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OPEN METHODS FOR DIGITAL CONSERVATION OF MUSICAL INSTRUMENTS

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Abstract

Historical musical instruments present a complex set of challenges within the heritage sector, as they span across many categories of value systems in heritage conservation. The research in this thesis was carried out as part of the NEMUS project, which seeks to address such challenges presented by musical instrument heritage objects, through the application of digital technologies. Two challenges of digital musical instrument heritage conservation are explored: interaction with digitised instruments and analysis for understanding material properties.

The challenge of interaction with digitised instruments is explored through the harpsichord, for which standard MIDI-based controllers fail to capture the distinct haptic experience during performance. This challenge is explored through the creation of a two-register haptic interface constructed from a custom-built, historically informed harpsichord keyboard that provides the same kinaesthetic response of an original instrument. The interface's design principles, prototyping and fabrication process are discussed alongside the open methodology which informed them, culminating in an exhibition at Museo San Colombano, Bologna.

To address the challenge of analysing material properties, an open source finite difference simulation framework for plate vibrations featuring adjustable elastic boundary conditions was created. The design and development of the software, titled MAGPIE, are discussed with particular attention paid to its cross-language implementation in MATLAB, Python and C++. MAGPIE aims to democratise access to acoustic modelling, benefiting researchers, educators, and instrument builders by visualizing mode shapes and frequencies, facilitating experimental exploration of the plate systems associated with string instrument soundboards.

Inherent to both projects is an open methodology, an adherence to FAIR principles in digital research. Digital technologies can support the conservation, analysis and recreation of historical musical instruments. With this technology, comes the challenges of sustaining digital artefacts, reproducibility, software citation and sustainable data practices. The future directions for each project are examined, with prospective developments and technical challenges contextualised with the broader open methodology.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

The work presented in this thesis was carried out as part of the NEMUS project [44], which seeks to address the challenges of historical musical instrument restoration through the application of digital technologies. Two aspects of the conservation process are considered here. The first concerns cases in which a historical musical instrument has fallen out of playing condition—and restoring it would compromise its structural or historical integrity. In such situations, can interaction be reintroduced through digitisation? Digitisation may involve sampling an instrument [76, 157, 187] or reconstructing it through numerical simulation [22, 235]. Despite the emergence of these techniques, the question of how to provide meaningful access to digitised instruments within museum contexts remains unresolved [119, 205].

The second aspect of conservation concerns the analysis of instruments—particularly string instruments with wooden soundboards. How can we provide access to modal analysis and an understanding of material properties in a manner that is accessible while minimising the risk of damaging the instrument?

The renowned Tagliavini Collection in Bologna exemplifies these challenges [167]. Housed at Museo San Colombano (Figure 1.1), it is comprised primarily of early Italian plucked-string keyboards. Fernando Tagliavini envisioned that the instruments in his collection would be maintained in their original playable condition. While the instruments are indeed playable, their use necessitates strict controls and is permitted only under special supervision. For example, instruments such as the Museum's 1547 Alessandro Trasuntino harpsichord are in a state where restoration to playable condition poses significant risks due to their fragility.

This issue is not unique to the Tagliavini Collection but also pertains to other notable historical instrument collections, such as those of Richard Burnett, Benton Fletcher, and Bate [17], which all house playable harpsichords dating from the seventeenth and eighteenth centuries. The two aspects of the conservation process relevant to these collections are reflected in the chapters titled "Analysis" and "Interaction."

This thesis addresses these questions through two interconnected projects. Chapter 2 examines what occurs after digitisation has taken place, asking how interaction with a digitised musical instrument can be meaningfully facilitated. Chapter 3 focuses on the development of an

Figure 1.1: Interior of Museo San Colombano, main hall [Image Courtesy of Dr. Craig Webb].

open source software tool for plate simulation, designed to be used alongside measurements to support decision-making in conservation strategies [15]. In this context, plate simulation refers to the digital simulation of thin plates, based on physics-based models, from which information such as modal frequencies can be derived. The "plates" represent the systems found on the soundboards of string instruments. Linking these two case studies is a broader investigation into the sustainability and reproducibility of digital conservation and the tools that underpin it. Reproducibility poses a significant challenge for digital research [192]. Accordingly, this thesis outlines the steps required to ensure the longevity and accessibility of digital research outputs [135, 225, 227, 230] within the context of musical cultural heritage.

