregistrement sans fil des données pour des analyses approfondies.
Mots-clés: Mesure des forces de coupe- Dispositif à faible coût- Arduino Uno.

الملخص العام:.

تتناول هذه المذكرة تطوير وتنفيذ جهاز عملي و منخفض التكلفة لقياس قوى القطع المسلطة على قطعة المشغلة أثناء عمليات التثقيب شمل المشروع مختلف الجوانب بدءا من التصميم الميكانيكي و دمج المستشعرات و تجميع دوائر إلكترونية وصولا الى برمجة النظام بهدف توفير قراءة فورية و دقيقة لقوى القطع أثناء التفريز. تم إختيار الألمنيوم كمادة لتصنيع اللوحات الداعمة نظرا لخواصه الميكانكية الجيدة, وتم تركيب أربع خلايا تحميل مزودة بجسور انفعالية على شكل"X" لضمان توازن توزيع القوى المقاسة ,حيث يعتمد النظام إلكتروني على مكبر إشارة من نوع HX711 متصل بلوحة أردوينو أنو , بينما يتم عرض نتائج على شاشة LCD . تمت معايرة الجهاز بإستخدام أوزان مرجعية معروفة, و أضهرت التجارب الأولوية إستقرار الجهاز بإستخدام أوزان مرجعية معروفة , و أظهر الجهاز سهولة في التركيب و التكرار بإستخدام مكونات بسيطة و متوفرة. يجمع هذا لمشروع بين تقنيات التصنيع الميكانيكي والإلكترونيات المدمجة ليقدّم حلًا فعالًا لمراقبة ديناميكية القطع، والتي تُعد من العوامل الأساسية في تحسين عمليات التشغيل من الممكن مستقبلاً تطوير النظام بإضافة قياس الاهتزازات ودمج نظام تسجيل بيانات لاسلكي لتحلي أكثر تقدما

الكلمات المفتاحية: قياس قوى القطع - جهاز منخفض التكلفة- خلايا تحميل (حساسات قياس الإجهاد)- لوحة أردوينو- التصميم الميكانيكي-مضخم- تحسين عمليات تصنيع

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General Introduction

In today's era of advanced industrialization and the emergence of smart manufacturing, the accurate control of machining processes has become a critical factor in ensuring both product quality and tool longevity. Among the key parameters to be monitored during drilling operations, cutting force stands out as one of the most significant. It directly reflects the interaction between the tool and the workpiece, influencing process stability, surface finish, and tool wear.

This thesis aligns with the objective of optimizing manufacturing processes by developing an experimental device for measuring cutting forces. The system is designed to be simple, reliable, and cost-effective, utilizing strain-gauge load cells, low-cost electronics (such as HX711 and Arduino Uno), and a real-time display unit. The main goal of this project is to propose an experimental solution capable of precisely acquiring cutting forces exerted on the workpiece during machining, in order to improve the understanding of mechanical phenomena and provide a foundation for cutting parameter optimization.

A multidisciplinary approach was adopted, combining mechanical design, instrumentation, embedded programming, and data analysis. This methodology provided a comprehensive and practical learning framework, aligned with the technological demands of Industry 4.0.

Structure of the Thesis

This thesis is organized into three main chapters:

- **Chapter 1** introduces the background of the study and presents a literature review on cutting forces, measurement techniques, and previous research on machining optimization.
- **Chapter 2** details the materials used and the experimental methodology, including sensor selection, system integration, data acquisition, and signal processing.
- **Chapter 3** focuses on the implementation, testing, and validation of the developed system, with performance evaluation through real drilling experiments on composite materials.

Each chapter contributes progressively to the realization and validation of a functional force measurement system, offering both academic and practical value.

Chapter 1:

Introduction and Literature Review

Chapter 1

1.Introduction:

1.1 Background and Justification:

Machinist operations are considered a critical element in modern industries. The process of sorting is widely used to diversify its application. This is due to the diversity of its applications and its high ability to produce complex shapes with perfect accuracy. However, this does not prevent the appearance of unwanted objects such as excessive cutting forces during disassembly operations Desperate to understand and control these critical aspects to enhance the productivity and quality of the factory product in sorting operations.

1.2 Problem Statement:

Despite the tremendous development in automation technology such as turning and drilling, there are still many obstacles that obstacles we struggle to overcome, including the following:

- accurate prediction of cutting forces the process and accurately measured them by adding to the perfect control of them to prevent their negative effects.

These challenges continue to impact production lines through:

- The decrease in efficiency is caused by the sudden stoppage of machines or the need for repeated repairs.
- Damage tools as a result of a lack of understanding of the interactions of cutting forces.
- Waste of time and resources such as high maintenance cost or waste of raw materials in manufacturing.

To understand the phenomenon more, we need to understand the complexity of why interaction between cutting forces is not as easy and simple as we see it depends on three main factors arranged as follows:

- Operating parameters: The rotation speed, cutting depth and feed rate each have an important role.
- Properties of materials: such as hardness, elasticity and chemical composition.
- Tool design: Tool shape and material made of it and its own cutting angles.

To find a solution to the proposed study, we will adopt an integrated approach that combines experimental methods using sensors to measure cutting forces and vibrations in real time and analyze data using algorithms and mathematical models to understand hidden relationships between different factors.

This study aims to improve the quality of products: by reducing surface distortions and increasing precision by extending the life of tools to reduce damage and reducing the costs of waste in primary substance by enhancing energy efficiency.

This approach is not only theoretical but applied in modern factories such as the aircraft industry and sophisticated cars to achieve micron accuracy.

1.3 Objectives of the Study:

The main objectives of this project are as follows:

- To measure and analyze cutting forces during drilling operations.

- To identify correlations between machining parameters and the observed phenomena.

-To propose optimized machining conditions that minimize adverse effects and enhance process performance.

1.4 General Methodology

The research study has a holistic experimental methodology that utilizes the design and implementation of a measurement system in the form of force sensors and data acquisition software tools. It consists of several steps namely, fabrication of aluminum workpieces, installation of force sensors, and performing drilling operations under different sets of conditions. After the data capture and accumulation, the data are extracted and analyzed utilizing software tools for optimal force metrics, and identifying trends to support optimization.

2. Literature Review:

2.1 Theoretical Models of Cutting Forces in drilling:

Successful prediction and analysis of cutting forces plays a crucial role in improving machining processes. When referring to metal cutting, cutting forces can influence tool life, and surface finish, but also stability of the process and energy consumption. The fundamental cutting force theory gives us a framework with which to better understand the evolution of cutting forces through the cutting process. Typically, there are two main approaches to the development of this theory:

- Analytical Models: This type of model use of mechanical and physical principles. They govern mathematical relationships by considering shear deformation, friction, cutting tool geometry (e.g. rake angle) and characteristics of the material. An example of an analytical model is Merchant’s model, which relates the shear angle and the true rake angle to the corresponding cutting forces. Analytical models give a grander understanding of the cutting process from a fundamental level, and they provide better insight into the mechanics of chip formation and energy distribution [1].

Empirical Models: Empirical models rely on experimental data derived from controlled experimentation. These models indicate the researcher has determined relationships between cutting parameters (feed rate, cutting speed, depth of cut) and resultant forces through a controlled experiment. Empirical models are particularly useful in industry practice as they are capable of predicting cutting forces under different conditions, even when there may be a theoretical model that is too complicated to fully represent all the relevant variables. Together, these two models provide a foundation for understanding and predicting forces during machining processes. Analytical or semi-analytical models provide useful physical process knowledge whereas an empirical model is capable of confirming these theories with experimental data, as well as use that model for implementation of the real process in order to optimize it.

- Drilling Forces and Related Models:

Drilling is a complex machining operation where the cutting forces are concentrated along the main axis of the tool. The total cutting force during drilling can be broken down into an axial thrust force and a torque. The axial force $F z$ and torque T can be estimated using the following empirical equations:

$$F_z = K_f \cdot d \cdot f$$

$$T = K_t \cdot d^2 \cdot f$$

Where:

Fz: Axial thrust force (force along the drill axis)

Kf : Empirical constant (depends on material and cutting conditions)

d : Drill diameter

F : Feed rate

T: Torque

K t : Empirical constant for torque.

The following figure illustrates Drilling Forces Distribution [2]:

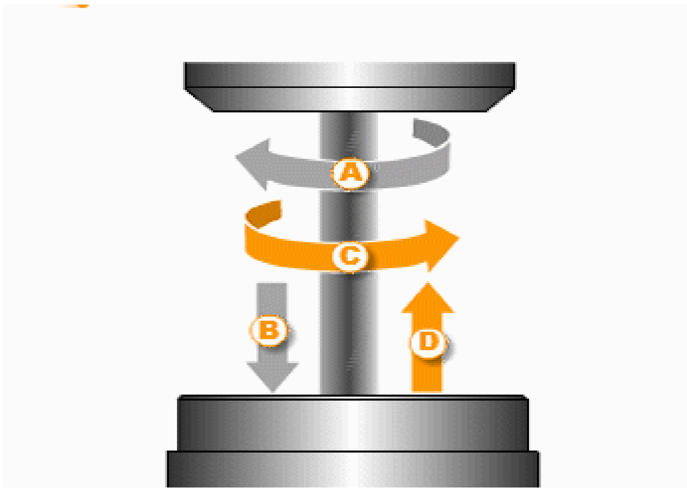

Figure 1: Drilling Forces Distribution.

2.1.1 Analytical Models:

Grasping and evaluating cutting forces is one of the key components of enhancing automated machining operations and the resulting product quality. The cutting force analysis includes two main approaches:

- Merchant's Model: merchant's theory is one of the cornerstone pieces of work for gaining an understanding of metal cutting mechanics. It analyzes the generation of a chip with a given set of geometric and mechanical elements. The theory is based on the examination of orthogonal cutting, which utilizes a simplified model of a group of cards stacked as a surface, where shear deformation occurs from the small relative movement of each layer of cards. This study led to a range of equations that relate the angle of shear to the angle of a rake, where the cutting force is applied. The equations enable the researcher to quantify the force related to cutting, while provide insight of the relationship between deformation and quality of the chip.[1]

Key Equations Derived:

1. Angular Relationship Equation:

$$cot\ \phi_i = cot\ \phi + tan\ (\phi - \alpha)$$

where:

- ϕ $is\ the\ shear\ angle$
- ϕ_i $is\ the\ observable\ angle\ in\ the\ microstructure\ of\ the\ chip$
- α $is\ the\ true\ rake\ angle\ of\ the\ cutting\ tool.$

2. Shear Strain Equation:

The shear strain E is given by:

$$E = cot\ \phi + tan\ (\phi - \alpha)$$

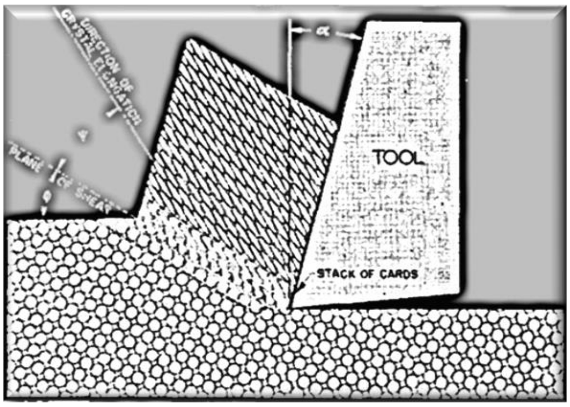

Figure 2: shows the chip's crystalline structure, showing angles and confirming the geometric relationship.

