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# Thesis Project Preparation

**João Nuno Valente**

Centre for Mechanical Technology and Automation
Department of Mechanical Engineering
Doctorate in Mechanical Engineering

Aveiro, June 2025

# Thesis Project Preparation

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# Resumo


Neste documento, encontra-se explanada a abordagem que pretendo seguir para desenvolver a minha tese de doutoramento. O doutoramento consiste em estudar a possibilidade de realizar vibrometria tridimensional com um único laser, recorrendo à integração de uma câmara de profundidade para estimar a posição. O coordenador é o Prof. Rui Moreira, e os orientadores são o Prof. Vítor Santos e o Prof. Sérgio Tavares.

A revisão da literatura focou-se em duas áreas distintas: os métodos e técnicas existentes para o registo de nuvens de pontos; e as soluções propostas para a realização de vibrometria tridimensional. A intenção desta análise é responder à principal questão de investigação: *É possível realizar vibrometria tridimensional com um único laser e integrando uma câmara de profundidade?*

A metodologia proposta consiste na utilização de um vibrómetro de varrimento – o modelo PSV-500 da Polytec – e na aplicação do método escolhido para o registo da nuvem de pontos, o *Exhaustive Grid Search* (EGS). A câmara selecionada para capturar os dados relativos às nuvens de pontos é a ORBBEC FEMTO MEGA.

O plano de trabalhos foi delineado para um período de quatro anos, e os resultados esperados incluem a realização de uma análise modal utilizando a técnica de vibrometria tridimensional com um único laser, demonstrando assim que não é necessário recorrer a três lasers. Além disso, espera-se que seja possível otimizar a posição do vibrómetro, minimizando o número de pontos de vista necessários da peça a analisar.

Por fim, o documento termina com algumas considerações adicionais, nomeadamente a inexistência de implicações éticas ou sociais a registar, e a identificação de espaços como o Laboratório de Automação e Robótica (LAR) e o Laboratório de Dinâmica das Estruturas do Departamento de Engenharia Mecânica da Universidade de Aveiro que serão usados para realizar a investigação.



**Palavras-Chave:** Projeto de Tese, Vibrometria 3D, Câmara de Profundidade, CSLDV

# Abstract

This document outlines the approach proposed for the development of my Ph.D. thesis. The research aims to investigate the feasibility of performing three-dimensional vibrometry using a single laser, by integrating a depth camera to estimate positional data. The coordinator of the project is Prof. Rui Moreira, and the academic supervisors are Prof. Vítor Santos and Prof. Sérgio Tavares.

The literature review focused on two distinct areas: existing methods and techniques for point cloud registration, and proposed solutions for conducting 3D vibrometry. The central research question addressed in this study is: *Is it possible to perform three-dimensional vibrometry with a single laser by integrating a depth camera?*

The proposed methodology involves the use of a scanning vibrometer—specifically, the Polytec PSV-500 model—and the application of the Exhaustive Grid Search (EGS) technique for point cloud registration. The ORBBEC FEMTO MEGA depth camera was selected to capture the 3D data.

The project is planned over a four-year period. The expected outcomes include the successful execution of a modal analysis using 3D vibrometry with a single laser, demonstrating that it is not necessary to employ three lasers. Furthermore, it is anticipated that the vibrometer's position can be optimized to minimize the number of viewpoints required to analyze a given part.

Finally, the document concludes with additional considerations. Specifically, no ethical or social implications have been identified, and the research is expected to be conducted primarily in the Laboratory of Automation and Robotics (LAR) and the Structural Dynamics Laboratory of the Department of Mechanical Engineering at the University of Aveiro, that will be used to conduct the research.

**Keywords:** Thesis project, 3D Vibrometry, Depth Camera, CSLDV, Pose Estimation

# AI Acknowledgement

I acknowledge the use of ChatGPT-4 (https://chatgpt.com) to improve the academic tone and enhance the accuracy of language in my work, including grammatical structures, punctuation, and vocabulary.

Additionally, I acknowledge the use of Overleaf (https://www.overleaf.com) to produce this document and Zotero (https://www.zotero.org/) to organize the bibliography. This document was created using a modified version of the original template developed by José Areia (https://github.com/joseareia/ipleiria-thesis).