This chapter situates the work within its broader context and is divided into two main areas. The first concerns the field of musical instrument conservation, addressing the challenges that arise and the limitations that persist, whether or not the wider community acknowledges them. The second examines the term "digital conservation" as it is used throughout this thesis, focusing on the challenges posed by digital technologies and their integration into cultural heritage and conservation practice. In particular, this section discusses an open methodology—in which digital research outputs are accessible, reusable, and sustainable—as a framework for the practice of digital conservation.

1.1 Musical Instrument Conservation

Historical musical instruments present a unique challenge within the field of cultural heritage. They are both aesthetic physical objects and tools with an inherent tactile dimension [211]. Maintaining instruments in playable condition introduces significant risks and costs [143], prompting ongoing debate about how best to balance preservation and access. Discussion within the field of musical instrument conservation has typically been divided between approaches that seek to balance the competing values of aesthetics and function [15, 17].

The harpsichord has found itself at the centre of the "playability" debate in more than one collection. Of particular note are the Benton Fletcher Collection at Fenton House [17, 157], the Musical Instrument Museums Edinburgh, and the Tagliavini Collection in San Colombano [258]. Instruments from the Tagliavini Collection [167]—in particular those dating from the sixteenth century—were a motivating factor and test case for part of this thesis. When discussing musical instrument conservation, it is the case of the harpsichord that is primarily being considered. Although some of the methodology can be translated to other instruments, much of what is discussed here is specific to the harpsichord.

1.1.1 Living Heritage, Dead Heritage

Barclay [17, p. 19] defines a schema of three states into which a historical instrument may fall: Currency, Conservation, and Restoration. The state of Currency—where the instrument is in working condition and actively maintained—is not relevant to the concerns of this thesis. Arguments in favour of restoration often appeal to aesthetics and sound quality, which have historically motivated restoration practices. However, the degree of accuracy with which instruments can be assessed varies considerably across the spectrum of musical instruments. Focusing specifically on the harpsichord, it will be argued that pursuing the original sound of a historical instrument is a questionable rationale for restoration. As Barclay suggests, museums should inform both players and audiences of the uncertainties inherent in such reconstructions, noting that "the speculative nature of the instrument's original sound" [15, p. 83] must be acknowledged.

This perspective stands in contrast to earlier views, such as those of Benton Fletcher, who insisted that instruments should remain playable in order to avoid becoming relics in a "dead museum of glass cases" [17, p. 154, quoted in a letter]. Fletcher's sentiments are echoed in a later report on the restoration of instruments within his donated collection. As relayed by Barclay [16], the report warns against instruments being relegated to "a temple of silence where it may be conserved as a piece of furniture, its musical function forgotten" [1]. The tension between Barclay's three states reflects a wider discourse in the heritage sector over the past decade concerning "living heritage" versus static, preservable "dead heritage" [197, 226].

Poulios [197] critiques values-based conservation for treating the past as dead, creating a discontinuity between past and present experiences. In contrast, the living heritage paradigm emphasises the ongoing, dynamic use and relevance of heritage, advocating for the preservation not only of physical artefacts but also of the practices, skills, and meanings that sustain them in contemporary life.

While Poulios' arguments are primarily directed at heritage sites and ceremonial objects, the underlying philosophy extends to the broader category of heritage artefacts, including musical instruments. The framing of conservation as a strict choice between static, dead heritage and perpetually living heritage constitutes a false dichotomy.[1] The reality is more complex: to treat heritage as endlessly living without acknowledging its material finitude risks producing an undead heritage—neither truly alive nor genuinely preserved.

1.1.2 A New Value for Conservation

The justification for conserving heritage objects often rests upon a complex matrix of values. Avrami et al. [13] provide a collection of value systems that underpin conservation decisions across different disciplines and organisations, summarised in Table 1.1.