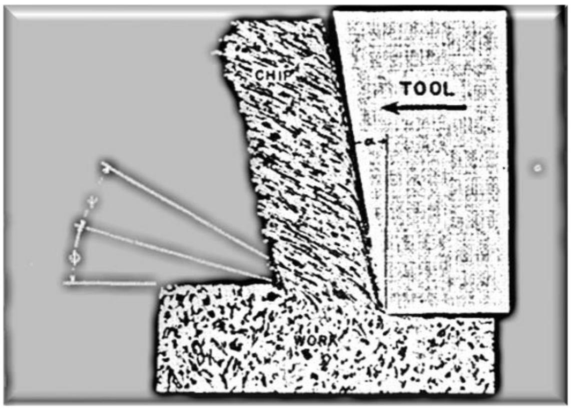

Figure 3: shows the geometric model focusing on the relationship when one-layer slides over another

❖ Oxley's Model: Oxley's analytical model provides a comprehensive description of plastic deformation and stress distribution in the primary shear zone of metal cutting. Unlike the other models, which assume a perfectly thin and sharp shear plane, Oxley's analysis assumes a finite shear zone that is carrying on with the flow of the material and assuming temperature effects into the deformation analysis. One of the many contributions of this model involves using slipline field theory as a graphical approach to analyzing the flow of material in chip formation. The slipline field itself enables the visualization of the stress trajectories and predicting the velocity and strain fields in the deformation region. It represents a vigorous analytical method to consider the plastic flow at the tool-chip interface, assist in estimating the cutting forces and chip thickness under different machining conditions.[3]

- The following figure illustrates the slipline field and hodograph developed by Enahoro and Oxley (1966), showing the direction and intensity of flow within the deformation zone.

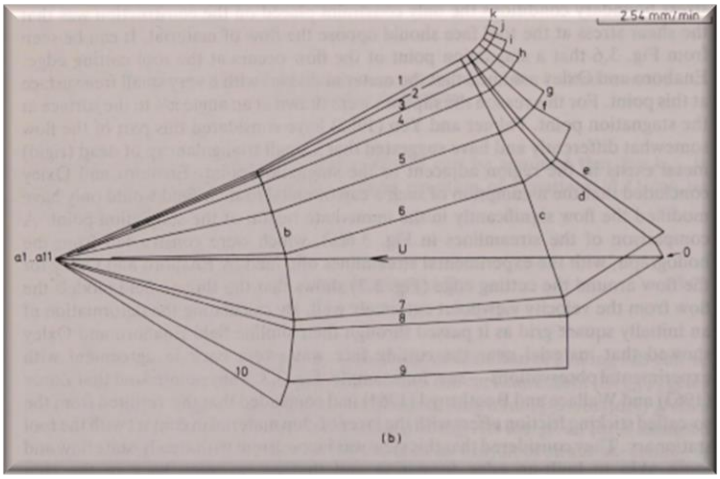

Figure 4: Slipline Field Based on Oxley's Model (Enahoro and Oxley, 1966)

2.1.2 Empirical Models:

A typical example of an empirical model is a force prediction equation developed using regression analysis or response surface methodology, where the relationship between input parameters and cutting forces is mathematically fitted from machining test data. This type of relationship is illustrated in Figure 5, which shows an experimental curve relating cutting force to feed rate under controlled conditions. prediction equation

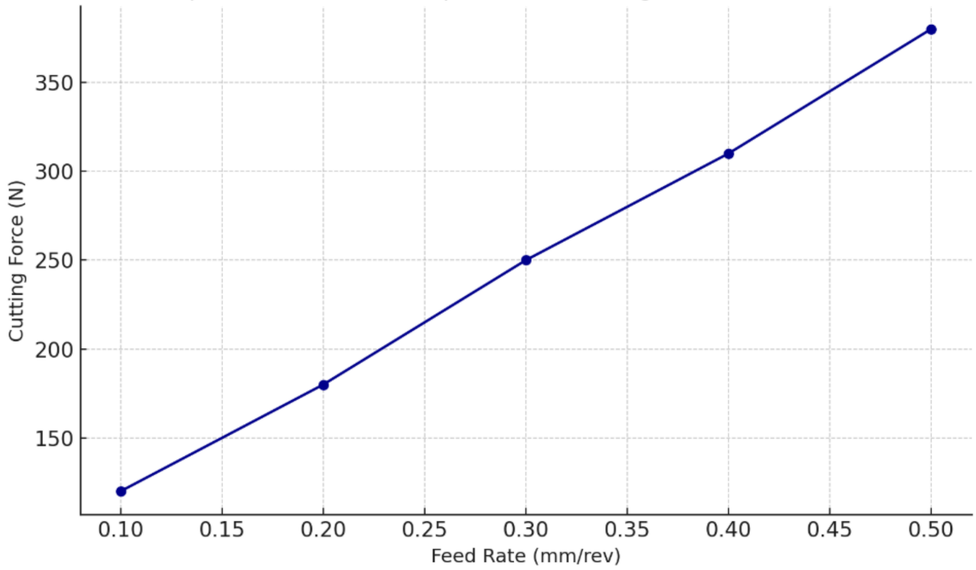

Figure 5: Experimental Relationship Between Cutting Force and Feed Rate.

found from machining data that relates cutting force components, and input parameters using either regression analysis or response surface methodology. [4]

2.2 Cutting forces in drilling:

Drilling operations generate significant mechanical forces that act on both the tool and workpiece. The primary forces include the Cutting Force (Fc), which acts tangentially to the cutting edge and drives material removal and torque generation, and the Thrust Force (Ff) (or feed force), which acts axially along the drill's axis to advance the tool into the material. Additional forces like the Radial Force (Fg) stabilize the drill, while Chip Evacuation Forces (Fa) influence swarf flow. The cutting speed (*VC*) and feed rate (*Vf*) directly impact these forces, affecting tool wear, hole quality, and process stability.

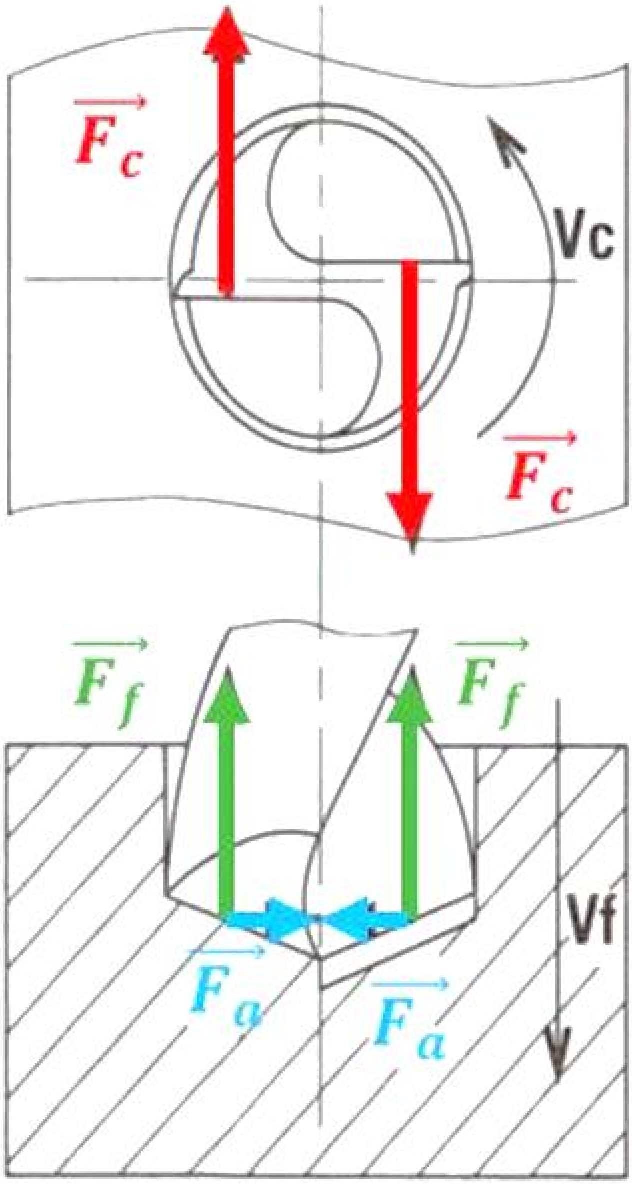

Figure 6: Cutting forces in drilling.

Power Calculation in Drilling:

The image below summarizes all the formulas related to power calculations.

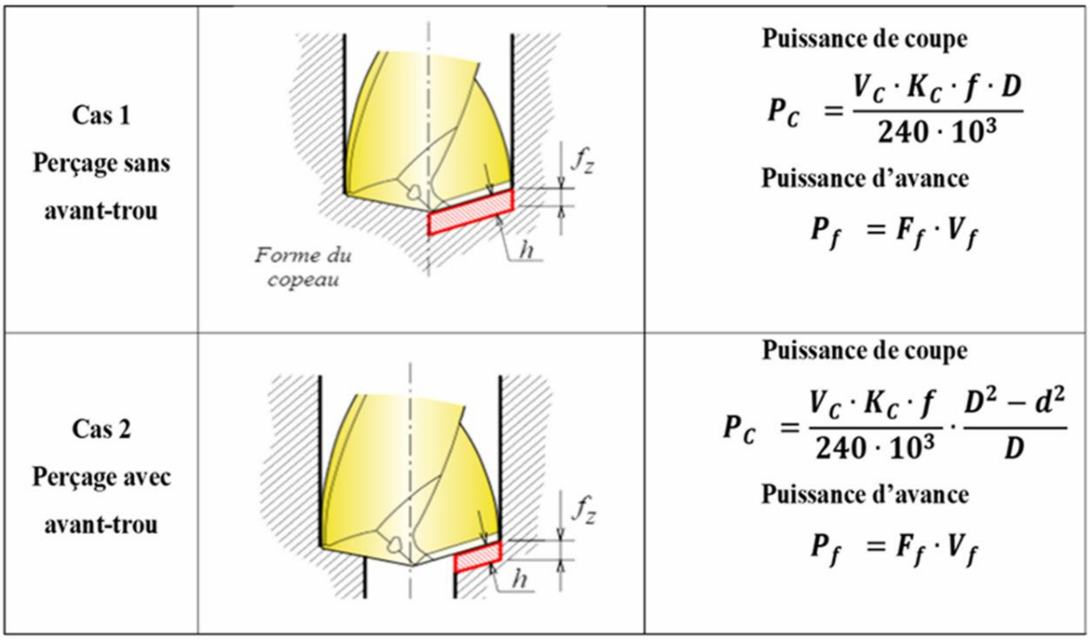

Figure 7: formulas related to power calculations.

2.3Techniques of Measuring Forces (Sensors, Experimental Methods):

Precise measurement of forces and vibrations is essential in the study of the response of mechanical systems and structures under different load conditions. Such measurements carry far-reaching implications in mechanical engineering, aeronautical engineering, automotive engineering, and civil infrastructure engineering. These measurement techniques generate data that enable the design of more safe and efficient systems, structural condition monitoring, and failure predictions. This study considers the major techniques applied to measure forces and vibrations, including a specific concentration on sensor technologies and experimental techniques.

2.3.1Force Measurement Methods:

Measuring force is generally possible by utilizing sensors that transfer mechanical deformations to electrical signals. Strain gauges are one of the best-known techniques, whereby when a force causes minute material deformations, the changes in electrical resistances are measurable. Strain gauges come in different types, including foils, wire, and semiconductor sensors, and are generally used in the development of pressure sensors and load cells.

Piezoelectric sensors take advantage of the phenomenon of some materials that produce a charge electrically when a mechanical strain is applied to them. Piezoelectric sensors are especially useful in impact testing and dynamic load measurement due to their sensitivity to dynamic forces.

2.3.3Experimental Methods:

Experimental approaches such as modal analysis complement sensor data by providing a system-wide view of dynamics. Modal analysis involves exciting a structure and identifying its natural frequencies, mode shapes, and damping ratios. Tools such as shakers, accelerometers, and impact hammers are used to conduct these tests. Modal analysis is common in aircraft wing testing, bridge construction, and heavy machinery analysis.[4]

2.4 Previous Work on Machining Process Optimization:

Many researchers have investigated techniques for improving machining processes by modifying critical parameters and monitoring operational conditions. Traditional approaches like Design of Experiments (DOE), Taguchi methods, and Statistical Process Control (SPC) have been proven to reduce variability and maintain process quality [5].

In recent developments, artificial intelligence (AI) and machine learning (ML) have enabled real-time optimization and predictive maintenance. These systems process large datasets to allow automatic fault detection and process adaptation, minimizing downtime and maximizing productivity [6].

2.5 Research Gaps and Proposed Approach:

While extensive studies have focused on cutting forces and vibrations independently, fewer have explored their combined and simultaneous effects during machining. Most past research lacks synchronized measurements of both phenomena, limiting the full understanding of their interaction. This study addresses that gap by proposing a detailed experimental setup to record and analyze both forces and vibrations in real time. The findings aim to enhance process optimization and serve as empirical evidence for improving milling operations [6].