# Contents

**Appendices**

# Glossary

**CSLDV** Continuous Scanning Laser Doppler Vibrometry (CSLDV) is a technique where a laser beam is continuously swept across a surface to measure vibrations, enabling faster data acquisition compared to point-by-point scanning.

**Depth Camera** A sensor that captures depth information (distance) along with 2D images, often used in computer vision and robotics to produce 3D point clouds.

**Digital Twin** A digital replica of a physical system used for simulation, analysis, monitoring, and optimization in real-time or offline.

**Galvanometer** An electromechanical instrument for detecting and measuring small electric currents. In laser systems, galvanometers are often used to control the direction of laser beams by rapidly adjusting mirrors.

**Modal Analysis** Modal analysis is the process of determining the natural vibration characteristics of a structure or mechanical system—specifically its natural frequencies, mode shapes, and damping ratios.

**Operational Deflection Shapes** The mode shapes of a structure under actual operating conditions, showing how it deforms while vibrating.

**Point Cloud Registration** The process of aligning multiple 3D point clouds into a single coordinate system by estimating the spatial transformation between them.

**Vibrometry** Laser Vibrometry is a non-contact measurement technique that uses laser beams to detect and analyze the vibration characteristics of a surface by capturing the Doppler shift or interference pattern caused by its motion.

# Acronyms

| | |
|---|---|
| **AAUAv** | Academic Association of the University of Aveiro. |
| **EBEC** | European BEST Engineering Competition. |
| **IEETA** | Institute of Electronics and Informatics Engineering of Aveiro. |
| **LAR** | Laboratory for Automation and Robotics. |
| **LDV** | Laser Doppler Vibrometer. |
| **MEMS** | Micro-Electrical-Mechanical Systems. |
| **SDL** | Structural Dynamics Laboratory. |
| **TEMA** | Centre for Mechanical Technology and Automation. |
| **ToF** | Time-of-Flight. |
| **UA** | University of Aveiro. |

# 1

# Introduction

*This chapter introduces the researcher, presenting a short biography, academic background, and the motivation behind pursuing a Ph.D. The research proposal is outlined, including its relevance. Additionally, the supervisory team is identified, along with their respective roles and contributions to the project.*

## 1.1 Researcher Identification

**Name:** João Nuno Baptista Valente
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## 1.2 Background and Motivation

### 1.2.1 Short Curriculum vitæ

I completed my Master's degree in Mechanical Engineering at the University of Aveiro in 2023. My dissertation focused on the measurement of mechanical vibrations using

Micro-Electrical-Mechanical Systems (MEMS) accelerometers, and on the use of microcontrollers — namely the ESP32 — for data acquisition and processing.

The following year, I began my Ph.D., currently funded by a research grant under the scope of `ATE - Alliance for the Energy Transition`. My research focuses on the development of innovative concepts for power transformers, particularly in areas such as three-dimensional vibrometry and continuous scanning, the identification of operational deflection shapes using stereoscopy-assisted *MotionScope*[1] techniques, and its validation using piezoelectric-based sensors.

The Laboratory of Automation and Robotics (LAR) is part of Department of Mechanical Engineering (DEM) and is where I'm currently doing my PhD research.

Previously, I was awarded a research grant under the project `CENTRO-01-0247-FEDER-069964`, in which I developed, designed, and built a prototype of a sanding system for the company *Primus Vitória - Azulejos, S.A.*[2].

Alongside my academic journey, I was involved with the student organization BEST Aveiro[3], where I was a full member and coordinated an edition of the European BEST Engineering Competition (EBEC). I also served as coordinator of the Chess Club of the Academic Association of the University of Aveiro (AAUAv)[4].

In the sports field, I achieved several national and university chess titles, which enabled me to represent Portugal in the World Junior Championships[5] and the European University Championships[6]. This journey culminated in being recognized as the Best Athlete at the University of Aveiro.

