**Thesis of the second year internship project**

To obtain the State Engineering Diploma

*Major: Autonomous Robotics*

# Real-Time Robotized Spine fusion Testing with UR5e System


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# Dedicated to

*To the W who stood by me during the challenging moments*

*To the two A's and N to whom I owe my life*

*To H... and all the unseen guardians whose love and guidance have shaped my life.*

M.

# Acknowledgments

Thank you, Dr. McGilvray, for providing me the opportunity to immerse myself in such a rich and dynamic environment. Thank you M. JOCHUM for your efforts in securing this internship. And a special thanks to Christian-Joël for being there alongside me. Lastly, I wish to express my heartfelt gratitude to Dr. Christian Puttlitz, head of the mechanical department, whose guidance and support were instrumental in facilitating our introduction to CSU.

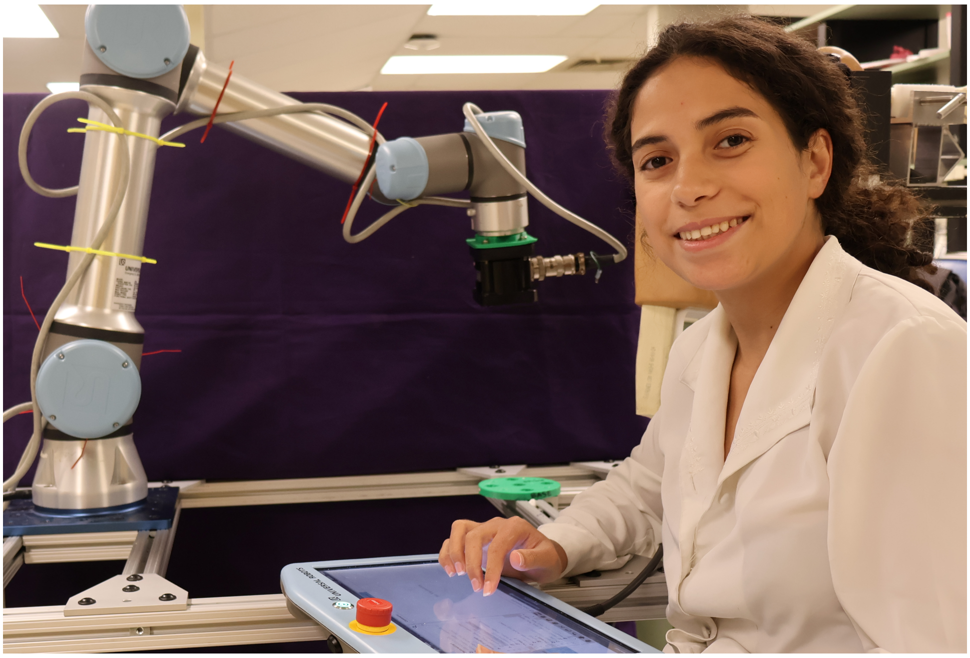

Figure 1: Working closely with advanced robotic systems provided invaluable hands-on experience in the field.

# Abstract

This project focuses on the integration and control of a UR5e robotic system for conducting orthopedic research, specifically through testing bone samples. The primary goal is to simulate pseudo loads on bone samples using real-time data to assess mechanical responses under various conditions. The project utilizes the AMTI MC3A transducer and Gen5 amplifier, alongside the UR5e robot, for precise data collection and control.

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**Key Words:** Robotic system, orthopedic research, pseudo loads, UR5e robot, force-torque sensors, AMTI transducer, real-time data.

## Résumé

Ce projet se concentre sur l'intégration et le contrôle d'un système robotique UR5e pour mener des recherches orthopédiques, en particulier à travers des tests sur des échantillons osseux. L'objectif principal est de simuler des charges sur les échantillons osseux en utilisant des données en temps réel pour évaluer les réponses mécaniques dans diverses conditions.

Le projet utilise le transducteur AMTI MC3A et l'amplificateur Gen5, en plus du robot UR5e, pour une collecte de données et un contrôle précis.

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**Mots-clés :** Système robotique, recherche orthopédique, charges pseudo-statiques, robot UR5e, capteurs de force et de couple, transducteur AMTI, données en temps réel.

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# General Introduction

In recent years, robotics and automation have increasingly revolutionized various fields, from industrial manufacturing to healthcare. Among these advancements, the development of precise and reliable robotic systems for biomechanical testing has become a focal point in both academic research and practical applications.

This report details my internship experience at the Orthopeadic bioengineering research laboratory OBRL at Colorado state university, where I had the opportunity to contribute to a new project aiming at enhancing spinal fusion testing methodologies through the integration of advanced robotics.

The purpose of this internship was to explore and implement solutions that would transition the current manual spine testing process to a robotic-assisted system. The ultimate goal is to find alternatives of biomechanical tests, which are crucial for understanding spinal mechanics and developing treatments for spinal disorders.

Throughout this internship, I was involved in several key activities, including the real-time reading of force-torque sensors, the programming of robotic movements, and the testing of spinal models using these robotic systems, and dissections of ovins. This report will provide an in-depth overview of the project context, the objectives set forth, the methodologies employed, and the results achieved. Additionally, it will discuss the challenges encountered during the project and the steps taken to overcome them.

By the end of this report, readers will have a comprehensive understanding of the progress made towards the automation of spine testing and the future prospects of this research. The work presented here not only contributes to the advancement of robotic testing technologies but also serves as a stepping stone towards more innovative solutions in the field of biomechanics.

# Chapter 1

# General Project Context

## Introduction

Orthopaedic biomechanics is essential for enhancing the treatment of musculoskeletal disorders. This project focuses on the integration and control of a UR5e robotic system for conducting spine testing. By integrating the AMTI SDK and RTDE protocol, we aim to simulate pseudo loads on bone samples. This chapter outlines the project's context, motivations, challenges, and potential impact on clinical practice and biomechanical research.

## 1.1 Presentation of The OBRL at CSU

### 1.1.1 Laboratory Overview

Figure 1.1: Laboratory logo

The Orthopaedic Bioengineering Research Laboratory (OBRL) at Colorado State University is a multi-disciplinary research facility dedicated to advancing the understanding of orthopaedic tissues in their normal, diseased, and treated states. The laboratory employs advanced experimental and computational methods to investigate the biomechanics and mechanobiology of orthopaedic tissues. [3]