Chapter 2:

Materials Used and Methods

Chapter 2

2.1Methods for measuring cutting forces:

Cutting forces were measured using four strain-gauge load cells arranged in an “X” pattern between the two aluminum plates. Each cell produces a small electrical signal

(in millivolts), which is amplified by an HX711 24-bit ADC board and then read by an Arduino Uno at a 200 Hz sampling rate. The circuit supplies a constant 5 V excitation to each load cell and reads the voltage change caused by the cell’s compression under cutting forces. The force values (in Newtons) are displayed in real time on a 16×2 LCD connected to the Arduino.

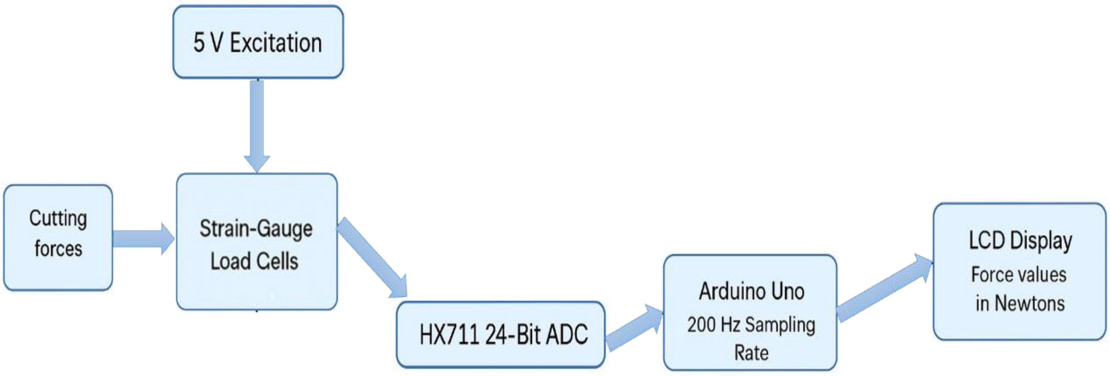

Figure8: Concept map of Methods for measuring cutting forces.

2.2Description of aluminum plates:

2.2.1 Description:

The system includes two aluminum plates used as the mechanical interface for force transmission. These plates are positioned above and below the load cells to ensure even distribution of forces and to maintain structural rigidity. Each plate is machined from a high-quality aluminum alloy and drilled with multiple alignment and mounting holes.

- Upper Plate: Fixed to the tool holder assembly, transferring cutting forces directly to the load cells
- Lower Plate: Resting on the load-cell assembly, it provides a stable base and ensures accurate force measurement.

This arrangement guarantees that all cutting forces pass uniformly through the sensors, minimizing measurement errors due to misalignment or uneven loading.

2.2.2 Mechanical properties:

The aluminum plates are manufactured from 6061-T6 aluminum alloy, chosen for its excellent combination of strength, stiffness, and corrosion resistance. Key properties include:

Property	Value
Material	Aluminum Alloy 6061-T6
Density	2.70 g/cm³
Ultimate Tensile Strength	≈ 310 MPa
Yield Strength	≈ 276 MPa
Elastic Modulus	≈ 68.9 GPa
Hardness (Brinell)	≈ 95 HB
Thermal Conductivity	≈ 167 W/m·K
Corrosion Resistance	High

Table 01: Mechanical properties of *6061-T6 aluminum alloy*

These properties operation ensure that the plates do not undergo significant deformation under applied machining loads and thus help maintain sensor alignment and measurement accuracy throughout the [7].

2.3Force sensors:

Force sensors are fundamental components in modern systems that require accurate measurement and conversion of mechanical forces into readable signals. These sensors are widely used in industrial automation, scientific research, and consumer applications. Their functionality is based on a variety of physical and electromechanical principles, each suitable for specific operational environments and accuracy requirements. Due to the diversity of applications—including robotics, medical devices, and smart vehicles—the force sensor market offers a wide range of technologies, each tailored to unique sensing needs [8].

2.3.1 types of force sensors and operating principles:

- Strain Gauge Load Cell:
  - **Output**: A small voltage change (millivolts), which needs amplification.
  - **Accuracy**: Very high.
  - **Applications**: Electronic scales, test machines, industrial weighing.

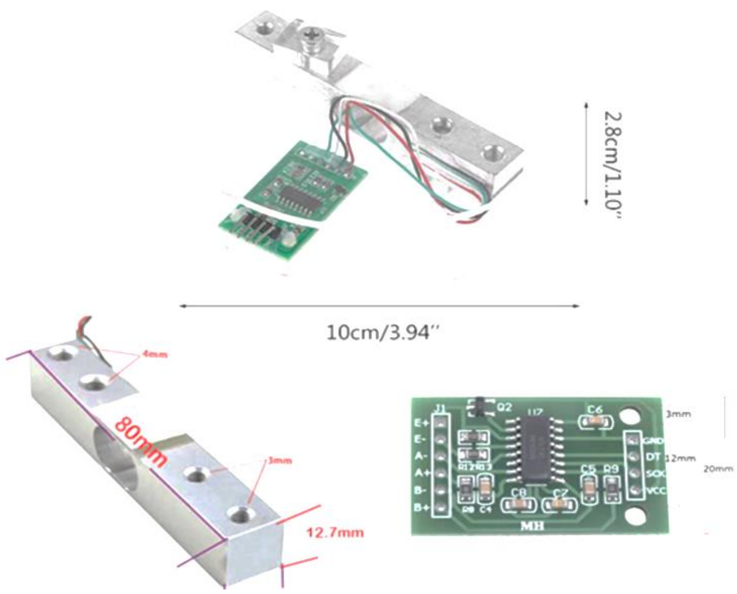

Figure 9: Key Dimensions in Metric and Imperial Units.

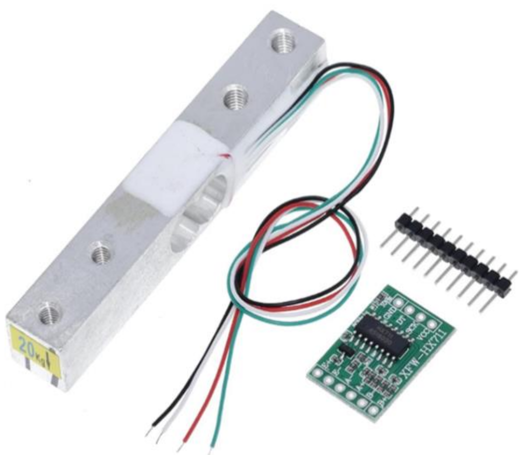

Figure 10: 20kg Load Cell with Amplifier Module.

- **Principle**: Uses tiny electrical resistors (strain gauges) bonded to a metal element. When a force is applied, the metal deforms slightly and the gauge's resistance changes.

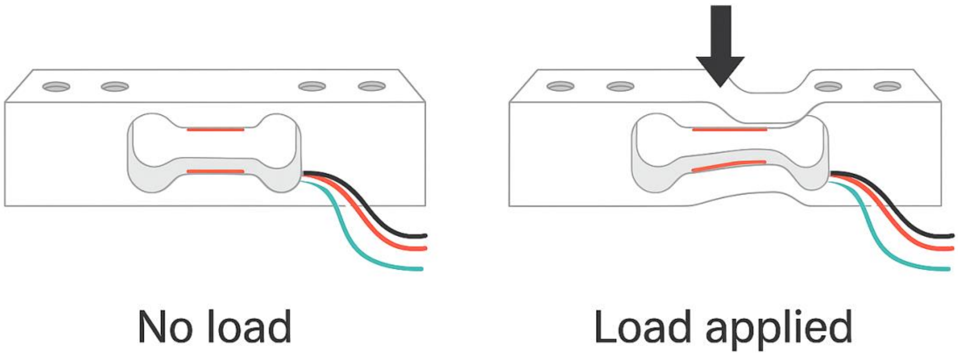

Figure 11: Strain Gauge Load Cell: No Load (left) vs. Load Applied (right).

- **Central Slot**: Allows the metal block to flex under load.
- **Wiring**: Typically, 4 or 6 wires:
- **4-wire**: Excitation+ / Excitation– and Signal+ / Signal–

Pneumatic Load Cells:

Pneumatic load cells use compressed air instead of liquid to measure applied forces. As the force is applied, it increases the air pressure in a sealed chamber, which is then read by a pressure sensor. They are ideal for environments requiring full electrical isolation or operation under elevated temperatures.

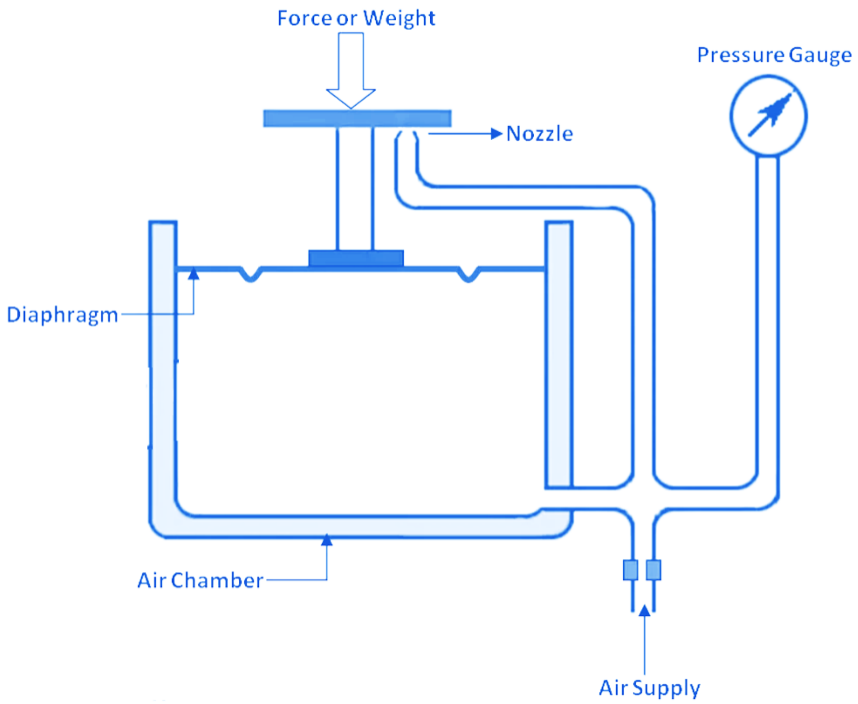

Figure 12: Illustration of a pneumatic load cell in operation.

- Piezoelectric Force Sensor:

  - **Output**: Direct electrical signal, no external excitation needed.
  - **Response**: Extremely fast—ideal for dynamic (rapidly changing) forces.
  - **Limitation**: Not suited for long-term static measurements.

Figure 13: Piezo Sensor Element 35mm.

Principle: Uses piezoelectric materials that generate a voltage when mechanically stressed

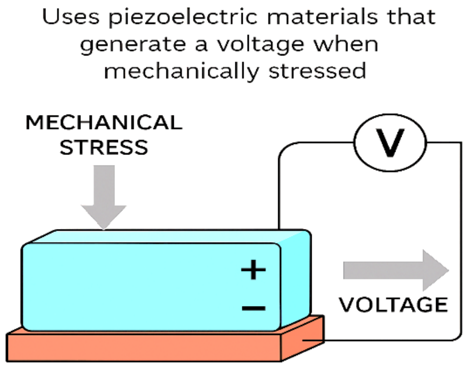

Figure 14: Piezoelectric Sensor: Voltage Generation Under Mechanical Stress.

- Capacitive Force Sensor:

  - **Accuracy**: Very good, with high sensitivity.
  - **Applications**: Medical devices, touch-sensitive controls, and more.
  - **Principle**: Measures change in capacitance between two plates as the distance between them varies under force.

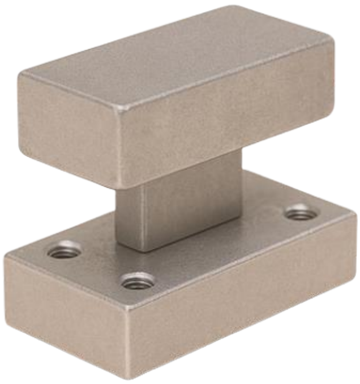

Figure 15: Realistic View of the Capacitive Force Sensor Stress.