## 1.3 Research Proposal

### 1.3.1 Thesis Title and Keywords

**English title:** Single-Laser 3D Vibrometry with Depth Camera Integration

**Portuguese title:** Vibrometria laser 3D com recurso a Câmara de Profundidade

**Keywords:** 3D Vibrometry, Depth Camera, Point Cloud Registration, CSLDV

[1] `https://www.motion-scope.com/`
[2] `https://primusvitoria.com/`
[3] `https://bestaveiro.web.ua.pt/`
[4] `https://www.aauav.pt/`
[5] `https://www.fide.com/`
[6] `https://www.eusa.eu/`

### 1.3.2 Summary

This Ph.D. research explores a new approach to 3D Vibrometry using a single scanning Laser Doppler Vibrometer (LDV) in combination with a depth camera. Traditional 3D modal analysis relies on multiple sensors, but this work proposes repositioning a single sensor and reconstructing its spatial orientation through point cloud registration.

By capturing the geometry of the object at each measurement viewpoint with a Depth Camera, the system estimates the transformation between views, enabling accurate 3D vibration mapping with minimal hardware. The research also investigates optimal placement for the laser, using machine learning algorithms to reduce redundant measurements while still capturing all relevant structural behavior.

Applications include scenarios where traditional multi-sensor or bulky equipment setups are impractical — such as in-field inspections, large or remote structures, and confined environments. The proposed methodology offers a flexible, low-cost alternative for full-field vibration analysis in these contexts. A key validation case will involve structural health monitoring of power transformers, where the acquired data will support the development of a digital twin. This project contributes to the fields of experimental modal analysis, robotic perception.

## 1.4 Research Supervision

The table below provides detailed information about the team members, their roles, affiliations, email addresses, and ORCID iDs.

**Table 1.1:** *Supervisors Identification*

| Name | Role | Affiliation \| Email \| ORCID iD |
|---|---|---|
| **Rui Moreira** | Coordinator | University of Aveiro<br>`rmoreira@ua.pt`<br>`https://orcid.org/0000-0001-5328-1705` |
| **Vítor Santos** | Supervisor | University of Aveiro<br>`vitor@ua.pt`<br>`https://orcid.org/0000-0003-1283-7388` |
| **Sérgio Tavares** | Supervisor | University of Aveiro |

| Name | Role | Affiliation \| Email \| ORCID iD |
|---|---|---|
| | | smotavares@ua.pt<br>https://orcid.org/0000-0003-0054-0771 |

### Supervisors Contribution

The contributions of the supervisor team to the research work are as follows.

**Rui Moreira** has focused his research on structural dynamics, mechanical vibrations, noise, and acoustics, making relevant contributions to Modal Analysis and the dynamic simulation of mechanical components. He founded and directs the Structural Dynamics Laboratory (SDL) at the University of Aveiro.

He is responsible for setting the overall research question of the project: *Is it possible to perform 3D vibrometry using only one vibrometer?* This question encompasses the knowledge required to conduct modal analysis using laser vibrometry, as well as traditional techniques for measuring mechanical vibrations.

**Vítor Santos**'s research focuses on mobile robotics, advanced perception, and humanoid robotics, with key contributions to autonomous driving and robotic competitions. He has led multiple projects, including ATLASCAR[7], and has extensively supervised academic research in these fields.

His contribution to this project consists of leading the integration of RGB-D cameras into the system being developed, suggesting paths to explore regarding point cloud registration and active perception, particularly in determining optimal camera placement. In addition, he is responsible for the Laboratory for Automation and Robotics[8] (LAR), where I am currently conducting my research.

**Sérgio Tavares** specializes in structural integrity, fatigue, and fracture mechanics, with a focus on aeronautical and industrial applications. His research includes advanced manufacturing processes and the development of lightweight structures for aerospace and mobility industries. He also works on additive manufacturing, digital twins, and lifecycle assessment of structural components.

[7] https://atlas.web.ua.pt
[8] http://lars.mec.ua.pt

His expertise in structural integrity, Digital Twins, and lifecycle assessment plays a key role in this research, particularly in modeling and validating the system's behavior under operational conditions. Additionally, his previous experience with EFACEC[9] provides a valuable opportunity, facilitating access to a case study involving power transformers, enabling real-world validation of the proposed approach.

9 https://www.efacec.com/

# 2

# Research Framework

*This chapter outlines the theoretical foundation for the development of a new, flexible, and low-cost 3D vibrometry system. It presents a critical review of the existing technologies, defines the research objectives and questions, and describes the planned workflow over the course of the Ph.D. project.*

## 2.1 Literature Review

The literature review can be divided into four main areas: multi-laser versus single-laser systems, continuous and automated scanning techniques, integration of depth cameras for LDV pose estimation, and point cloud registration methods.