Art History	**ICOMOS Australia**	**Economics**	**English Heritage**
Alois Reigl	Burra Charter	Bruno Frey	
1902	1998	1997	1999
Age	Aesthetic	Monetary	Cultural
Historical	Historic	Option	Educational and academic
Commemorative	Scientific	Existence	Economic
Use	Social	Bequest	Resource
		Prestige	Recreational
		Educational	Aesthetic

Table 1.1: Comparative analysis of value systems in heritage conservation (Adapted from Avrami et al. [13]).

In addition to those discussed above, this work proposes a new category for musical instruments—and potentially for all heritage objects that embody craft and practice—termed "instructional value." Instructional value refers to the capacity of a heritage object to convey knowledge of practice, technique, and skill intrinsic to its use and creation. A painting or sculpture may reveal insights into artistic methods through "witness marks," the traces of the artist's hand or materials. Similarly, a musical instrument can serve as a pedagogical tool for performers, luthiers, and scholars, instructing through its construction, wear patterns, and interaction how music was historically produced and experienced.

Instructional value may superficially appear to be a subset of educational or academic value. This conflation obscures a critical distinction between "descriptive knowledge" (knowing

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[1] "A handful dismissed the idea of heritage as a negative idea, noting, for instance, that heritage was keeping that which ought to be alive dead." [226]

that) and “procedural knowledge” (knowing how). This division is essential to resolving tensions in musical instrument conservation, where preserving the physical object alone cannot fully capture its performative essence without maintaining or reviving the skills and practices it embodies. The information derived from playing an instrument is difficult to convey to performers, who in turn find it difficult to express [143].

The discourse around conservation frequently centres on the notion of “authenticity” [144, 194], particularly in the context of historically informed performance [47]. Setting aside the complexities and debates surrounding the meaning of “authenticity,” it is important to recognise that the audience’s experience often dominates discussions of musical heritage. Yet consider a scenario in which a performer rehearses a piece fifty times before performing to an audience of fifty who hear it once. Which value is represented, and by what magnitude, in the course of the performance? This thesis argues for the performer’s experience—shaped by the instrument’s unique qualities—and for the significant instructional value derived from it, which is equal to or greater in magnitude than those values relevant to the audience.

Through hours of embodied interaction, the performer acquires a richer, more nuanced understanding, gained through tactile feedback and “gestural repertoires” [146] intrinsic to playing the instrument. The instrument shapes the performance as much as the performer shapes the music. This interplay is especially salient when comparing, for instance, a modern Steinway piano with a historical harpsichord, where differences in touch, sound production, and response create distinct musical experiences. Put simply, this is yet another example of McLuhan’s maxim that “the medium is the message” [160].

Conventional museum practice rarely permits visitors to handle or play historical instruments. Though instruments may be in “playing condition,” they are not typically playable by the average museum visitor. Instead, instruments are cordoned off behind a—real or imagined—“red velvet cord” [157], displayed as objects to be seen but not touched. This approach deprives visitors of the vibrotactile and kinaesthetic cues encoded into the instrument’s interface. The challenge, then, is how to reintroduce embodied interaction with historical instruments in ways that respect conservation imperatives while restoring some degree of their living function.

Regarding the “priorities for future collecting” for the harpsichord collection at the Musical Instrument Museums Edinburgh, from *Collections Management Policy 2020-2030* [151]:

> The collection is generally considered to have the widest scope of any in the world. Each item is important for reasons relevant to research and teaching, and in some cases, performance potential.

For instruments that originated from a fixed point in time (e.g., sixteenth-century harpsichords), “performance potential” is becoming increasingly unlikely. A holistic conservation framework for musical instruments must integrate both values-based and living heritage perspectives. Such a synthesis acknowledges the physical realities of ageing instruments while honouring their performative and instructional roles. This integration opens pathways to novel conservation strategies that extend beyond current paradigms.