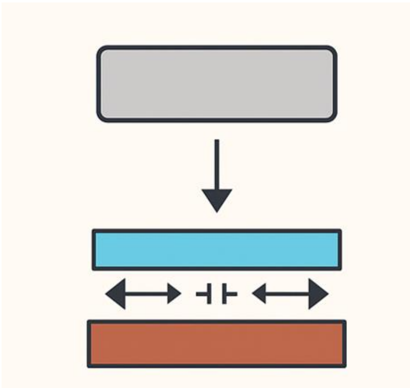

Figure 16: Schematic of the Capacitive Sensor's Operating Principle.

Hydraulic Load Cells:

Hydraulic load cells function based on the principle of fluid pressure variation. When an external mechanical force is applied to a piston, it compresses a sealed fluid inside a chamber. This pressure increase is directly proportional to the applied force and is measured by a pressure transducer. These sensors are especially suited for heavy-duty industrial environments, where mechanical robustness and durability are prioritized over high-resolution electronic accuracy. Their resistance to harsh conditions, including shock, temperature variations, and electromagnetic interference, makes them ideal for construction, transportation, and press-based machinery applications [9].

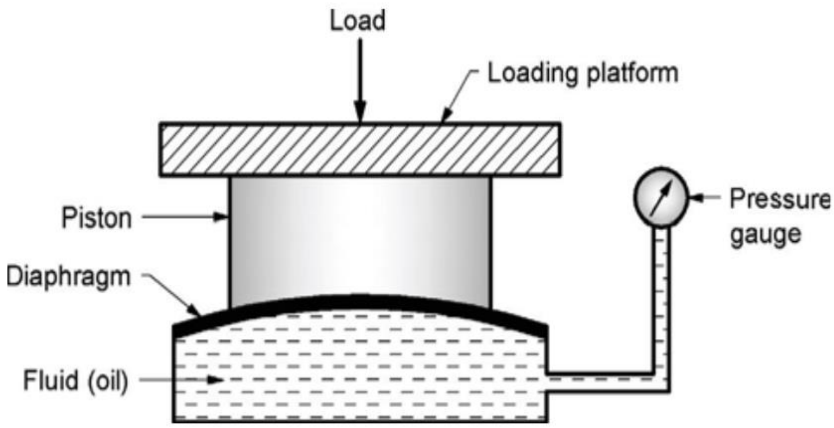

Figure 17: Schematic representation of a hydraulic load cell.

- Optical Force Sensor:
  - **Advantage**: Immune to electromagnetic interference.
  - **Applications**: Precision instruments and environments requiring electrical isolation.
  - **Principle**: Detects force via changes in a light beam (e.g., deflection or refraction angle).

Figure 18: Realistic View of the Optical Force Sensor.

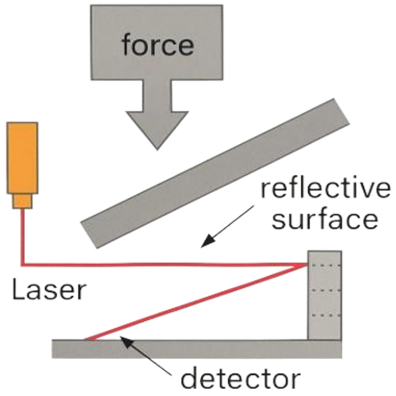

Figure 19: Schematic of the Optical Sensor's Operating Principle.

2.3.2 selection criteria:

For the purpose of measuring cutting forces during milling, a strain-gauge load cell was selected based on several technical and practical considerations. Strain-gauge sensors are widely available, cost-effective, and benefit from standardized designs, making them easily replaceable and simple to recalibrate. Their compact size and universal mounting interfaces allowed for seamless integration into our experimental setup, without requiring specialized fixturing or custom tooling.

Moreover, strain-gauge load cells provide excellent linearity and repeatability within the typical range of cutting forces encountered in milling operations. This enables accurate dynamic force measurement, which is essential for reliable data acquisition during tests.

Another key factor in their selection is their mechanical robustness. Constructed with metallic housings, these sensors are capable of operating reliably in environments with high vibrations, cutting fluid exposure, and temperature variation—conditions that are common in milling machines.
Given these features, the strain-gauge load cell was the most suitable and cost-effective solution for the objectives of our experimental work [8].

2.4 Electronic boards: data acquisition and signal processing:

2.4.1Types of Electronic Boards Used in Data Acquisition:

Several types of electronic boards are commonly used for data acquisition and signal processing in machining applications. Each type has its own strengths depending on the complexity of the system and required precision.

1. **Arduino UNO:**

Widely used in academic and prototyping contexts, Arduino is an open-source microcontroller platform. It is ideal for small-scale projects involving sensors like load cells. It supports analog-to-digital conversion via external modules such as the HX711, and provides real-time data display on LCDs.

- **Advantages:** Low cost, ease of programming (Arduino IDE), wide community support.
- **Use case in this project:** Reading amplified signals from strain gauge sensors and sending them to the LCD display.

The Figure below summarizes everything

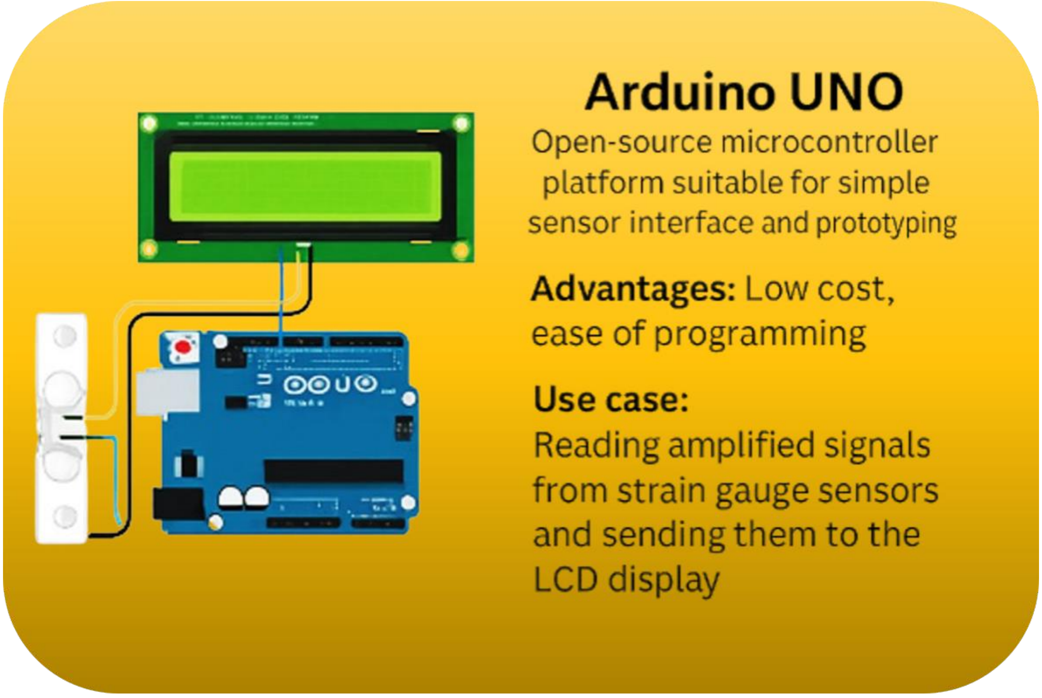

Figure 20: Schematic of the Optical Sensor's Operating Principle.

2. **NI DAQ (National Instruments Data Acquisition Systems)**
   These are professional-grade boards used for high-speed and multi-channel data acquisition. They are typically connected to a PC via LabVIEW software and are suitable for precise force, vibration, and temperature measurements.
   - **Advantages:** High accuracy, fast sampling rate, integration with LabVIEW.
   - **Use case:** Research labs and industrial setups requiring synchronized multi-sensor data acquisition.

   The Figure below summarizes everything.

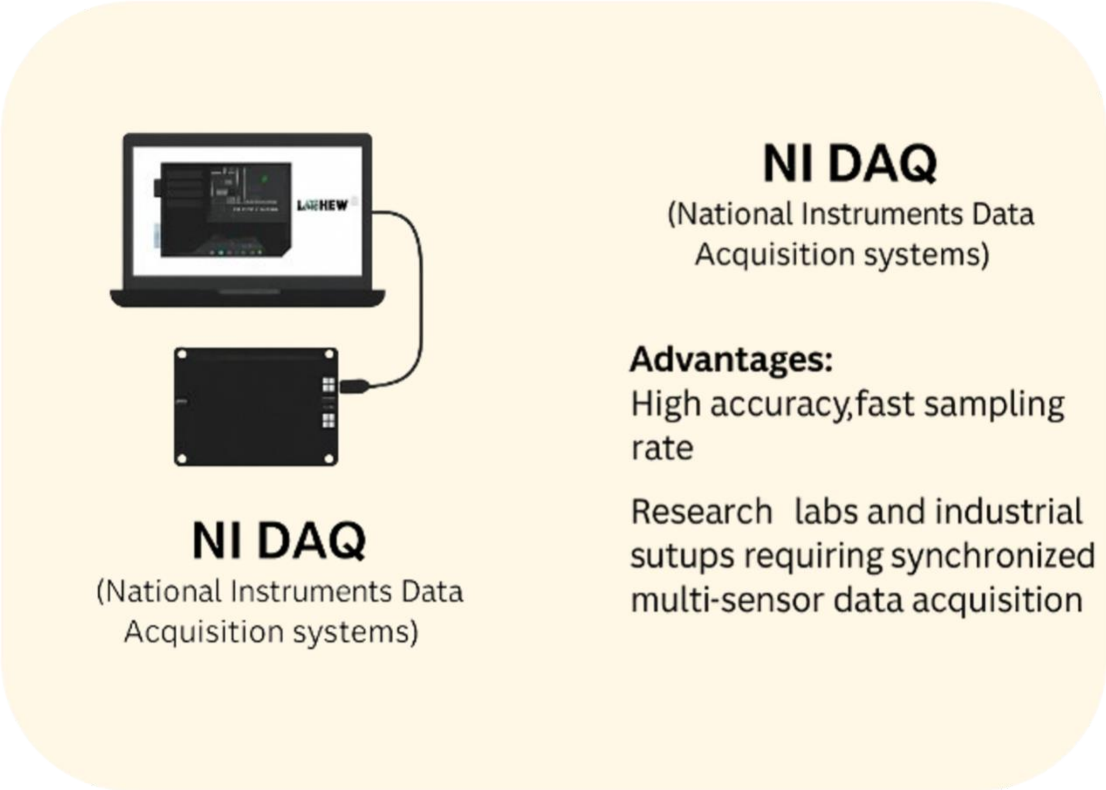

Figure 21: Overview of NI DAQ System: Visual Identification and Key Features.

3. **Raspberry Pi**
   A small single-board computer capable of more complex data processing than microcontrollers. It supports Python-based data handling, cloud connectivity, and user interface integration.
   - **Advantages:** Multi-tasking, can store and analyze large data sets, WiFi/Bluetooth capability.
   - **Use case:** Edge computing systems, cloud-based monitoring, or AI-based optimization in machining.

These boards vary in complexity, price, and performance, allowing the user to select the most appropriate platform based on project scope and precision requirements.