### 2.1.1 From Multi-Laser to Single-Laser 3D Vibrometry

3D vibrometry has long been performed using three orthogonally oriented laser beams to simultaneously capture the in-plane and out-of-plane components of structural vibration. Commercial systems, such as the Polytec[1] PSV-500-3D, exemplify this setup and provide highly accurate measurements. However, these systems are typically expensive, mechanically complex, and restricted in their application to controlled laboratory environments. Their rigidity and cost have motivated researchers to explore simplified and more flexible alternatives.

A major direction in this evolution has been the use of a single LDV to reconstruct 3D vibration fields. In one of the earliest efforts, Kim et al. [1] demonstrated that full 3D vibration vectors could be obtained by repositioning a single scanning LDV to three

[1] https://www.polytec.com/

distinct locations. By using geometric transformations and a laser scanner for spatial alignment, they were able to reconstruct complete directional data, provided the excitation remained consistent during repositioning. While this method significantly reduced the hardware burden, it required careful calibration of the laser scan and introduced practical limitations in dynamic or field scenarios.

To increase portability, Sels et al. [2] introduced a handheld single-point LDV system coupled with a 2D camera. This system tracked the LDV's pose in real time by aligning images with a known CAD model of the structure. The resulting orientation data allowed for directional vibration measurements to be consistently transformed into a global coordinate system. Although cost-effective, the system was found to be sensitive to speckle noise and surface symmetries, which could degrade the accuracy of 3D reconstruction. Additionally, it required access to a CAD model of the structure under analysis.

### 2.1.2 Continuous and Automated Scanning Techniques

In parallel, Continuous Scanning Laser Doppler Vibrometry (CSLDV) has emerged as a method to improve both spatial resolution and measurement efficiency. Rather than capturing point-by-point data, systems move the laser spot smoothly along a predefined path, allowing vibration measurements to be acquired continuously. Weekes and Ewins [3] demonstrated how 3D Operational Deflection Shapes could be extracted by repeating continuous scans from three different angles. Di Maio et al. [4] provided a comprehensive overview of 's practical strengths and limitations, showing its potential for high-resolution measurement and the technical challenges it introduces, such as speckle interference and the need for precise scan trajectory calibration.

In recent years, new approaches have been presented to improve . These systems typically use two orthogonally mounted mirrors to steer a single laser beam along a predefined path. This contrasts with conventional point-by-point scanning systems and enables faster data acquisition [4]. has been applied to curved or rotating structures [5], often incorporating reflective mirrors [6] and image-based tracking [7]. However, such setups are complex, requiring precise mirror control and advanced signal processing.

Beyond handheld and continuous scanning systems, more sophisticated automation has been explored through robotic platforms. Oliver and Schuessler [8] developed a fully automated LDV scanning system in which a robotic arm repositioned scan heads. A Time-of-Flight (ToF) geometry scanner was used to generate a 3D model of the test object when CAD data was unavailable. Although this setup involved multiple LDV sensors, it demonstrated the benefits of automating scanning.

### 2.1.3 Depth Camera Integration and Registration Challenges

Despite these developments, a notable gap in the literature remains: the successful integration of depth cameras into 3D vibrometry. Depth cameras, widely used in robotics and computer vision, offer the ability to capture dense 3D point clouds in real time. As noted by Sels et al. [2] in 2019, "One means of obtaining a large number of 3D point coordinates simultaneously is by using 3D range sensors. Recently, Weekes et al. [3] and Sels et al. [9] proposed the use of a Kinect camera to perform this task. Unfortunately, both the spatial resolution and the accuracy of the used 3D cameras is too low to allow an accurate pose estimation."

At that time, the Kinect v1 and similar devices primarily relied on structured light or stereo vision, which limited both their resolution and accuracy. Since then, ToF cameras have become increasingly available, offering higher precision, faster acquisition, and better performance in various lighting conditions. Importantly, the cost of such ToF sensors has also decreased, making them a practical option for integration into low-cost, non-contact 3D vibrometry systems. An example of such camera is the ORBBEC Femto Mega[2].