### 1.1.2 Organizational Chart

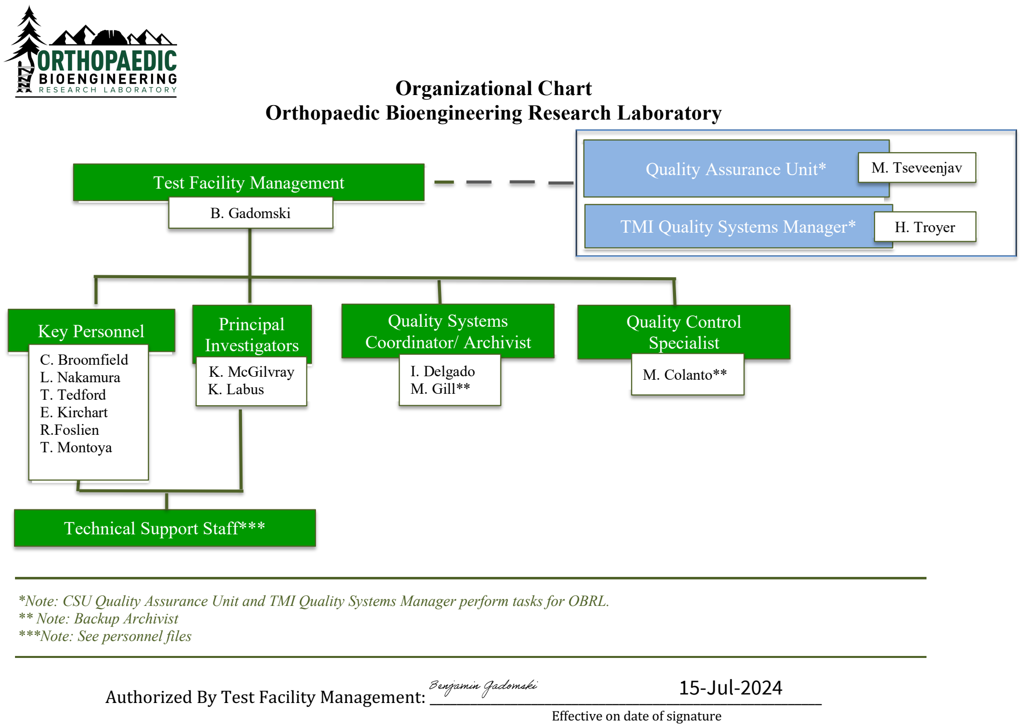


Figure 1.2: Organizational Chart

### 1.1.3 Research Focus

The OBRL focuses on several key research areas, including:

- Evaluation of a Titanium-Polyether-Ether-Ketone-Electromechanical Polymer (Ti-PEEK-EMP) Spinal Interbody Cage for Spine Fusion: Lumbar fusion is the standard of care for lumbar degenerative disease that can't be managed medically. This surgical technique involves the fusion of two or more vertebrae, using an implant (e.g, spinal cage) as a supportive scaffold for bone ingrowth, to achieve spinal stability and alleviating symptoms related to degenerative issues, such as disc degeneration, spinal stenosis, or spondylolisthesis

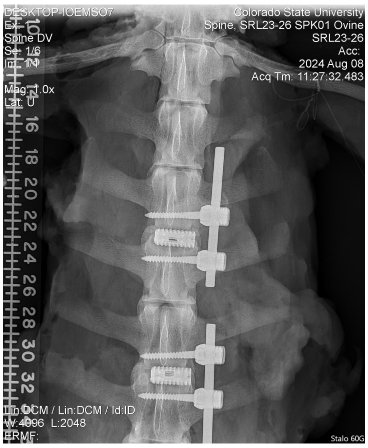


Figure 1.3: Radiograph of a lumbar interbody fusion model.

In this context, and pertinent to my project, the laboratory conducts various tests on spinal tissues to assess the effectiveness of vertebral fusion. These tests are crucial for developing improved clinical treatments and enhancing patient outcomes.

### 1.1.4 Facilities and Capabilities


Figure 1.4: Servohydraulic axial testing system

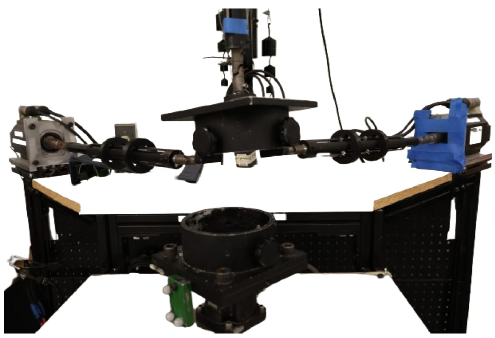

Figure 1.5: spine tester

To support these research activities, the laboratory is equipped with a Servohydraulic axial testing system, the MTS MiniBionix Model 858 (1.3), which applies axial forces to the spine, and a spine tester (1.5) capable of applying rotational movements, including flexion/extension, lateral bending, and axial rotation. The lab also utilizes motion capture cameras for precise tracking of spine movements during testing, complemented by software that analyzes data from both the cameras and the force/torque (F/T) sensor integrated into the spine tester. Traditionally, these machines have offered a very limited range of testing capabilities.

To streamline this process and improve efficiency, the laboratory acquired a Universal Robot UR5e. This acquisition is where my project originates, with the aim of utilizing the robot to automate bone testing procedures, thereby reducing testing time, and expanding the range of possible tests beyond the traditional limitations. By integrating the robot with the existing motion capture cameras, the system will allow for more comprehensive and precise data collection during spine tests.

### 1.1.5 Collaborative and Interdisciplinary Approach

The OBRL operates adjacent to the Translational Medicine Institute and Veterinary Teaching Hospital, fostering a collaborative and interdisciplinary environment. This proximity enables the integration of veterinary and medical sciences with bioengineering research, enhancing the laboratory's capability to translate findings into clinical applications.

By conducting rigorous biomechanical testing and collaborating closely with clinical partners, the OBRL aims to translate these research findings into practical, human clinical applications. This includes optimizing surgical techniques, enhancing the design of spinal implants, and ultimately improving patient outcomes in spinal fusion surgeries. Through ongoing partnerships with industry, government agencies, and academic institutions.

## 1.2 Presentation of the project

The project repository can be accessed at the following URL: https://github.com/Maintihami/ur5-pseudo-load

### 1.2.1 Project Framework

This project is designed to control a robotic system for conducting tests on bone samples, primarily for orthopaedic research. The system consists of two main components:

- **Program on the Robot's Polyscope Interface:** This program controls the robot's movements based on commands and data processed by the control system. It handles the execution of predefined movement sequences and real-time adjustments.
- **Control and Data Acquisition Program on PC:** This program runs on a computer, gathering data from force-torque sensors and adjusting the robot's trajectory in real-time. The adjustments are based on the detected forces to simulate various load conditions on bone samples.

The system allows for the simulation of pseudo loads on bone samples, driven by user-defined inputs such as velocity vectors and force thresholds. The data collected are crucial for analyzing the mechanical responses of bones under these loads, which is essential for determining whether the vertebrae have fused or not. The primary tools and technologies utilized in this project include:

- **Python**: Used for developing the data acquisition and control application.
- **AMTI SDK**: Interfaces with the FT MC3A sensor to collect force-torque data.
- **RTDE Protocol**: Facilitates real-time data exchange with the UR5e robot.

The project is conducted in a controlled laboratory environment using a UR5e robot equipped with both an external FT MC3A sensor. This setup ensures precise measurement and control, enabling the development and testing of advanced data acquisition and robotic control algorithms.

### 1.2.2 Project Objectives

The primary objective of this project is to enhance the scope of bio-mechanical testing by applying controlled forces and torques to specific joints and bones across various applications. The specific goals include:

- **Simulation of Physiological Loads**: To accurately replicate various physiological loads and movement patterns, providing valuable insights into their impact on joints, such as the knee. This can aid in the development of personalized rehabilitation programs and improve patient outcomes.
- **System Integration and Validation**: To integrate the developed system into clinical settings for comprehensive testing and validation, ensuring that it meets the rigorous standards required for medical device applications.