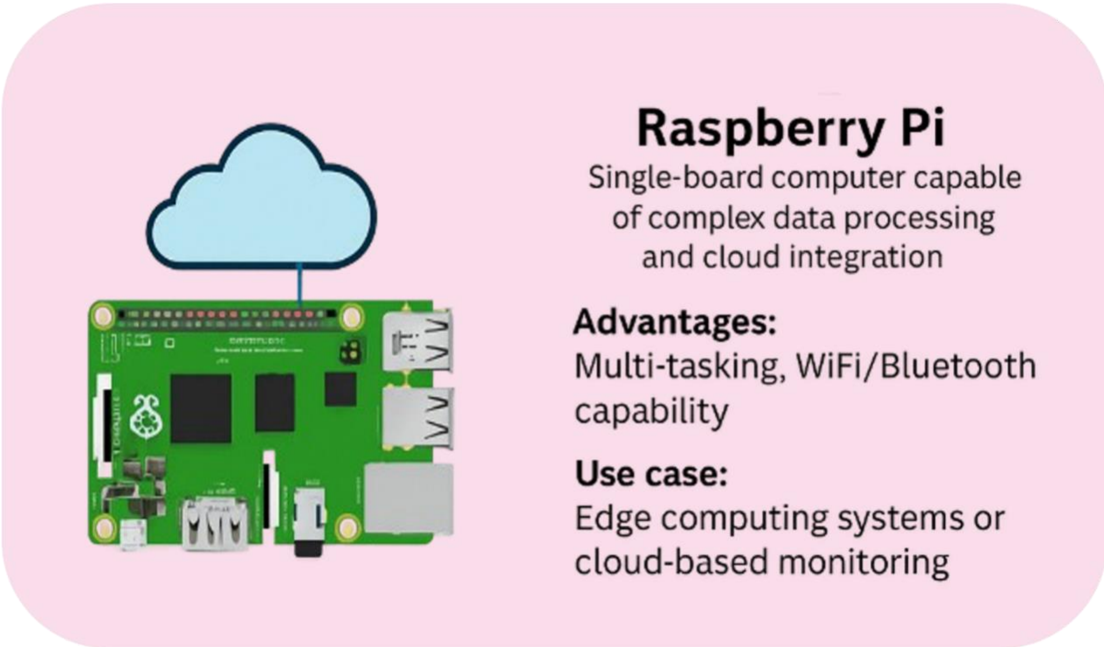

Figure 22: Raspberry Pi Board: Hardware Layout and Functional Capabilities.

2.4.2 System Components:

We developed in our project a specific electronic processing board that is tasked with acquiring information from force sensors and processing it to be displayed or logged. This is composed of a number of interconnected electronic boards, depicted in the picture:

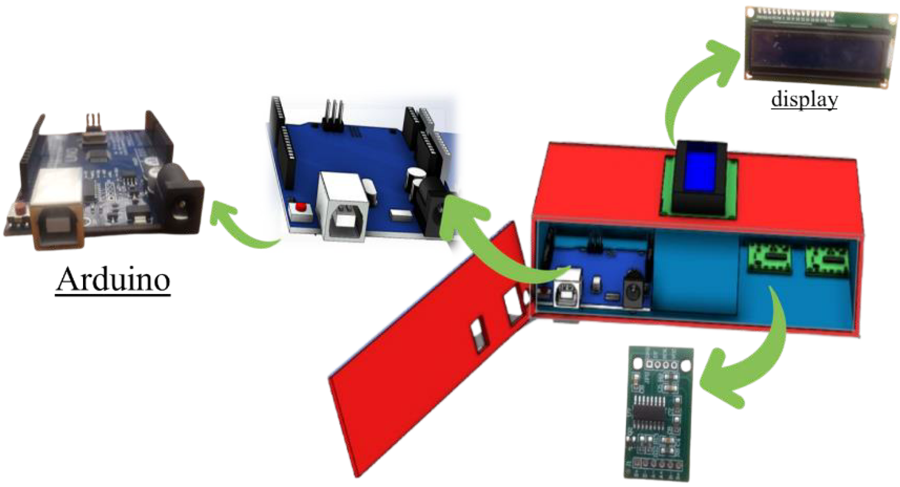

Figure 23: Electronic Data Acquisition and Signal-Processing System Architecture.

Arduino Board: Acts as the main processing unit. It takes in the analog signals from the force sensors (e.g., a load-cell with a strain gauge) and digitizes them with its onboard A/D converter so that additional software processing is enabled.

Signal Conditioning Board (HX711 Example): Because the load cell signal is quite tiny (in units of millivolts), the board is employed to amplify and enhance the signal and accuracy before it is sent to the Arduino. The HX711 module, for example, provides high-gain and 24-bit digital output.

LCD Display: Used to display measured values to the user directly. An Arduino compatible display was chosen to allow smooth integration.

Integrated Electronic Enclosure: A specially designed enclosure that accommodates and keeps the mentioned components in order. It has dedicated ports of access to allow easy handling, disassembly, and maintenance.

Connections and Power Supply: The circuit also has power connectors and a USB port to connect the Arduino to a computer or power source externally, which is shown by the direction of the arrows in the diagram.

The combined design is in complete synergy of sensing, signal processing, and visualization to offer a portable and reliable device that can measure and analyze cutting forces with accuracy.

2.4.3 Operational Workflow and Methodology:

The heart of our measurement system is a compact electronic module that integrates three main boards—a microcontroller, a precision ADC/amplifier, and a display interface—housed in a custom enclosure. First, the strain-gauge load cell produces a very small differential voltage (millivolt level) proportional to the applied cutting force. This signal is routed into an HX711 load-cell amplifier board, which provides a stable excitation to the Wheatstone bridge, amplifies the bridge output, and performs a 24-bit analog-to-digital conversion.

The digital output from the HX711 is then read by an Arduino Uno microcontroller via its two-wire data interface. Within the Arduino firmware, raw counts are calibrated against known weights, and simple digital filtering (e.g., moving-average smoothing) is applied to reduce high-frequency noise induced by the milling vibrations. The calibrated force values are further processed—converted into Newtons using the cell's sensitivity constant—and scaled for human-readable output.

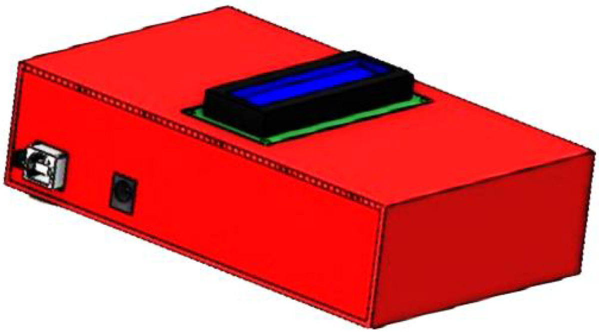

Figure 24: Data Acquisition and Signal-Processing Enclosure with Integrated LCD.

Finally, the processed force data are sent over the Arduino's parallel interface to a

16×2 character LCD module, where they are updated in real time. USB power and communication are provided through the Arduino's standard connectors, and the entire assembly is mounted in the red-printed enclosure for mechanical protection and easy integration on the milling machine. This layered architecture—sensor → signal conditioning & ADC → microcontroller → display—ensures accurate, stable, and easy-to-interpret force measurements during machining.[10]

2.5Machine tools and milling cutters used:

2.5.1Cnc vertical Machining Center:

The machining operations required to manufacture the aluminum sensor support plates were carried out on a vertical CNC milling center of model F-VMC 510L from PEARL RIVER NC, as shown in figure 24.

Figure 25: Pearl River F-VMC 510L Vertical Machining Center with Integrated Coolant Nozzles.

- Spindle speed: up to 8000 rpm (visible on the spindle marking).
- Tool holder type: ISO 30 taper.
- Built-in coolant system: Clearly used in operation, via multiple nozzles for efficient chip removal and thermal control.
- Controller interface: based on G-code, with canned cycles such as CYCLE83 for deep drilling and HOLE2 for pattern drilling.

The machine provided a rigid, precise, and reliable platform for machining 10mm thick aluminum plates with high surface finish and dimensional accuracy. [11]

Figure 25 shows various stages of the machining process, from tool engagement to chip evacuation.

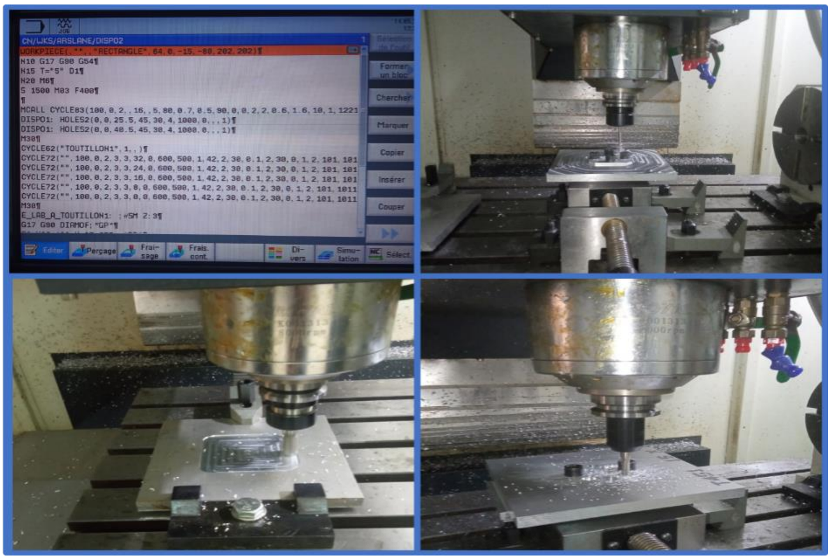

Figure 26: CNC Control Panel Displaying G-Code and Real-Time Machining Process.

2.5.2 Milling and Drilling Tools :

the following tools were employed:

Tool Type	Diameter	Material	Coating	Operation
Flat End Mill	10 mm	Solid Carbide	None	Surface facing, contouring
Flat End Mill (finishing)	6 mm	Solid Carbide	None	Pocket finishing and wall cleanup
HSS Drill Bit	5 mm	HSS	None	Pre-drilled mounting holes (M5 clearance)
Center Drill	3 mm	HSS	None	Spotting before drilling

Table02: configuration of various stages of the machining

- **Spindle Speed Used:** 1,500 rpm
- **Feedrate:** Approximately 400 mm/min
- **G-Code Example:** S1500 M03 F400 (as shown in Figure 16)
- **Canned Cycle Example:** CYCLE83(...) for deep-hole drilling
- **Control Panel Language:** French.

2.6Assembly design:

2.6.1 choice of materials:

Upper and Lower Plates: We selected the aluminum alloy type T6-6061 due to its following advantages:

1) high hardness.

2) corrosion resistance.

Load cells: they are made of aluminum to provide precise conversion of force into an electrical signal.

Fasteners: We used M5 type screws made of stainless steel, along with a steel clamp for fastening.

Arduino Enclosure: We printed it using a 3D printer.

2.5.2 dimensions:

The dimensions were designed according to the following model:

Upper aluminum plate: All dimensions are recorded according to the Figure 27 below.