### 2.1.4 Point Cloud Registration

Point Cloud Registration is therefore an interesting solution. Traditional methods such as ICP [10], SHOT [11], and FPFH [12] align point clouds based on geometric features or correspondences. While widely used, these techniques often struggle under noisy conditions, with occlusions, or in the presence of non-distinctive surface geometries. More recently, learning-based approaches - including 3DMatch [13], FCGF [14], DCP [15], and GeoTransformer [16] - have shown promise by learning local or global descriptors to predict transformations directly. However, these methods typically require large labeled datasets and tend to generalize poorly to unseen or unstructured surfaces.

[2] https://www.orbbec.com/products/tof-camera/femto-mega/

To overcome these limitations, featureless registration techniques have gained traction [17], [18]. Among them, EGS [19] performs a brute-force optimization over translation and rotation parameters, seeking the highest voxel-level spatial correlation between input point clouds. EGS has proven effective in low-overlap and noisy environments, making it a viable candidate for LDV systems that incorporate real-time depth sensing.

In summary, the field of 3D vibrometry has evolved significantly - from rigid, multi-laser systems to more agile, cost-effective single-laser approaches, including continuous scanning and handheld setups. Yet the integration of depth cameras for LDV pose estimation remains largely unexplored with success. Combining this capability with robust registration algorithms - particularly those that are generalizable or featureless - could enable a new generation of portable, flexible, and autonomous 3D vibrometry systems suitable for both laboratory and field applications.

## 2.2 Research Questions

The following research questions guide the Ph.D.:

1. **Can 3D vibrometry be accurately performed using a single scanning LDV, repositioned across multiple viewpoints and tracked using depth camera data?**
   This question explores the feasibility of replacing traditional multi-LDV setups with a lower-cost, single-sensor approach by estimating rigid transformations between measurements using point cloud registration.

2. **How can the number and placement of scanning viewpoints be optimized to achieve complete and accurate 3D modal analysis?**
   This question investigates strategies to minimize the number of required laser positions while ensuring full coverage of the structure and the reliability of the extracted modal parameters.

3. **How can continuous scanning using galvanometer-mounted mirrors be implemented to ensure that the laser accurately targets consistent points on the structure?**
   This question focuses on the engineering challenges of synchronization, calibra-

tion, and scan trajectory design, aiming to ensure spatial consistency across repeated measurements and across different scanning methods.

## 2.3 Work Plan

### 2.3.1 Description

The detailed description consists of seven tasks to be completed over a four-year period starting from 01/01/2025. Each task builds on the previous stages.

**Task 1 – State-of-the-art review (throughout the Ph.D.)**

An ongoing literature review will be conducted throughout the Ph.D. to check for advances in 3D vibrometry, continuous scanning LDVs, depth-sensing technologies, and point cloud registration. This task will ensure that the research approach remains current, enabling adjustments to methodology as new techniques emerge.

**Task 2 – Hardware setup and preliminary experiments (6 months)**

This task involves preparing and configuring the available hardware in the lab, including the scanning LDV and the UR10e robotic arm. A depth camera and galvanometer mirrors will also be acquired and integrated into the experimental platform. Preliminary integration will involve developing synchronization routines, initial calibration procedures, and basic tests to confirm system interoperability. These activities will establish the foundation for later experimental phases.

**Task 3 – Depth-camera-based LDV repositioning (12 months)**

This task focuses on evaluating the feasibility of tracking LDV repositioning using point clouds acquired by a depth camera. Registration methods will be tested, with an emphasis on recent featureless and learning-based approaches, including EGS, DIP, and GeDi. These methods will be evaluated for accuracy, robustness to noise and occlusion.

**Task 4 – Continuous scanning using galvanometers (8 months)**

A system will be developed by integrating two galvanometer mirrors to control the direction of the LDV beam. Software will be created to define custom scan trajectories and synchronize mirror actuation with data acquisition. The system will be evaluated in terms of spatial resolution, acquisition speed, and the quality of modal data it produces, and compared against traditional step-by-step scanning.

**Task 5 – Robotic scanning with the UR10e arm (10 months)**

In this task, the LDV will be mounted on the UR10e robotic arm to automate repositioning and scanning from multiple viewpoints. An algorithm will be developed to optimize the number and placement of viewpoints based on the structure's geometry. This setup will be tested on representative components to validate performance in complex scanning scenarios.