# Chapter 2

# Reading a force torque sensor in real time

## Introduction

The UR5e robotic arm is equipped with an integrated force torque sensor. While this sensor provides a certain level of accuracy and resolution, as depicted in the accompanying figure, these specifications fall short of the stringent requirements necessary for applications in an orthopaedic environment. In such settings, higher precision and resolution are critical to ensure the safety and efficacy.

| **Force sensing, tool flange/torque sensor** | **Force, x-y-z** | **Torque, x-y-z** |
|---|---|---|
| Range | 50.0 N | 10.0 Nm |
| Precision | 3.5 N | 0.2 Nm |
| Accuracy | 4.0 N | 0.3 Nm |

Table 2.1: Performance Characteristics of the UR5e F/T Sensor [2]

Figure 2.1: Multi-axis transducer MC3A [1]

## 2.1 Integration of the MC3A-1K Force Torque Sensor

The MC3A force and torque sensor is ideal for applications requiring precise, simultaneous measurement of multiple forces and moments. It measures the three orthogonal force and moment components along the X, Y, and Z axes, providing a total of six outputs. Key features include high stiffness, high sensitivity, low cross-talk, excellent repeatability, and long-term stability. These characteristics make the MC3A suitable for use in research and development across fields such as robotics, ergonomics, production processes, biomechanics, and dynamics. The sensor is available in several capacities, including 100, 250, 500, and 1000 pounds [4].

### 2.1.1 Gen5 Amplifier

The Gen5 device uses USB communication for interfacing with the software. This communication type is handled through the Dynamic Link Libraries, which allows for sending commands and receiving data via the USB connection. The digital data stream is in a fully conditioned format, making it ready for immediate use by the software.


Figure 2.2: AMTI Gen5 Amplifier

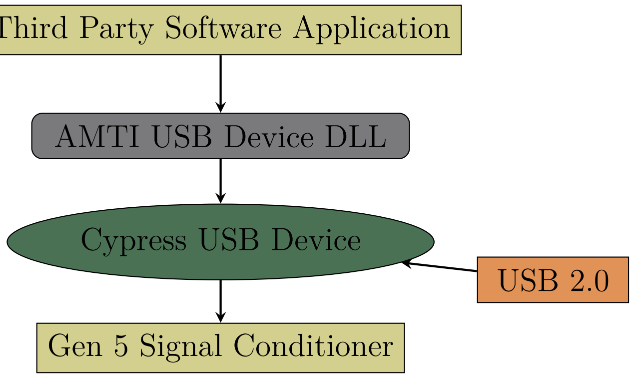


Figure 2.3: software System overview

## 2.2 Software Development

### 2.2.1 What prompted this need?

The Gen5 comes with a software called AMTINetForce, this application can plot forces and torques. I needed to use the Force vector data as an input to a pseudo load - which is basically just controlling the robot on basis of the F/T sensor output. To develop my own application, I considered integrating the AMTI Software Development Kit (SDK). There are two options, full integration or partial integration. I choosed a Full integration, which involves integrating most of the features of this SDK into the application to give the application full control of the signal conditioners

In the following, I am going to present the development and analysis of a data acquisition system using a DLL provided by the manufacturer. The objective is to collect data from the F/T sensor.

### 2.2.2 Flowchart for Data Acquisition and Analysis

For the Data Collection I choosed **the Polling method** that consist of simply polling the DLL continuously to see if data is available. The data transfer function will either give you data or return FALSE if no new data is available