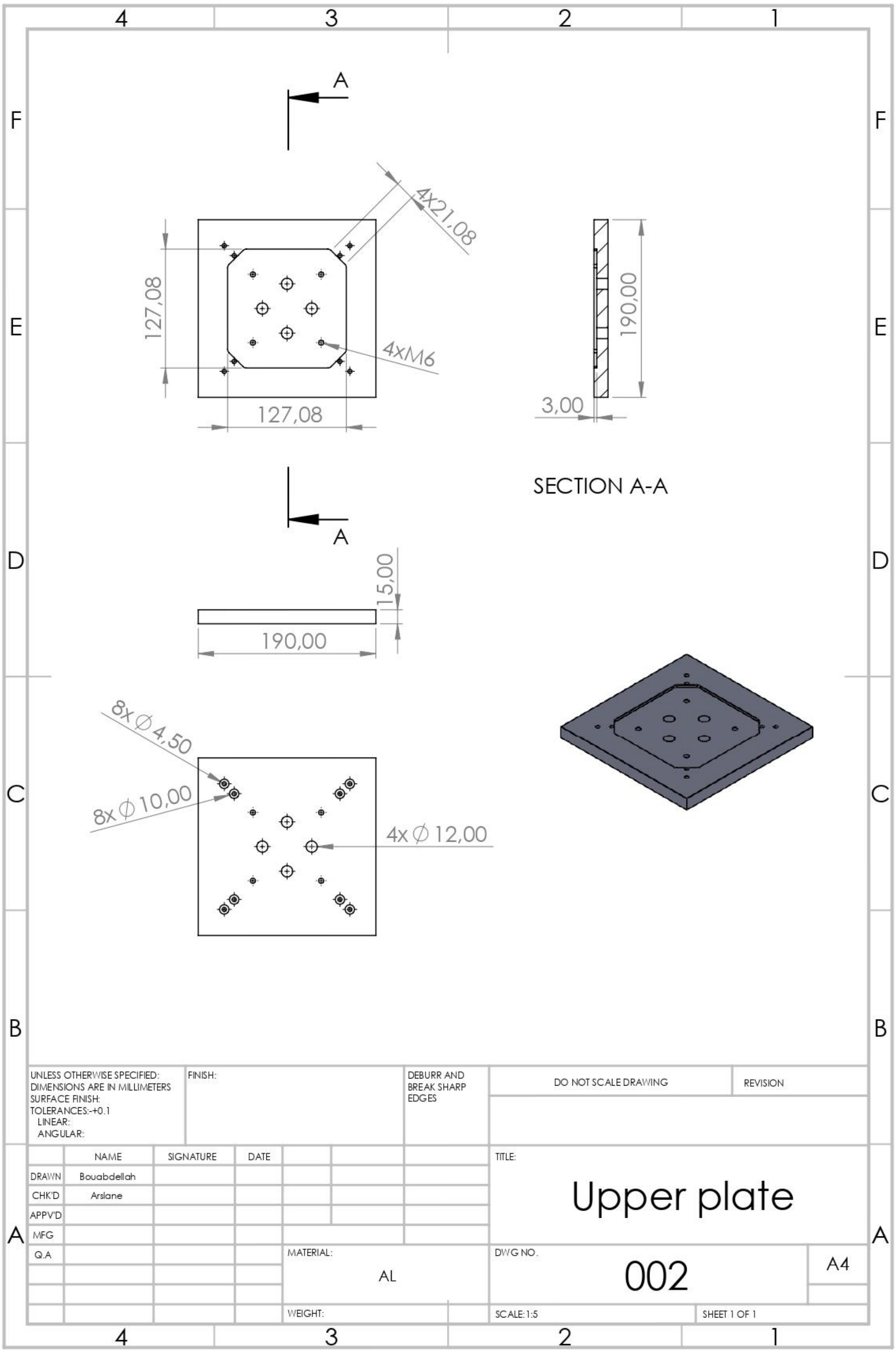

Figure 27: Standardized engineering drawing of the upper plate with dimensions

Lower aluminum plate: All dimensions are recorded according to the Figure 28 below.

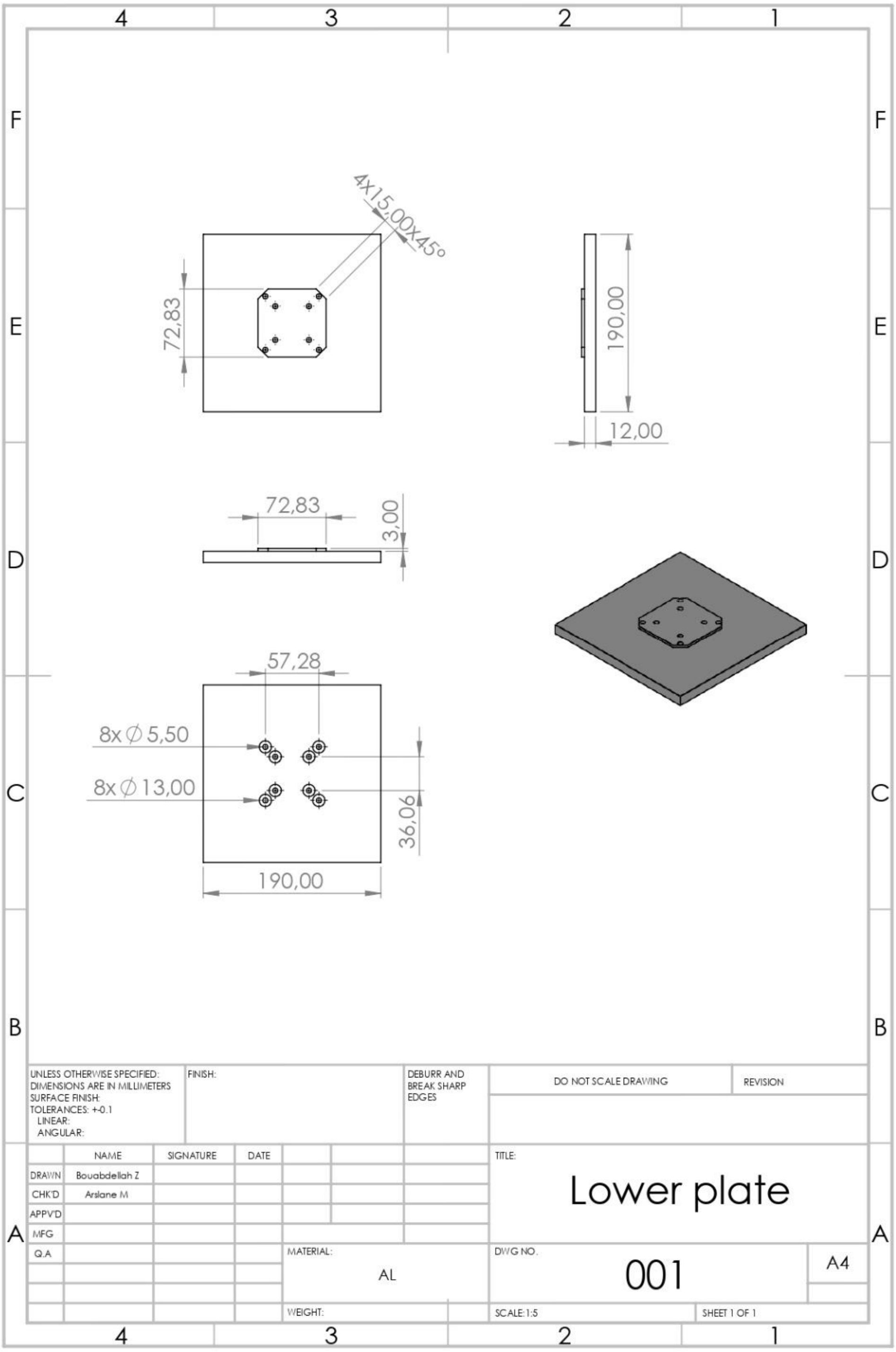

Figure 28: Standardized engineering drawing of the Lower Plates with dimensions

Arduino Enclosure: All dimensions are recorded according to the Figure 19 below.

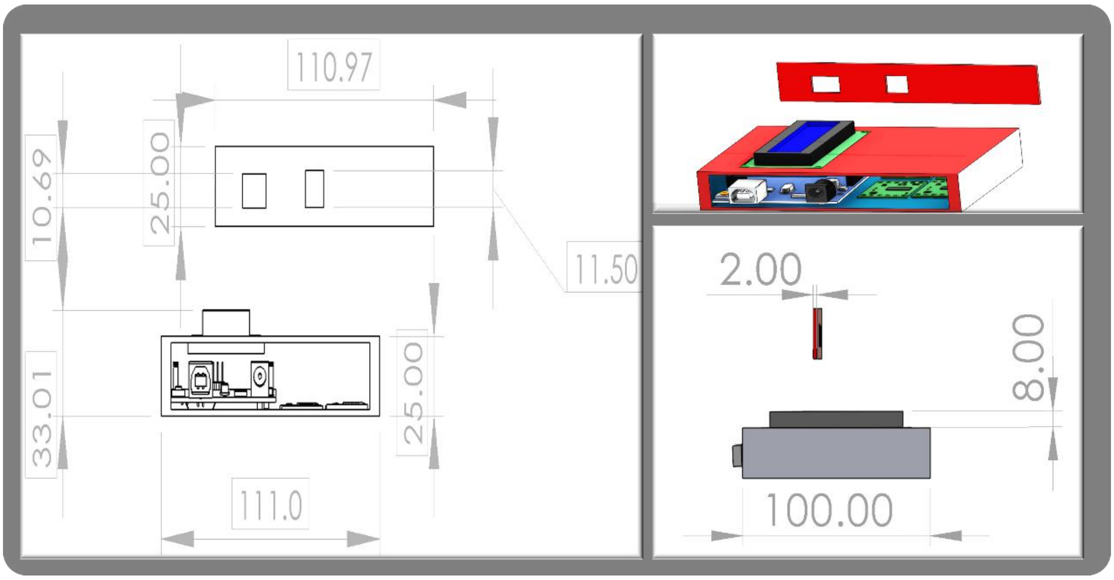

Figure 29: dimensions of Arduino Enclosure.

2.7Data analysis methods (signal processing, statistical analysis):

2.7.1 signal processing:

Raw force signals from the load cells were first offset-corrected (tare) by subtracting the no-load baseline. A fourth-order low-pass Butterworth filter (cutoff frequency 50 Hz) was applied to remove high-frequency noise induced by spindle run-out and electrical interference. For vibration signals, a band-pass digital filter (100–500 Hz) isolated the dominant chatter frequencies. Both force and vibration data were down-sampled to 200 Hz after filtering to reduce data volume without losing relevant frequency components. A moving-average window of 50 samples smoothed transient spikes. Fast Fourier Transform (FFT) analysis was then performed on 5-second time windows (Hann window) to identify dominant frequency peaks associated with chatter and tool-pass impacts [10][12][6].

2.7.2 statistical analysis:

The acquired cutting force signals were statistically analyzed to evaluate the measurement stability and the influence of machining parameters. Descriptive statistics—including the mean, standard deviation, and coefficient of variation—were calculated across three repeated trials for each cutting condition. An analysis of variance (ANOVA) was performed to assess the effect of spindle speed and feed rate on the average cutting force values. The level of statistical significance was set at $\alpha = 0.05$. Post-hoc Tukey tests were used to identify which parameter levels differed significantly in terms of cutting force magnitude. These statistical insights contribute to a better understanding of the system's repeatability and support the determination of optimal cutting parameters.

Chapter 3:

Assembly Implementation

3.1 Fabrication of Aluminum Support Plates:

The manufacturing of the aluminum support plates was carried out using a CNC vertical milling machine, specifically the **F-VMC 510L** model from **PEARL RIVER NC**. The fabrication process involved two main components: the **bottom plate** and the **top plate**, which were produced in separate stages to ensure precision. This sequence is illustrated in the figure 29 below, showing the intermediate steps of the machining process for both plat

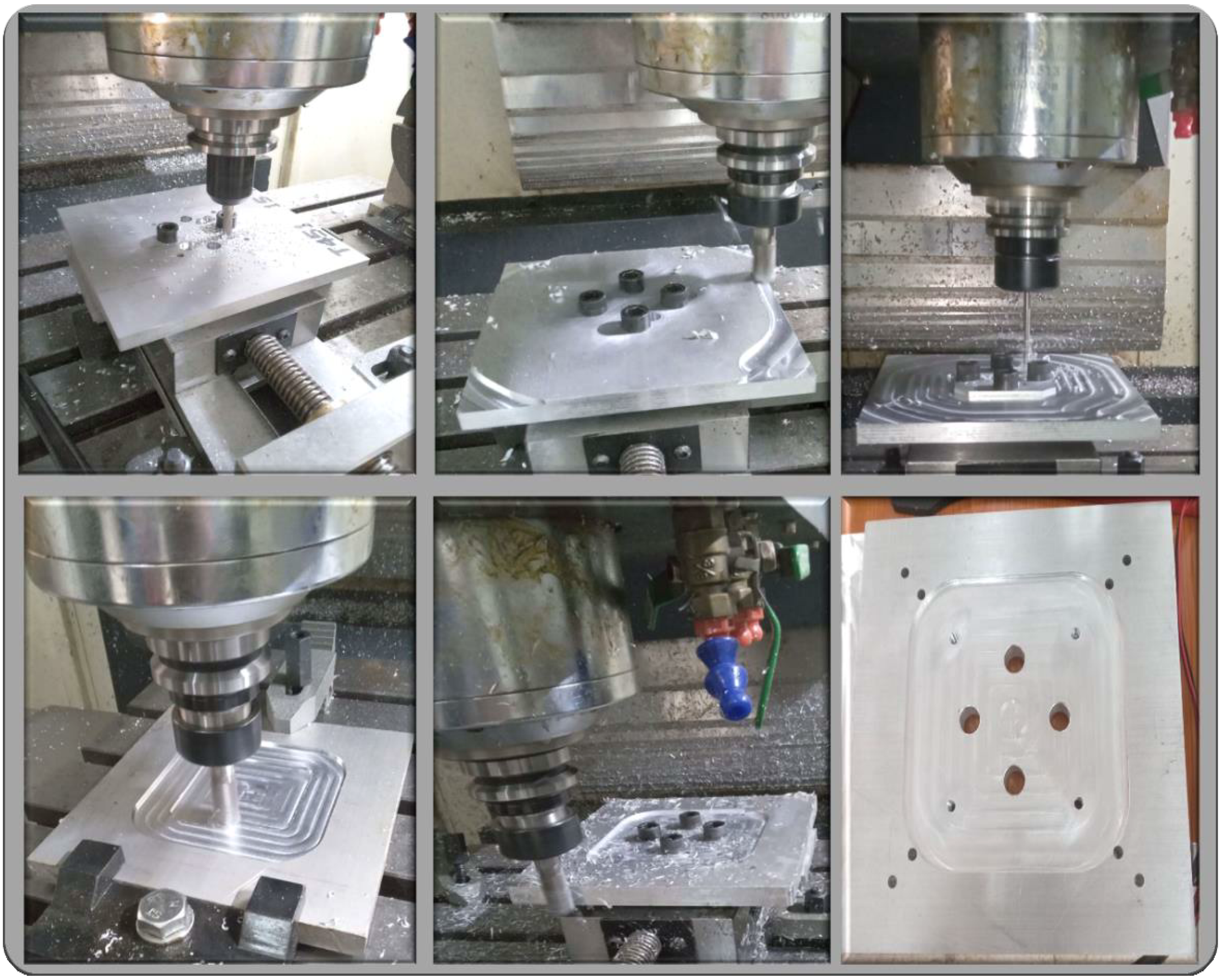

Figure 30: Machining steps of the lower and upper aluminum plates.