**Task 6 – Integration and testing on real structures (8 months)**

This task will unify the components developed in previous stages into a complete 3D vibrometry system. It will be applied to real mechanical structures, such as power transformers built by EFACEC, to evaluate overall performance.

**Task 7 – Writing and dissemination (final 12 months)**

The final year will be dedicated to disseminating research outputs and writing the doctoral thesis. The thesis will detail the motivation, methodology, experimental validation, and main contributions of the project. A complete prototype demonstration will be organized for the thesis defense.

### 2.3.2 Risk Management and Contingency Plan

**Hardware failure or delays:** Any malfunction or delivery delay of essential hardware (LDV, UR10e, Galvanometer) could affect progress. As a contingency, manual repositioning and previously available hardware will be used to continue algorithm development.

**Registration accuracy is insufficient:** Should selected algorithms fail to meet accuracy requirements, hybrid or semi-supervised alternatives will be considered. Synthetic datasets may also be created to fine-tune existing models.

**implementation complexity:** Technical challenges in mirror synchronization may delay results. In that case, point-by-point scanning will be used as a fallback until is fully operational.

**UR10e integration difficulties:** If robotic integration proves more complex than expected, manual repositioning will be used while development continues incrementally.

The project is modular and designed for flexibility. Core tasks such as algorithm evaluation, viewpoint planning, and data analysis can proceed independently, reducing dependency on sequential hardware deployment. Regular supervisory meetings will help assess risk and adjust priorities when needed.

### 2.3.3 Gantt Chart

This Gantt chart outlines the timeline and structure of the planned research tasks over the duration of the project.

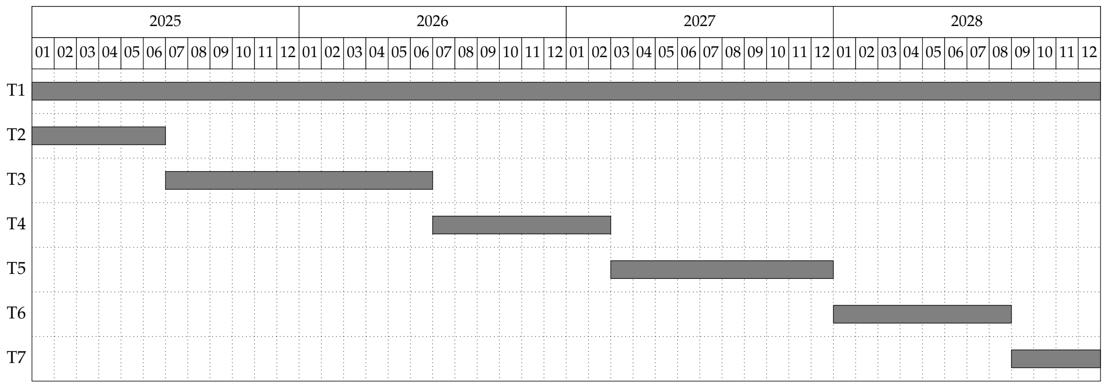


**Figure 2.1:** *Project Gantt chart from 2025 to 2028*

## 2.4 Dissemination Strategy

Depending on the scope and maturity of the results, the research may lead to the publication of up to three peer-reviewed journal articles, each potentially addressing one of the core research questions. These publications would reflect key contributions in areas such as:

- Depth-camera-based pose estimation for single-LDV 3D vibrometry.
- Optimization of scanning viewpoints for accurate and efficient modal analysis.
- Implementation and validation of continuous scanning using galvanometer-mounted mirrors.

# 3

# Additional Considerations

*This chapter addresses supporting aspects of the Ph.D. project that go beyond technical execution. It briefly reflects on potential ethical considerations, institutional infrastructure, and available resources.*

## 3.1 Ethical and Social Implications

This project does not anticipate any direct ethical or social implications. That said, the pursuit of a Ph.D. often gives rise to philosophical or even existential questions such as: *Who am I?*, *Does free will exist?*, or *Why am I doing a Ph.D.?* I will reserve the resulting reflections for myself.