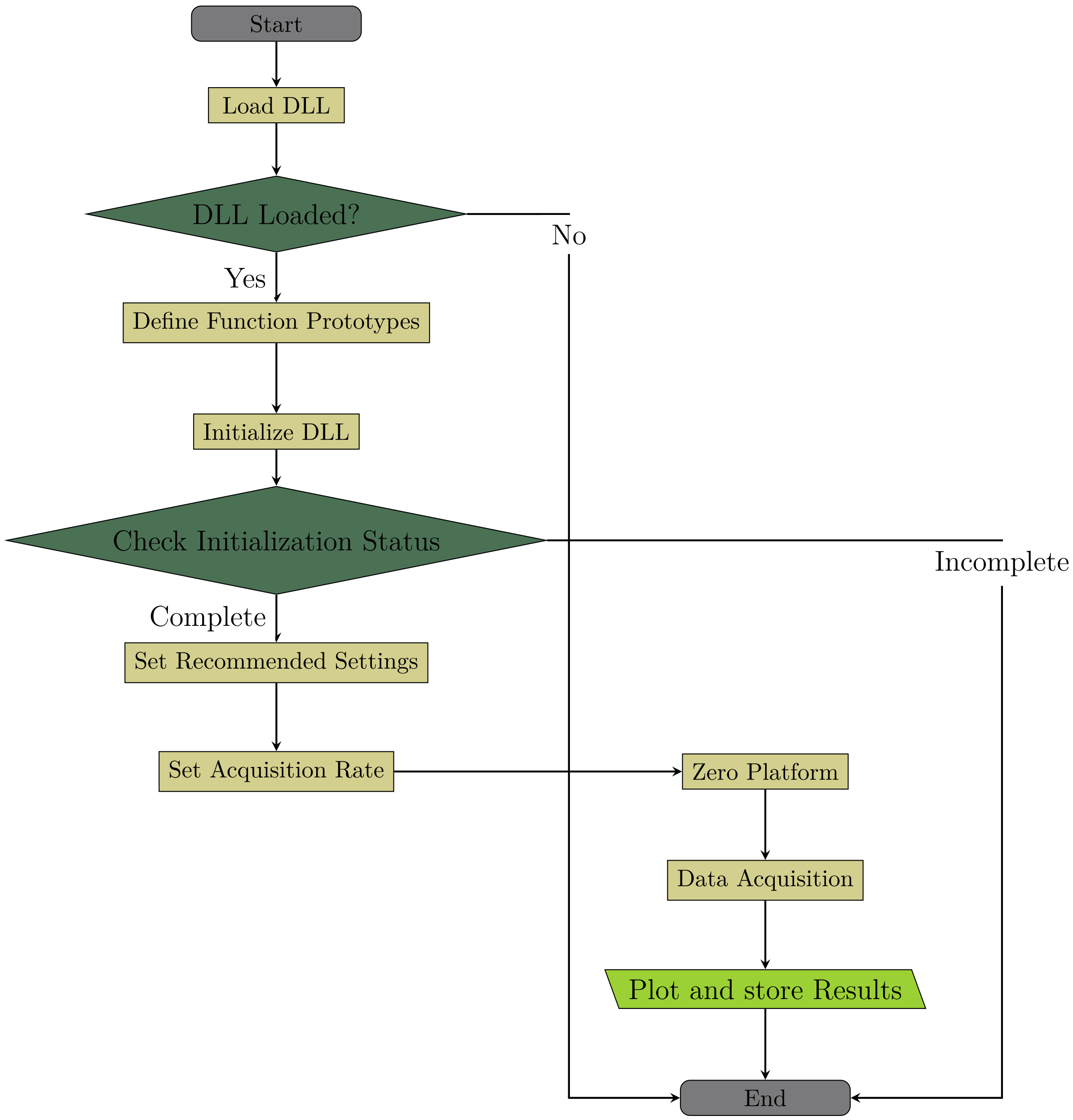


Figure 2.4: Flowchart of the Python Code for Load Cell Data Acquisition

### 2.2.3 Results

#### 2.2.3.1 Force Torque Output File

The output file, output.lvm, is formatted for compatibility with analysis software that was initially designed to process data captured by cameras alongside readings from the force/torque (F/T) sensor. However, this approach was eventually abandoned due to the ability to gather the robot's positional data without using cameras, which not only reduced the setup time but also eliminated potential issues with unsynchronized data between the cameras and the F/T sensor. As a result, an additional program is needed to calculate the stiffness. Below is an excerpt from the output file generated by the program:

```
LabVIEW Measurement
Writer_Version  2
Reader_Version  2
Separator       Tab
Decimal_Separator       .
Multi_Headings  No
X_Columns       One
Time_Pref       Absolute
Operator        PythonScript
Date    2024/08/16
Time    14:34:08
***End_of_Header***

Channels        6
Samples 16
Y_Unit_Label    N       N       N       Nm      Nm      Nm
X_Dimension     Time    Time    Time    Time    Time    Time
X0      0.0000000000000000E+0
Delta_X 0.016666666666666666
packet size: 512bytes
number of packets: 16.0
signal frequency: 100
sample frequency: 200.0
***End_of_Header***
1.0             0.00000         0.00000         0.00000         0.00000         0.00000
    ↪          0.00000
...
20.0            -0.02225        0.08748         -0.14555        0.00000         0.00080
    ↪          -0.0031
21.0            0.08899         -0.12029        -0.33961        -0.00080        0.00160
    ↪          0.00522
...
```

The program can present data in different units depending on the selected mode, For compatibility with the analysis software use the metric system. The available modes are as follows:

| Mode | Force Units | Moment Units | Description |
|---|---|---|---|
| 0 | N | Nm | metric MSA 6 Compatible. |
| 1 | N | Nm | metric fully conditioned. |
| 2 | lb | lb-ft | English MSA 6 Compatible. |
| 3 | lb | lb-ft | English Fully Conditioned. |
| 4 | bits | bits | Bits MSA 6 Compatible. |

Table 2.2: Units dictionary for data presentation modes.

For the spine data analysis program to correctly interpret the output file, the file name must include one of the following terms: ”Axial,” ”Lat,” or ”Flex,” depending on whether the analysis involves axial rotation, lateral bending, or flexion-extension movement.

#### 2.2.3.2 Position Output File

After gathering the force and moment data, it is necessary to obtain the positional data of a specific point in the setup. In a separate thread, the position of the tool center point (TCP), which is defined at the center of the intervertebral space, is captured. This data is then transformed to translate the TCP to another, more visually intuitive point (Marked with an orange point on the picture). This transformation is particularly useful for accurately capturing rotational movements.

The transformation is performed in two main steps: a translation followed by a rotation, and then a final translation back to the desired visual point. The mathematical formula used for this transformation is as follows:

$$\mathbf{A} = \mathbf{R}(\theta_x, \theta_y, \theta_z) \cdot (\mathbf{P}_{\text{TCP}} - \mathbf{T}) + \mathbf{T}$$

where:

- $\mathbf{P}_{\text{TCP}}$ represents the Cartesian coordinates of the tool center point.
- $\mathbf{T} = (7.7, 7.7, 15.8)$ is the fixed translation vector.
- $\mathbf{R}(\theta_x, \theta_y, \theta_z)$ is the rotation matrix derived from the Euler angles $\theta_x, \theta_y, \theta_z$.

Figure 2.5: Transformed Tool Center Point (TCP) Location within the assembly

#### 2.2.3.3 Generated Plots

The code generates and saves one .png plot in the output folder: `force_moment_graph` wich is a combination of the force and torque graphs in a single plot.

It is primarily for keeping a record of the applied forces and torques, without any further analysis. The focus was not on achieving the clearest graphics, considering the possibility of simultaneously starting the acquisition using the AMTINetForce application, which allows for real-time data plotting with clearer graphics.

Real-time plotting was omitted in my code to ensure faster loops, thereby avoiding any slowdown in data acquisition.

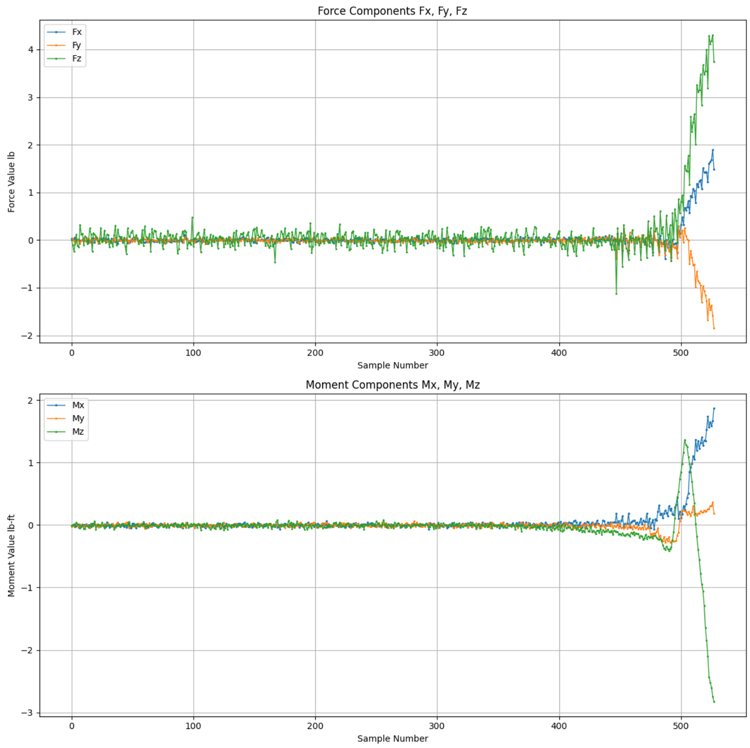


Figure 2.6: Combined plot of forces ($F_x$, $F_y$, $F_z$) and moments ($M_x$, $M_y$, $M_z$) generated by the code

### 2.2.4 Analysis of Sampling Rates and Data Integrity

The Nyquist–Shannon sampling theorem is a fundamental principle in digital signal processing that establishes the relationship between the frequency range of a signal and the necessary sampling rate to avoid aliasing. According to the theorem, the sampling rate must be at least twice the highest frequency component of the signal (the bandwidth) to accurately reconstruct the signal without aliasing.

The primary challenge I encountered was missing data from the force/torque sensor, which was caused by the differing frequencies between the sensor and the code loop. The first step was to quantify the missing data across various signal frequencies and sample rates.

#### 2.2.4.1 Analysis of the frequencies

I chose 500 Hz as the highest allowed signal frequency for the transducer since the robot operates at a control frequency of 500 Hz. The figures below illustrate the percentage of missed data points for different sampling rates at two signal frequencies: 500 Hz and

200 Hz. The blue bars represent the "Missed Data Points Percentage", which is of higher importance in this study, while the gray bars represent the percentage of "No Data from Load Cell," indicating that the loop is requesting data, but none has been provided. This latter data is not relevant to this study.