1.1.3 Reproduction or Restoration

Musical instrument states of Currency and Restoration must contend with a Ship of Theseus problem: how much alteration can the original instrument undergo before it ceases to be considered the same object? The drawback of restoration is twofold: the process can be irreversibly destructive both to the instrument's longevity [15] and to the surviving evidence of original craftsmanship [132]. If the authenticity of performance requires the use of an original instrument [133], and if "every restoration [...] wipes away evidence and makes the original [...] condition more remote" (from Waitzman [250], quoted in Barclay [16]), then there exists only a finite reservoir of authentic music to be played. This is not a sustainable long-term approach for enabling performance on historical instruments.

Barclay has been critical of restoration [15], while at the same time expressing caution regarding the notion of an "authentic copy" [17]. For a replica to be of instructional value, Barclay appears to assume—perhaps mistakenly—that we must still make this assemblage of materials into a working musical instrument, comfortable and useful to players of the twenty-first century [17]. This assumption risks overlooking the possibility that it is from the "gestural repertoires" [146] of the original instrument that the most meaningful insights may be gained.

Approaches to historical instruments that prioritise either strict conservation or reproduction preserve the informational integrity of the original and thus avoid the Ship of Theseus problem altogether. Even so, reproduction is not without contention. Barclay cites two cases of copying—a recorder and a natural trumpet—to address the broader issue of fidelity to measurements, a concern also raised by Koster [139]. In raising the "thorny issue" [17] of reproduction, Barclay draws on Koster [140], who argues not for aesthetics but for tonal quality. In evaluating a 1785 Jacques Germain harpsichord copy, Koster concludes that "a direct comparison of the Germain harpsichord and its copy shows that the tone of the copy does not quite match the surpassing elegance of the original" [140]. The conclusion that the older instrument sounded superior to its copy is echoed by contemporaries,[2] and even a team of museum experts may hesitate before creating a copy.

However, given recent studies by Fritz et al. [85–87]—which demonstrate that the acoustic quality of older violins, including those by Guarneri and Stradivari, deteriorates over time—Koster's conclusion may be unsound. His objections to copies also extend beyond acoustics: they might deceive by being misrepresented as originals, or deviate from the original simply through the act of replication. Yet an argument against reproduction based on acoustics must be tested empirically. To demonstrate that a copy sounds inferior, an ideal study would require a double-blind design. Great care is also necessary to clarify exactly what is being assessed.[3]

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[2] " 'A Stradivari has the ability to deliver the whole range of tonal colors [...]' [says] Simon Morris, the director of Beare's [...] 'New violins don't have the range of tonal colour. The depth of personality isn't there [...]' " [166]

[3] "Of course, the community didn't like these results. And so, the study was heavily criticised. We basically got killed on the Internet, on phones—'What have you done? How can you disrespect Stradivarius so much?' People were really not happy, and then they found all different excuses to justify that the study was necessarily badly conducted, starting with the fact that we definitely chose a bad Stradivarius—which was already a good move because, I mean, now people were happy to acknowledge that there could be a bad Stradivarius. That was always

"That's where the 'accurate copy' inevitably falls from grace. And this is, of course, grist for the mills of those who argue for restoring as opposed to copying." In light of recent scientific studies, it would appear that neither approach can be considered accurate. The limitations of copying are no longer "grist for the mills" [17, p. 81] of restorers, as that approach cannot be deemed "authentic" for all instruments either, and is detrimental to other heritage values an instrument may hold. An "authentic ruin" may provide more valuable information than a "falsely stored original" [Citing Martin Skowroneck 17, p. 78]. This was already apparent in 1985 when Karp wrote: "it is becoming obvious that restored older instruments do not necessarily behave or sound as they did when they were new" [133].

There is also an implication in this rhetoric that the original makers of these historical instruments could perform perfectly—"a true acoustical copy" [139]. In the work of Viala et al. [249], material variability and the effects of geometry mean that, if the goal is indeed an "acoustical copy," the construction will likely deviate from the original. The environmental impact of musical instrument fabrication should not be discounted [3], suggesting that the opposition between replication and restoration is a false dichotomy, and that environmental concerns make neither approach feasible at scale.