## 3.2 Infrastructure and Resources

This Ph.D. project will be hosted at the University of Aveiro (UA), an institution internationally recognized for its research in mechanical vibrations, structural dynamics, and intelligent systems. The Department of Mechanical Engineering offers access to two key laboratories: the Laboratory for Automation and Robotics (LAR), and the Structural Dynamics Laboratory (SDL), both integrated within the TEMA research unit. These facilities are equipped with a scanning LDV, the UR10e robotic arm, and other essential tools for structural testing and automation.

The project will also benefit from access to a depth camera and galvanometer mirrors, which will be integrated during the development phase. For computational needs, UA provides DeepLar — a high-performance GPU server infrastructure suitable for data processing, simulation, and algorithm training.

The Institute of Electronics and Informatics Engineering of Aveiro (IEETA) will provide complementary expertise in artificial intelligence, perception, and robotic control — which is especially relevant for tasks involving depth camera integration.

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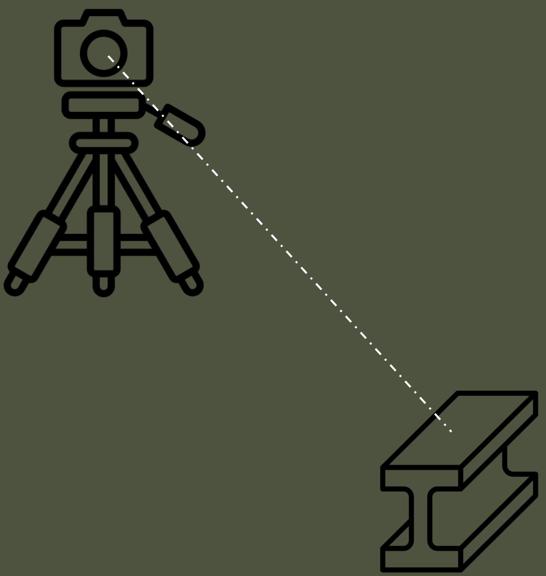
# Appendices

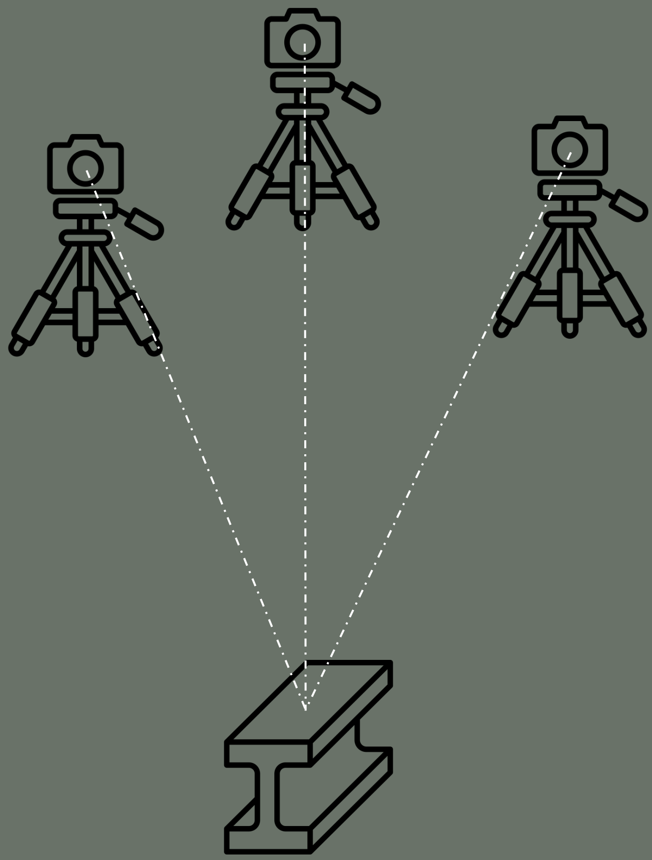
# A

# Graphical Abstract

## Can 3D vibrometry be performed using only one vibrometer?

My research focuses on developing a new system for three-dimensional vibrometry that integrates a depth camera for precise laser targeting.





## Polytec PSV-500-3D

3D vibrometry is currently performed using three distinct vibrometers targeting the same points.

## Using depth camera to repositioning the vibrometer

By repositioning only one vibrometer to measure all three directions, it may be possible to reduce the cost of the system.