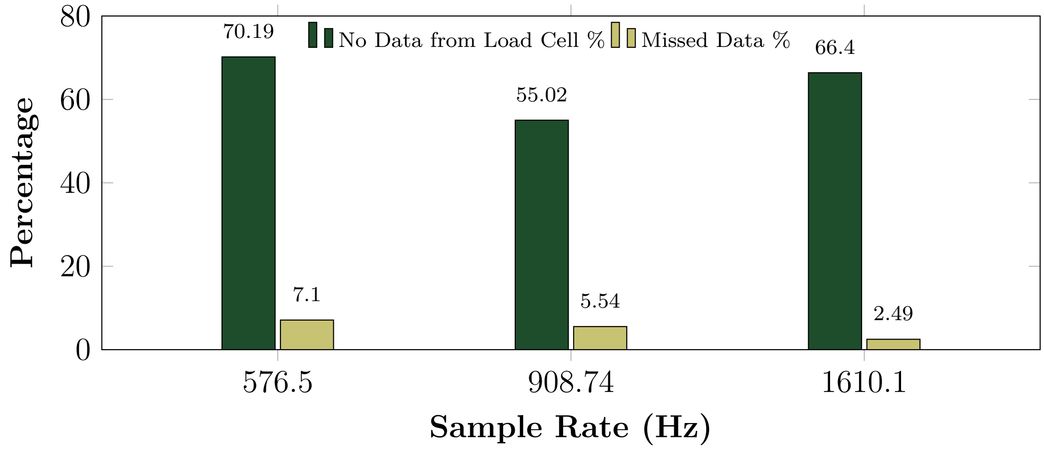


Figure 2.7: Comparison of missed data percentages at different sample rates with a signal frequency of 500 Hz.

At a signal frequency of 500 Hz, the system shows a "Missed Data Points" percentage of 7% at a sampling rate of 500 Hz, which drops to 5.5% at a sampling rate of 1000 Hz.

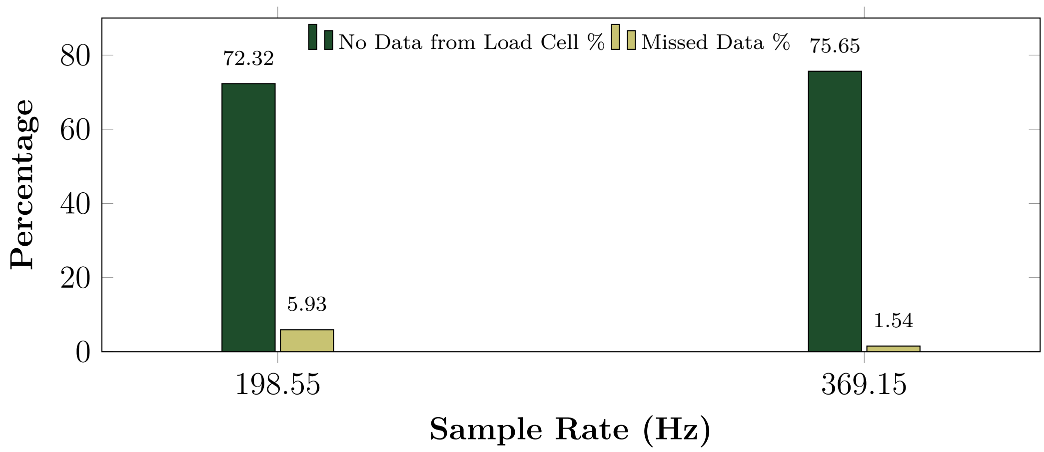


Figure 2.8: Comparison of missed data percentages at different sample rates with a signal frequency of 200 Hz.

At a signal frequency of 200 Hz, the system shows a "Missed Data Points" percentage of 6% at a sampling rate of 200 Hz, which drops significantly to 1.5% at a sampling rate of 400 Hz.

**For integration with the motion capture system, which operates at a sampling rate of 60 Hz, the program has been configured to use a signal frequency of**

**30 Hz, resulting in a median sample rate of 57 Hz.**

#### 2.2.4.2 Conclusion

The analysis underscores the importance of selecting appropriate sampling rates based on the signal frequency to minimize data loss and ensure accurate signal representation. The results suggest that while higher sampling rates generally improve data integrity, the data acquisition system must also be optimized to handle the increased data flow efficiently. The Nyquist–Shannon sampling theorem provides a theoretical foundation for these observations, emphasizing the need for sampling rates at least twice the highest signal frequency. This explains the choice in my programs of doubling the sample rate. For more information on how the sample rate values were calculated, see Appendix C.1.

### 2.2.5 Comparison of Performance

To highlight the benefits of using an external FT sensor like the MC3A, the following bar charts visually compare the precision, accuracy between the internal and the MC3A FT sensors. The MC3A sensor's performance was evaluated using these metrics.(see Appendix C.2) The data collected from the sensor was processed to calculate the fidelity, accuracy as described. The following results were obtained for a period of 7.02 seconds and with **a load of 0** On the other hand the internal sensor's performance were taken from the product datasheet [5]

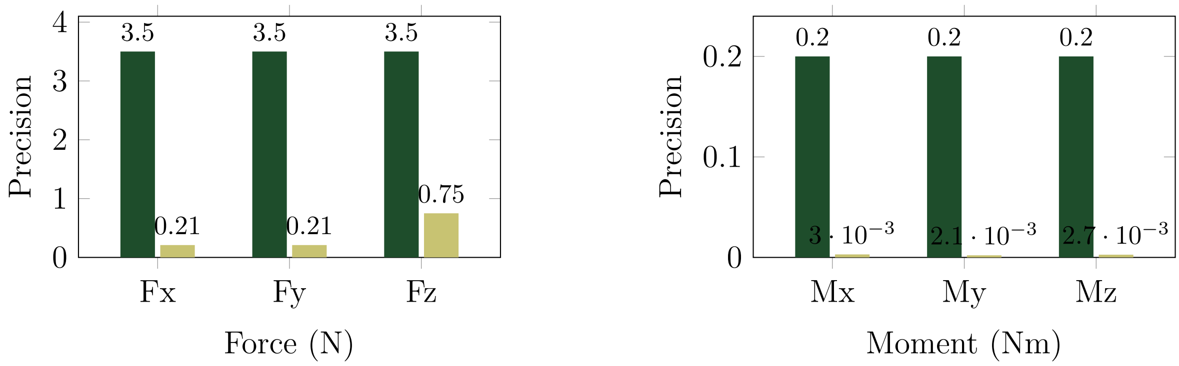


Figure 2.9: Precision of Forces and Moments

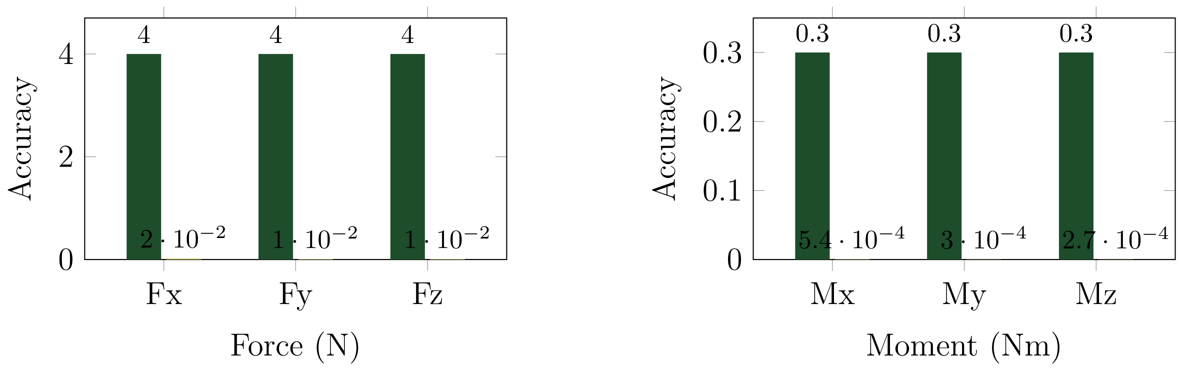


Figure 2.10: Accuracy of Forces and Moments

Figure 2.11: Comparison of Precision and Accuracy between Internal and MC3A FT sensor

The comparison between the internal sensor and the external FT MC3A sensor clearly shows that using an external sensor offers significant advantages in terms of accuracy and precision. These improvements are essential for our application requiring precise and reliable force and torque measurements.