1.1.4 Conservation and Sustainability

Musical instrument restoration and reproduction do not exist in isolation. Instruments require raw materials for their manufacture, and many of the materials historically employed are no longer readily available—or may soon become scarce. As part of the broader discussion on the preservation of musical instrument heritage, environmental concerns must also be considered.

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is a multilateral treaty that protects animal and plant species threatened by international trade. CITES maintains three Appendices, which classify species according to the degree of threat they face, with Appendix I representing the highest level of protection and Appendix III the lowest. Among the species listed under these Appendices are several materials traditionally used in the manufacture of musical instruments. Table 1.2 presents examples of woods commonly used in instrument making that are currently subject to CITES regulations.

The use of these woods, and the implications of their inclusion in the CITES Appendices for the musical instrument industry, are far from trivial. For example, a large seizure of illegally harvested Pernambuco—used in the manufacture of violin bows—was reported in Brazil [243]. Similarly, in 2008, the Gibson Guitar Company was implicated in the import of illegally harvested wood from Madagascar [201]. Such cases highlight the significant environmental impact that the musical instrument industry can exert on endangered ecosystems.

As more tree species become at risk and are brought under the protection of CITES, many of the materials historically employed in instrument making are no longer legally obtainable.

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something going forward." [84]

Common Name	Scientific Name	Appendix	Year Added	Use
Brazilian Rosewood	Dalbergia Nigra	I	1992 [224]	Fretboards
Pernambuco	Paubrasilia Echinata	II	2007 [178]	Bows
Madagascar Ebony	Diospyros spp.	II	2013 [101]	Fingerboards
Rosewood	Dalbergia spp.	II	2017 [9]	Fretboards

Table 1.2: Species of wood used in musical instrument manufacture, their CITES Appendix, and the year they were added. The Convention on International Trade in Endangered Species of Wild Fauna and Flora lists species in Appendices, with Appendix I providing the most severe protection and III the least. The abbreviation "spp." denotes all species of a higher taxon.

Beyond legality, it is also financially and ecologically unsustainable to maintain historical instruments in their original form on a large scale. Viewed through the lens of environmental responsibility, the binary choice between replication and restoration appears increasingly untenable. Neither option, pursued at scale, is financially or ethically viable. Moreover, the number of historical instruments that could realistically undergo such processes is inherently limited, raising a further question: who decides which instruments are deemed worthy of replication or restoration?

1.1.5 A Third Path

DeSilvey [50] poses the question, "what could be gained if we were to care for the past without pickling it?" If heritage can exist in a living state—and a conservation approach is akin to the 'dead' [197]—then there must also be a transitional phase in which heritage dies and moves from one state to the other. Rather than resisting or fearing this transition, DeSilvey [50] suggests that we might instead embrace this natural process. Barclay [17, p. 75] touches on a similar idea in his discussion of 'benign neglect,' where the preservation of the playing state—or Currency—is passive, yet the decision to allow it is deliberate. We might then turn to other approaches to maintaining the 'idea' of an instrument. Rather than striving for the "exact copy," we can consciously and deliberately seek an 'imperfect' reconstruction that elicits the "social, political, historical, conceptual, and contextual" aspects of musical instrument heritage [119].

What is presented here is an approach to the conservation of historical harpsichords that is equal parts reconstruction, emulation, and re-enactment of the original interface. In creating this new augmented interface, however, a question arises: how should this new artefact itself be conserved as it ages? If the same process were to be repeated—preserving and reconstructing each copy in turn—it would become 'harpsichords all the way down.' Instead, this new interface should be regarded as finite, with the focus of conservation directed not toward the interface itself but toward the 'instructions' for recreating it.

For this reason, the term 'conservation,' rather than 'preservation,' is used deliberately throughout this thesis in reference to musical instrument heritage. As the discussion above has shown, the working lifespan of an instrument—the period during which it can provide instructional value—is finite. To attempt to 'preserve' a specific instrument with instructional value in mind is a futile endeavour. What can be achieved, at best, is 'conservation:' sustaining the instrument for as long as possible through careful treatment and documentation.