The design of the plates was based on a 3D model created using **SolidWorks**, which enabled accurate positioning of the holes and mounting surfaces required for the load cells. The SolidWorks assembly model served as a reference to determine the plate geometry, hole placement, and structural alignment to ensure full mechanical integrity.

Special attention was given to aligning the plates and fixing the sensors symmetrically. The load cells were distributed evenly and bolted securely between the plates to ensure uniform load transmission. Additional care was taken during the drilling and finishing stages to avoid any deviation or misalignment, which could compromise the accuracy of the measurements.

Finally, the fully assembled system including the plates, sensors, and wiring is shown in the figure 30 below. This configuration represents the final physical integration of the designed components, ready for experimental testing and data acquisition.

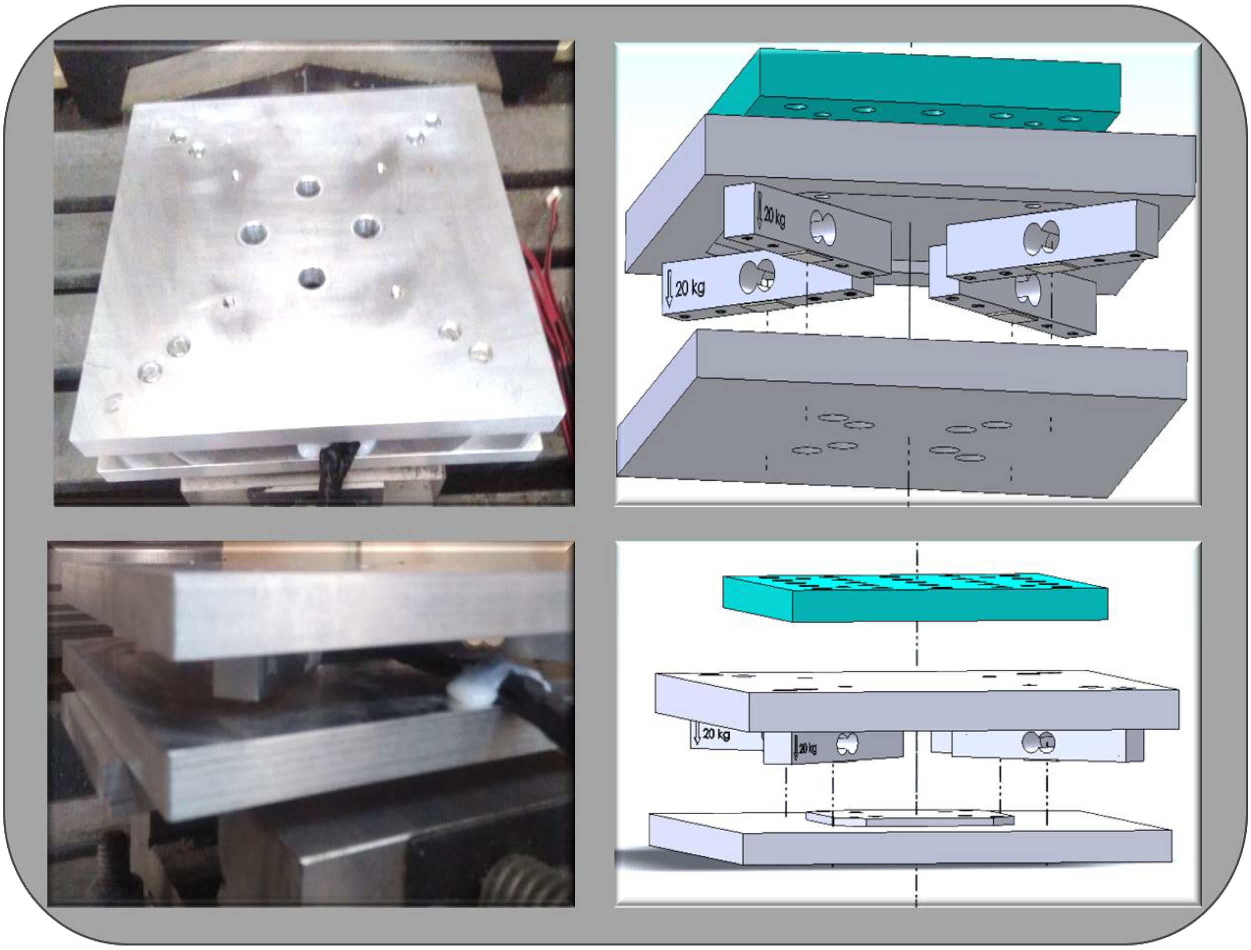

Figure 31: Final assembled structure of the sensor support system.

3.2 Sensor Mounting

3.2.1 Installation of force sensors on the plates.

The four load cells were positioned in an "X" formation between the two plates for symmetric loading. The sensors were screwed into the aluminum base plate directly through respective holes to secure them well and minimize any movement during usage. Cables were guided externally and plugged into a special data acquisition system

(Arduino + HX711 module). Sensors were mounted on the lower plate, whereas loads were applied through the upper plate during the milling or the calibration process.

All the previously described elements are summarized in the figure 31 below.

Figure 32: Installation of force sensors.

3.2.2 Calibration of the sensors for accurate measurements:

To ensure accurate force measurements, the strain-gauge load cells were calibrated before being used in milling tests. The calibration process involved applying known reference weights to the aluminum structure where the sensors were mounted. Each applied force generated a small analog voltage output from the load cell, typically in the millivolt range. These signals were then amplified using the HX711 24-bit analog-to-digital converter and read by the Arduino Uno.

All the previously described elements are summarized in the figure 32 below.

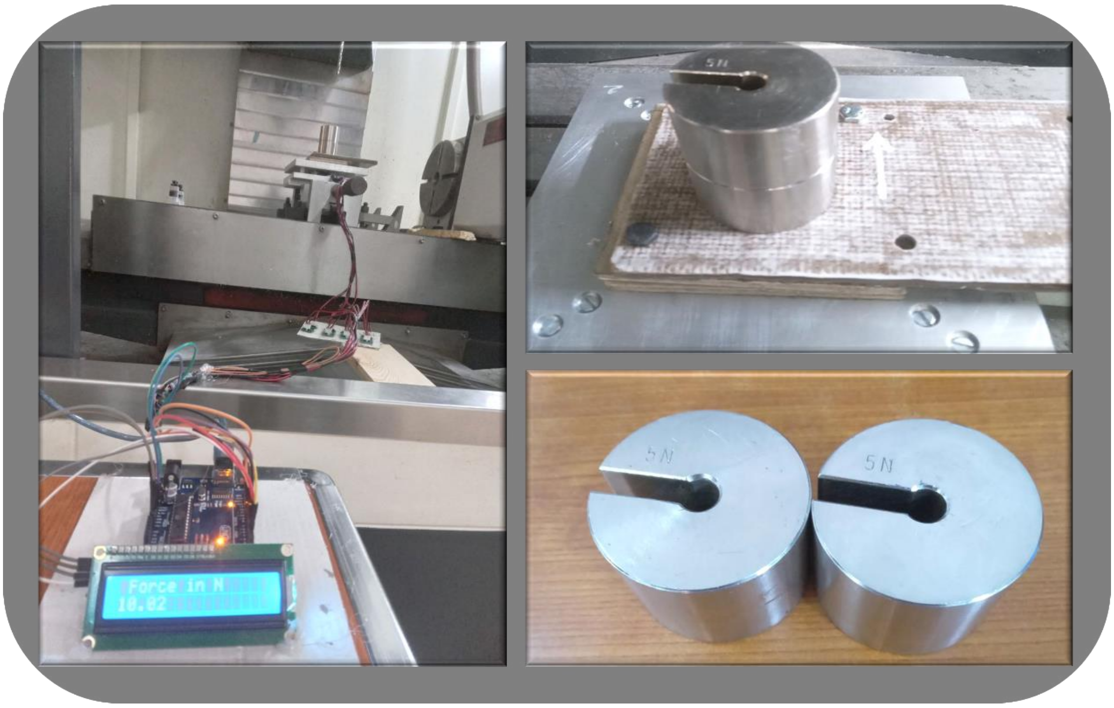

Figure 33: Calibration of the force sensors.

3.3 Electronics Assembly and Wiring:

The wiring process aimed to ensure both signal integrity and mechanical safety. Each of the four strain gauge load cells was connected to the HX711 amplifier module using insulated wires, with careful attention to wire routing and color coding. The output signals from the HX711 were then fed into the Arduino Uno, following the same pin configuration developed during the software stage.

All wiring was tested before final assembly to verify proper signal transmission, and cable lengths were optimized to avoid unnecessary slack. This careful setup ensures consistent performance of the data acquisition system during cutting force measurements.

3.4 Programming and Testing

3.4.1 Development of software for data acquisition and processing:

due to the lack of prior experience with Arduino programming, the task of developing the data acquisition and processing software was carried out by the supervising professor. The professor was responsible for writing the Arduino code necessary to read sensor values, calibrate the measurements, and transmit the data to a computer for further processing or visualization.

The developed program included the following functionalities:

- Reading analog signals from the force sensor and converting them into digital values.

- Calibrating the acquired values based on predefined reference data.
- Transmitting the data via the serial port to the computer.
- Ensuring stable and continuous operation of the system during experimental testing.

Although the programming was not directly performed by the researcher, the general structure and functioning of the code were studied and understood for documentation and analysis purposes.

3.4.2 Preliminary tests to verify proper system operation:

After completing the wiring and programming phases, preliminary tests were carried out to verify the system's global functionality. These tests focused not on sensor calibration—which was already addressed in section 3.2.2—but rather on evaluating the system's responsiveness and data stability under real-time operation.

The LCD display was observed while applying small, random loads by hand or placing objects of unknown mass. The system responded consistently, showing force variations without lag or erratic behavior. Additionally, no disconnection or electrical noise was noticed, confirming the robustness of the wiring and the reliability of the software loop.

3.4.3 Adjustments and assembly optimization:

enhance the system’s stability and accuracy. These included improving the mounting of the sensors to ensure firm contact and minimize unwanted vibrations, as well as reorganizing the wiring to reduce electrical interference and enhance signal quality. Additionally, the electronic boards were more securely fixed within the metallic structure to minimize movement and noise caused by operational vibrations.

3.5 Final Validation Test on Jute Epoxy Composite Workpiece

To evaluate the performance of the developed force measurement system, a final validation test was conducted using a **jute epoxy composite workpiece**, a material classified under *composite materials*. The setup involved positioning the device beneath the test specimen and drilling 25 individual holes while recording the corresponding cutting force values.