# Chapter 3

# The control system

## System Overview

The control system for the robotic application integrates two primary components: a program operating on the Polyscope interface of the robot, and a control and monitoring system on a PC. This architecture enables real-time data collection and adaptive control, leveraging sensory feedback.

## 3.1 Polyscope Program

The Polyscope program is structured into several key sections:

1. **Initial Setup (BeforeStart):** This stage initializes a vector (‘`setp`‘) with zero values and signals readiness by writing to an output register, ensuring the system is prepared for operation.

2. **Main Control Loop (Robot Program):** The robot’s movements are managed based on inputs received from the PC. The program checks an integer register to determine whether to execute a movement command (‘`speedl`‘) using the ‘`setp`‘ vector.

3. **Data Handling (Thread_1):** This thread continuously updates the ‘`setp`‘ vector with values read from specific input float registers. These values, determined by the control logic on the PC, are transmitted to the robot in real-time, facilitating dynamic adjustments.

## 3.2 PC Control and Monitoring Program

The PC-based program complements the Polyscope by handling data collection, processing, and adaptive control:

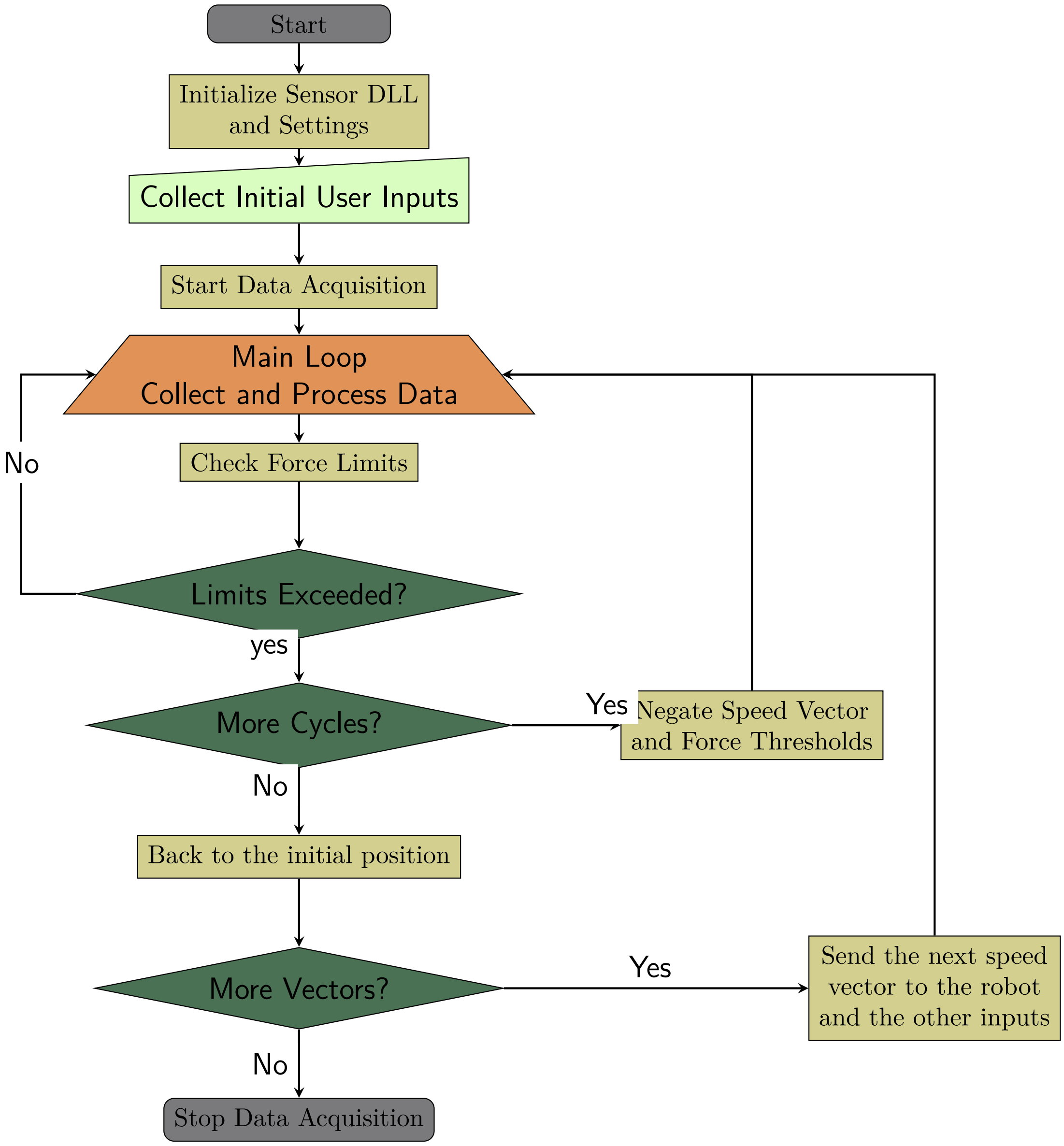


Figure 3.1: Flowchart of the Program Workflow

## 3.3 User Interaction Example

Below is an example of how a user might interact with the system via the terminal interface. The user inputs settings such as data output mode, signal frequency, and speed vector values, then the forces to monitor and there thresholds.

Here is a video demonstration of the project in action: Watch the Video on YouTube

```
Successfully loaded DLL: e:\ur5-pseudo-load\src\..
/lib/Sensor/AMTIUSBDevice - 64.dll
Initializing the DLL...
DLL initialization complete and devices found.
Enter the desired mode (0-4) [0&1: metric, 2&3: english, 4: Bits]: 1
Enter the name of the output file.lvm : force_torque.lvm
Configured data output mode to metric fully conditioned.
Acquisition rate set to 100 Hz.
USB Packet size set to 512 bytes
Enter the name of the output file.lvm : adf
Enter the initial data inputs.
Enter the number of cycles: 1
Enter the speed vector values in the base frame (m/s)(rad/s) (0.03,0,0,0,0,0):
    ↪ 0.03,0,0,0,0,0
Enter the forces you want to monitor (separated by commas): fx
Enter the threshold for fx (N/Nm): -3
Do you want to add another set of inputs? (yes/no): yes
Enter the number of cycles: 1
Enter the speed vector values in the base frame (m/s)(rad/s) (0.03,0,0,0,0,0):
    ↪ 0.03,0,0.01,0,0,0
Enter the forces you want to monitor (separated by commas): fz, fx
Enter the threshold for fz (N/Nm): -3
Enter the threshold for fx (N/Nm): -5
Enter the logic operator ('or' or 'and'): or
Do you want to add another set of inputs? (yes/no): no
Cannot send when RTDE synchronization is inactive
Platform zeroed.
Starting data acquisition...
Data acquisition started.
Collecting data. Press Ctrl+C to stop.
```

## 3.4 Project Directory Structure

The project's directory structure is organized to facilitate ease of navigation and clarity of purpose for each component. Below is an illustration of the directory layout:

```
UR5-PSEUDO-LOAD/
    config/
        control_loop_configuration_spine.xml
    docs/
    lib/
        rtde/
        Sensor/
    output/
        force_moment_graphe.png
        position.txt
        output.lvm
    src/
        pseudo_load.py
        spine_tester.py
    README.md
```

**output/**

Contains the output from the project, including graphical representations of data (`force_moment_graphe.png`) and 2 log files, one for the forces and torques (`output.lvm`) and the other one for the position of the right upper part of the sensor (`position.lvm`).

**src/**

The main source code directory, with scripts like `pseudo_load.py` for automated control of the robot using RTDE.

# Chapter 4

# Bioengineering Contributions

## Introduction

In addition to my work on the development and integration of robotic solutions for spine testing, I also contributed to the bioengineering aspects of the project. This involved the dissection and preparation of biological samples, which were essential for conducting the biomechanical experiments. The following sections detail the procedures and methodologies I employed in this process.

## 4.1 Dissection and Sample Preparation

An ovine model was utilized for this study due to the anatomical and physiological similarities between the ovine and human lumbar spine, making it an accepted translational model for lumbar interbody fusion. The animal was humanely euthanized using an intravenous overdose of pentobarbitone sodium (88 mg/kg), in accordance with the American Veterinary Medical Association (AVMA) guidelines and Preclinical Surgical Research Laboratory (PSRL) Standard Operating Procedures (SOPs).

Following euthanasia, the lumbar spine was carefully removed en bloc. It was labeled with the collection date, animal ID, and PSRL study ID, and all collected samples were immediately transferred to the Orthopaedic Biomechanics Research Laboratory (OBRL) at Colorado State University (CSU) with an accompanying Necropsy Record.

At the OBRL, I prepared the vertebrae for testing through a detailed dissection process. The flesh was meticulously removed, taking care to preserve any present implants, and the L4 and L5 vertebrae were separated from the remainder of the spine. Subsequently, three screws were inserted into each end of the L4 and L5 vertebrae. The preparation of the mold involved mixing equal parts of liquid plastic components A and B, which were then poured into the mold, greased and lined with a plastic film to ensure easy removal.

Figure 4.1: Ovine Lumbar Spine After Dissection

Figure 4.2: Vertebrae Positioned for Casting

Figure 4.3: L4 and L5 Vertebrae Secured in Mold for Casting


Figure 4.4: Final Preparation of Vertebrae for Testing

# Conclusion

The dissection and preparation of these samples were crucial for the success of the experiments. By ensuring that the samples were prepared to a high standard. This work not only supported the mechanical testing process but also provided valuable insights into the biomechanical properties of the ovine spine, furthering the project's overall goals.

# General Conclusion and Perspectives

This experience has been incredibly valuable, offering me profound insights into both American culture and the collaborative work environment in research labs. Throughout this internship, I have made significant progress in our project, bringing us close to fully replacing the current spine tester and the motion tracking cameras with the robot after the necessary adjustment and validation. The remaining tasks include developing a program that can accurately calculate stiffness by analyzing the provided positional data alongside the recorded forces and torques. Additionally, we need to design and machine improved components for mounting the spine with the robot; the current designs can be found in our GitHub repository.

# Appendix A

# Glossary

**Universal Robot (UR):** A type of industrial robot known for its flexibility and ease of programming, commonly used in manufacturing and research applications.

**PolyScope:** The graphical user interface used for programming and controlling Universal Robots.

**URScript:** The scripting language used to program Universal Robots, allowing for control of the robot's movements and behaviors.

**URControl:** The low-level control system of a Universal Robot, running on a dedicated PC within the robot's control box.

**Real-Time Data Exchange (RTDE):** A protocol used for exchanging real-time data between a PC and a Universal Robot, facilitating control and monitoring.

**Dynamic Link Library (DLL):** A file that contains code and data that can be used by multiple programs simultaneously, often used for handling specific functions or operations.

**Tool Center Point (TCP):** The specific point on the robot's tool or end effector that is used as a reference for movement and positioning.

**Nyquist–Shannon Sampling Theorem:** A fundamental principle in signal processing that states a signal can be completely reconstructed if it is sampled at a rate that is at least twice its highest frequency.

**TCP/IP:** A suite of communication protocols used to interconnect network devices on the internet, standing for Transmission Control Protocol/Internet Protocol.

# Appendix B

# Acronyms

| | |
|---|---|
| **UR** | Universal Robot |
| **RTDE** | Real-Time Data Exchange |
| **TCP/IP** | Transmission Control Protocol/Internet Protocol |
| **DLL** | Dynamic Link Library |
| **I/O** | Input/Output |
| **MSA** | Multi-Sensor Array |
| **PC** | Personal Computer |
| **URScript** | Universal Robot Scripting Language |
| **URControl** | Universal Robot Control |
| **TCP** | Tool Center Point |
| **GUI** | Graphical User Interface |
| **Nm** | Newton-meter |
| **lb** | Pound |
| **lb-ft** | Pound-foot |
| **Hz** | Hertz |

# Appendix C

## C.1 Sample Rate Values

#### C.1.0.1 Note on Sample Rate Values

It is important to note that the sample rate values shown in the figures are not exact and should be considered approximate. These values were used for illustrative purposes to provide a general understanding of the relationship between sample rates and data integrity.

The figure below shows the loop durations in relation to the sample numbers, illustrating the variability in the loop execution times.

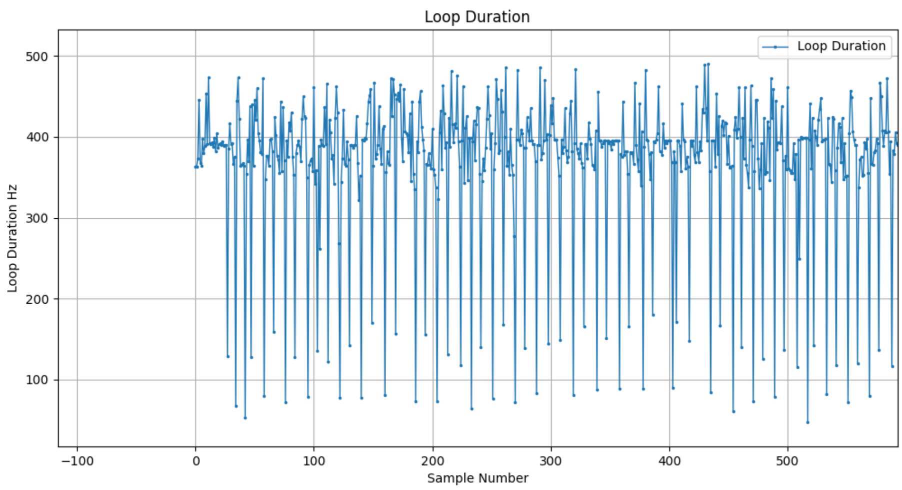


Figure C.1: Loop Duration vs. Sample Number

#### C.1.0.2 Median Loop Frequency Calculation

These values were obtained by calculating the median loop frequency using the following mathematical expression:

Given a sorted list of values $x_1, x_2, \ldots, x_n$, the median is defined as:

$$\text{median}(x) = \begin{cases} x_{\left(\frac{n+1}{2}\right)} & \text{if } n \text{ is odd} \\ \frac{1}{2}\left(x_{\left(\frac{n}{2}\right)} + x_{\left(\frac{n}{2}+1\right)}\right) & \text{if } n \text{ is even} \end{cases}$$

This method provides a more robust measure of central tendency by mitigating the effect of outliers.