This test aimed to verify the system’s sensitivity, consistency, and peak response under dynamic cutting conditions. For each hole, the highest cutting force value was extracted and tabulated for analysis. These peak values were used to assess the device’s ability to detect significant load variations accurately.

As shown in the two images below, the first image illustrates the test setup with the jute epoxy plate mounted on the measurement device, while the second presents a summary of the recorded force data in tabular format.

Figure 34: illustrates the test configuration with the wooden plate mounted on the device.

hole 25	hole 24	hole 23	hole 22	hole 21	hole 20	hole 19	hole 18	hole 17	hole 16	hole 15	hole 14	hole 13	hole 12	hole 11	hole 10	hole 9	hole 8	hole 7	hole 6	hole 5	hole 4	hole 3	hole 2	hole 1
0	0	0.01	0	0	0	0	0	0.01	0.07	0	0.01	0	0.02	0	0.02	0.01	0	0.01	0	0.03	0	0	0	0.03
2.49	6.53	20.71	0.01	1	0.03	7.19	0.02	11.21	0.27	0.4	14.89	17.18	5.88	5.36	21.61	1.53	12.97	0.09	7.27	3.11	4.64	2.29	3.44	0.04
14.18	16.08	11.27	0.25	14.65	13.99	22.83	20.65	21.03	11.71	24.61	24.2	22.54	19.55	13.71	24.31	26.57	24.27	11.85	10.98	28.02	27.72	18.41	15.48	0.02
0	0.02	0	22.27	17.96	15.43	0.94	19.04	15.47	17.59	10.62	2.9	6.37	20.9	17.27	1.21	23.59	22.07	20.68	16.38	27.52	25.36	25.06	18.65	0.02
	0		18.39	15.63	0	0	0.59	0.08	15.67	0	0	0	13.27	15.01	0	9.27	13.07	19.5	18.05	25.97	24.26	23.24	20.26	0.03
			0	11.83			0	0	15.5				0	15.44		0	0	19.75	16.78	20.71	24.95	23.23	20.83	5.83
				0					11.74					13.67				16.73	15.45	2.13	9.99	22.88	20.22	11.41
									1.15					9.64				2.56	17.7	0	0.89	20.58	20.55	13.12
									0					2.35				0	14.13		0	7.62	18.83	15.52
														0					13.1			0	18.96	17.78
																			9.26				17.98	21.36
																			3.57				8.42	16.84
																			0				3.48	20.69
																							0	17.81
																								18.29
																								18.08
																								17.39
																								17.18
																								17.32
																								15.39
																								14.31
																								15.86
																								13.03
																								13.29
																								8.62
																								6.34
																								3.87
																								2.45
																								0

Figure 35: presents the recorded force data in tabular format.

3.6 Data Visualization:

To better understand the performance of the developed force measurement device, the maximum cutting force recorded for each of the 25 drilled holes was extracted and visualized. Instead of using average force values, the highest value recorded during each drilling operation was selected to reflect the peak load encountered.

This approach allowed a clearer evaluation of the system's ability to detect force peaks and transient changes during the cutting process. The figure below illustrates the variation of maximum cutting forces with respect to hole number. The trend shows how forces fluctuate across different drilling points, confirming the system's sensitivity and consistency under variable load conditions.

As shown in the figure below, each data point represents the peak force value in Newtons for its corresponding hole. This visualization serves as a valuable tool for performance validation and future optimization efforts.

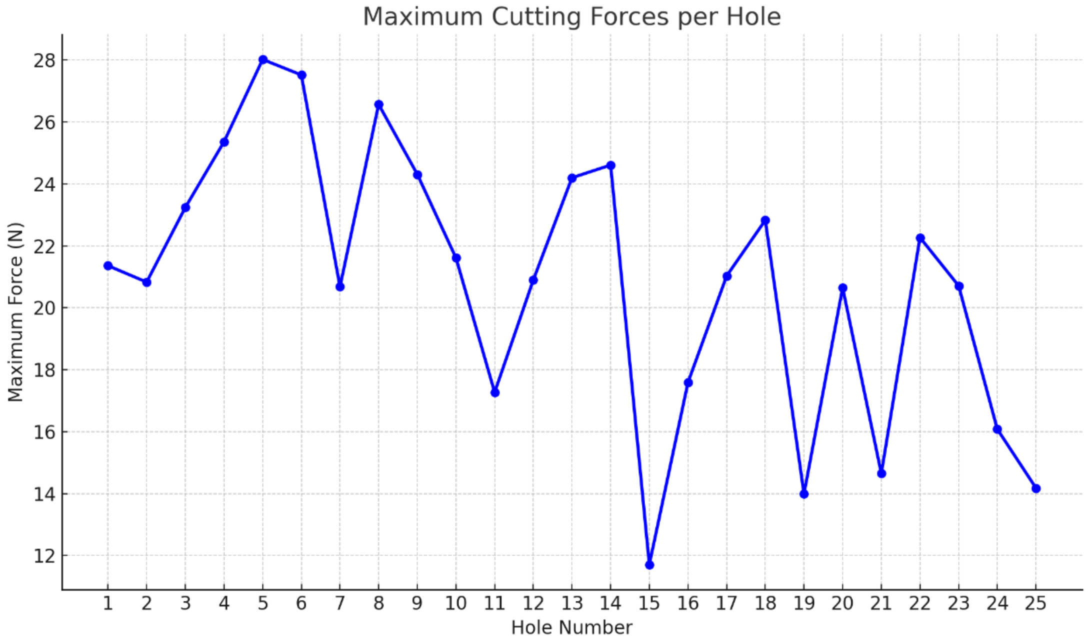

Figure 36: Peak Cutting Force per Hole

3.7 Justification of the Validation Material:

The validation tests were conducted on a composite material known as jute epoxy, which consists of natural jute fibers embedded in an epoxy resin matrix. This material was chosen due to its increasing relevance in lightweight structural applications where sustainability, low cost, and moderate mechanical strength are desired.

Chapter 3

Jute epoxy composites are widely studied for machining analysis because they provide a unique combination of non-uniform fiber distribution, heterogeneous stiffness, and sensitivity to thermal and mechanical loads, which make them suitable for validating force measurement systems. These characteristics make the material a meaningful candidate for experimental validation, as it introduces real-life challenges such as fluctuating forces and material inconsistencies.

The selection of this material allows a more realistic evaluation of the device's ability to measure cutting forces in complex, fiber-reinforced materials, which are increasingly used in modern manufacturing sectors such as automotive, aerospace, and eco-friendly construction.

3.8 Selection Criteria for Peak Force Values:

During the drilling test, multiple force values were recorded per hole due to the dynamic nature of the process. Instead of calculating average values, the **maximum force value** per hole was extracted to serve as the key performance metric.

This choice was motivated by the fact that the **peak cutting force** reflects the moment of highest mechanical stress exerted on the tool and the workpiece. In real industrial applications, it is often these peaks that cause tool wear, vibration, or even system failure. Therefore, focusing on peak force values provides a more **conservative and safety-driven evaluation** of the system's performance.

Using peak values also allows for better comparison and visualization, as it highlights extreme conditions the system must handle, and ensures the robustness of the developed device under load variations.

3.9 Interpretation of the Curve:

The plotted curve of maximum cutting forces per hole provides critical insights into the behavior of the machining process and the performance of the measurement system. The force distribution across the 25 holes shows noticeable variation, with peak forces ranging between approximately 6 N and 28 N.

This variation may be attributed to material inhomogeneity, slight differences in tool positioning, or local fiber orientation within the composite. The curve confirms that the system is capable of detecting transient force changes and capturing relevant data at every drilling event.

The consistency in force patterns for certain sections (e.g., holes 3–10) and the presence of drops (e.g., hole 24–25) also suggest that the system responds sensitively and in real time, thus validating its accuracy and reliability for force acquisition tasks.

3.10 Limitations and Perspectives:

Although the developed force measurement system has demonstrated satisfactory performance in terms of sensitivity, stability, and response time, several limitations remain, along with promising avenues for future improvement.

Technical Limitations:

The current system is designed to measure cutting forces lower to 800 Newtons, which is sufficient for light to medium machining operations. However, this range may not be adequate for high-force industrial processes, such as heavy-duty milling or turning.

Functional Limitations:

At present, the system is limited to measuring only one physical quantity — cutting force. It does not yet support the simultaneous acquisition of other relevant parameters such as temperature and vibrations, which also significantly affect machining performance and tool life.

Future Perspectives for Improvement:

At present, the system is limited to measuring only one physical quantity — cutting force. It does not yet support the simultaneous acquisition of other relevant parameters such as temperature and vibrations, which also significantly affect machining performance and tool life.

Future Perspectives for Improvement:

To overcome these limitations and enhance the system's versatility, several improvements are proposed:

- Integration of additional sensors to measure vibrations (e.g., triaxial accelerometers) and temperature, enabling a multiparametric monitoring approach.
- Extension of the measurable force range through the use of more robust or multi-axis load cells.
- Incorporation of wireless data acquisition modules (Bluetooth, Wi-Fi) for real-time monitoring on CNC machines.
- Development of a more advanced software interface, featuring graphical visualization, real-time data plotting, and automated export functions.

These enhancements would significantly expand the system's applicability in smart manufacturing environments, allowing its use in predictive maintenance, process optimization, and real-time quality control.

General Conclusion

This Master's thesis focused on the design, development, and validation of a practical and cost-effective system for measuring cutting forces during machining processes. The work led to the successful implementation of a device capable of acquiring and displaying force values in real time, using an Arduino-based architecture and strain-gauge load cells.

The system specifically targeted the measurement of cutting forces during drilling operations, a process where forces can fluctuate significantly due to tool-material interactions, chip formation dynamics, and material heterogeneity. The experimental tests, conducted on a jute epoxy composite workpiece, confirmed the system's ability to detect and analyze peak forces generated during each drilling cycle. The device demonstrated good sensitivity, repeatability, and stability under real machining conditions.

The adopted methodology combined mechanical manufacturing, sensor integration, signal processing, and embedded programming, offering a multidisciplinary platform that meets the requirements of Industry 4.0. By focusing on drilling forces, the project addressed a crucial aspect of tool monitoring and process optimization, with potential applications in tool wear detection, quality control, and predictive maintenance.

Despite the system's successful performance, several limitations were identified, including the lack of vibration or temperature measurements and a limited force range. Future improvements could include integrating additional sensors, expanding wireless capabilities, and enhancing the software interface for advanced data visualization and analysis.

This work provides a solid foundation for real-time monitoring of cutting forces in drilling and opens the door for further research into intelligent machining systems and smart manufacturing solutions.

References

1-Merchant, M. E., 1945. (n.d.).

2-Drilling. (n.d.). Retrieved from https://www.mmc-carbide.com/permanent/courses/81/drilling-forces.html#:~:text=For%20drilling%20only%202%20forces,are%20experienced

3-Oxley and Enahoro, 1966. (n.d.).

4-Kalpakjian, S. & Schmid, S. R., Manufacturing Engineering and Technology, 7th Edition, Pearson, 2014. (n.d.).

5-International Journal of Machine Tools and Manufacture. (n.d.).

6-Kumar, A. &. (2020). Design and Development of a Low-Cost Dynamometer using Arduino. *International Journal of Scientific & Engineering Research*.

7-Mechanical Properties of Aluminum Alloys. (n.d.). Retrieved from https://machiningconcepts.com/mechanical-properties-of-aluminum-alloys

8-Fraden, J. (2010). *Handbook of Modern Sensors: Physics, Designs, and Applications.* New York.

9-cells, h. l. (n.d.). Retrieved from https://studybookpage.com/hydraulic-load-cell/

10-Arduino Uno Technical Specifications. (n.d.). Retrieved from https://docs.arduino.cc/hardware/uno-rev3

11-NC, P. R. (n.d.). *6-F-VMC 510L CNC Machining Center Specifications*. Retrieved from https://pearlrivernc.com/f-vmc-510l-specifications

12-Inc., M. T. (2020).*8-HX711 Datasheet – 24-bit ADC for Weigh Scales*. Retrieved from https://www.microchip.com/en-us/product/HX711