## C.2 Accuracy and Fidelity of the FT Sensor MC3A

In this section, we discuss the methods used to evaluate the accuracy, fidelity, and precision of the FT sensor MC3A. These metrics are essential for understanding the performance and reliability of the sensor in various applications.

### C.2.1 Fidelity

Fidelity, in this context, refers to the sensor's ability to consistently reproduce the same measurement when the measurand value does not change. It is an indicator of the reproducibility of the sensor.

The standard deviation, which characterizes the dispersion of measurements around the mean, is often used as an indicator of the sensor's fidelity. The fidelity error $\sigma_{\text{fidel}}$ is defined as follows:

$$\sigma_{\text{fidel}} = \sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(v_i - \bar{m})^2} \tag{C.1}$$

where $v_i$ is the individual measurement and $\bar{m}$ is the mean of the measurements.

### C.2.2 Accuracy

Accuracy refers to the sensor's ability to measure a value close to the true value of the measurand. The error of accuracy $\sigma_{\text{just}}$ is defined as the absolute error between the true value $v_{\text{vraie}}$ and the mean of the measurements $\bar{m}$:

$$\sigma_{\text{just}} = |v_{\text{vraie}} - \bar{m}| \tag{C.2}$$

where the mean $\bar{m}$ is calculated as:

$$\bar{m} = \frac{\sum_{i=1}^{n} v_i}{n} \tag{C.3}$$

### C.2.3 Precision

Precision combines both accuracy and fidelity. It quantifies the total measurement error, taking into account both systematic (accuracy) and random (fidelity) errors. The precision error $\sigma_{\text{prec}}$ can be estimated using the following formula:

$$\sigma_{\text{prec}} = \sqrt{\sigma_{\text{just}}^2 + \sigma_{\text{fidel}}^2} \tag{C.4}$$

This formula assumes that the accuracy and fidelity errors are decorrelated, which allows for a simple combination of the two types of errors.

## RAPPORT D'EVALUATION
## *ASSESSMENT REPORT*

ENSTA Bretagne

**Merci de retourner ce rapport par courrier ou par voie électronique en fin du stage à :**
***At the end of the internship, please return this report via mail or email to:***

*ENSTA Bretagne – Bureau des stages - 2 rue François Verny - 29806 BREST cedex 9 – FRANCE*
☎ 00.33 (0) 2.98.34.87.70 / stages@ensta-bretagne.fr

**I - ORGANISME / *HOST ORGANISATION***

NOM / *Name* Orthopaedic Bioengineering Research Lab : Colorado State University

Adresse / *Address* 1374 Campus Delivery, Fort Collins, CO 80523 USA

Tél / *Phone (including country and area code)* +1 (970) 413-1545

Nom du superviseur / *Name of internship supervisor* Kirk McGilvray, Ph.D.

Fonction / *Function* Associate Professor

Adresse e-mail / *E-mail address* kirk.mcgilvray@colostate.edu

Nom du stagiaire accueilli / *Name of intern* Main Tahami Ouazzani

**II - EVALUATION / *ASSESSMENT***

Veuillez attribuer une note, en encerclant la lettre appropriée, pour chacune des caractéristiques suivantes. Cette note devra se situer entre **A (très bien)** et **F (très faible)**
*Please attribute a mark from **A (excellent)** to **F (very weak)**.*

**MISSION / *TASK***

- La mission de départ a-t-elle été remplie ?
  *Was the initial contract carried out to your satisfaction?* — **(A)** B C D E F

- Manquait-il au stagiaire des connaissances ? ☐ oui/*yes* ☒ non/*no*
  *Was the intern lacking skills?*

  Si oui, lesquelles ? / *If so, which skills?* N/A

**ESPRIT D'EQUIPE / *TEAM SPIRIT***

- Le stagiaire s'est-il bien intégré dans l'organisme d'accueil (disponible, sérieux, s'est adapté au travail en groupe) / *Did the intern easily integrate the host organisation? (flexible, conscientious, adapted to team work)* — **(A)** B C D E F

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* Hard working, diligent, solid presentation skills, great robotics background

**COMPORTEMENT AU TRAVAIL / *BEHAVIOUR TOWARDS WORK***

Le comportement du stagiaire était-il conforme à vos attentes (Ponctuel, ordonné, respectueux, soucieux de participer et d'acquérir de nouvelles connaissances) ?

*Did the intern live up to expectations? (Punctual, methodical, responsive to management instructions, attentive to quality, concerned with acquiring new skills)?*

(A) B C D E F

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* very hard worker, completed project as outlined, excellent researcher

**INITIATIVE – AUTONOMIE / *INITIATIVE – AUTONOMY***

Le stagiaire s'est –il rapidement adapté à de nouvelles situations ? (A) B C D E F
(Proposition de solutions aux problèmes rencontrés, autonomie dans le travail, etc.)

*Did the intern adapt well to new situations?* A/B C D E F
*(eg. suggested solutions to problems encountered, demonstrated autonomy in his/her job, etc.)*

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* solid grasp of the research problem, needs to be more confident in presenting her own solutions

**CULTUREL – COMMUNICATION / *CULTURAL – COMMUNICATION***

Le stagiaire était-il ouvert, d'une manière générale, à la communication ? (A) B C D E F
*Was the intern open to listening and expressing himself /herself?*

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* —

**OPINION GLOBALE / *OVERALL ASSESSMENT***

❖ La valeur technique du stagiaire était : (A) B C D E F
*Please evaluate the technical skills of the intern:*

**III - PARTENARIAT FUTUR / *FUTURE PARTNERSHIP***

❖ Etes-vous prêt à accueillir un autre stagiaire l'an prochain ?
*Would you be willing to host another intern next year?* ☒ oui/*yes* ☐ non/*no*

Fait à ______, le ______
In ______, on 2025+
Summer Semester (Fall or Spring)

Sept. 3 2024

Signature Entreprise K McDilvray Signature stagiaire
*Company stamp* *Intern's signature*

***Merci pour votre coopération***
***We thank you very much for your cooperation***

# Bibliography

[1] AMTI. Multi-axis transducer mc3a. https://www.amti.biz/product/mc3a/. Accessed: 2024-07-02.

[2] Universal Robots. *UR5e Technical Specification*. Accessed: 2024-08-01.

[3] obrl csu. Obrlhome. http://obrl.colostate.edu/. Accessed: 2024-07-15.

[4] AMTI. *MC3A Force and Torque Sensor Manual*. Accessed: 2024-07-02.

[5] AMTI. Gen5 amplifier. https://www.amti.biz/product/gen-5/. Accessed: 2024-07-02.