1.2 Digital Conservation

Having outlined the broader challenges of musical instrument conservation, this section examines the role of digital technology within that context, under the term 'digital conservation.' Although the phrase more commonly appears in biodiversity and environmental research [251], it is employed here with reference to "digital heritage" [174], "digital preservation" [92], and "digital cultural heritage" [82].

To clarify the terminology used throughout this thesis:

- **Digital preservation** refers to the process of creating and maintaining digital surrogates of artefacts to ensure a persistent record.
- **Digital heritage** encompasses all "digital materials of enduring value" [174], including documents, datasets, and software.
- **Digital cultural heritage** designates heritage artefacts that have undergone digitisation, with specific reference to their digital instances.

Digital conservation is a compound problem. It inherits the systemic challenges of digital preservation while introducing domain-specific issues for musical instruments—most notably, the difficulty of preserving the tactile, embodied experience of performance. As discussed previously, this is not an exclusively digital problem, but it becomes more acute when interaction is mediated through screens, sensors, and code.

The heritage sector's use of digital technology remains far from settled. Immersive media and interactive systems are frequently heralded as transformative [61, 93, 147], yet a critical question persists: have museums truly been transformed by digital technologies, or have they merely deployed them with an analogue mindset? The digital should not replace the physical artefact; rather, it should extend the artefact's reach and interpretive context [79, 190]. Digitisation is not a single act but an ongoing process [136, 209]. Both digital and analogue collections ultimately depend on physical media [209], and the financial and energy costs of keeping bits alive can exceed those of maintaining an analogue equivalent [37]. For example, *The digital dilemma: Strategic issues in archiving and accessing digital motion picture materials* [216] reported in 2007 that archiving a physical film cost \$1,059, while the equivalent digital archive cost was an order of magnitude higher at \$12,514.[4]

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[4] "Based on an annual cost of \$500 per terabyte of fully managed storage of three copies of an 8.3-terabyte 4K digital master." [216]

One clear advantage of the digital domain is its capacity to aggregate data from disparate sources. Projects such as Musical Instrument Museums Online (MIMO) collate catalogue data from distributed collections, improving access and enabling large-scale comparison. The usefulness of such systems depends on data quality and stewardship [54], both of which require multidisciplinary expertise. Museum professionals need training in data management, obsolescence, and silent corruption [190, 209, 215]; across the humanities, significant gaps remain in sustainable data practices [238].

A further consideration concerns the ‘digital heritage we create’—the software, datasets, and workflows produced during conservation. If instruments are preserved digitally, then the tools of preservation must themselves be preservable. Software reproducibility remains a persistent challenge [192], with processes often becoming irreproducible after surprisingly short periods [204].

The digital components of this thesis therefore adhere to current best-practice guidelines. The remainder of this section outlines the organisational approach and motivations underlying the chosen methodology.

1.2.1 Open Methods

Addressing digital musical instrument conservation requires frameworks that account for preservation, access, and reuse. Open Science [246] provides a foundation by promoting the open sharing not only of results[5] but also of the processes through which those results are obtained. Digital technologies make such openness feasible, yet they also necessitate structure. The FAIR principles—Findable, Accessible, Interoperable, Reusable—offer a practical framework for managing digital assets [254]:

- **Findability:** digital assets should include rich metadata and persistent identifiers.
- **Accessibility:** access protocols should be open, free, and universally implementable.
- **Interoperability:** data and tools should integrate seamlessly across heterogeneous systems with minimal effort.
- **Reusability:** assets should be released with clear, accessible licensing and provenance.

For software, FAIR also implies citability [227]. This requires coordinated action by authors [225], by those citing software [135], and by journals that must cross-reference software artefacts [230]. Open software is ideally “living,” yet research demands that specific versions remain discoverable and stable. Version control systems (e.g., `git`) allow releases to be tagged, while public repositories (e.g., GitHub) enhance discoverability. For long-term reference, archival deposition (e.g., Zenodo) provides persistent identifiers (DOIs) [225, 230].

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[5] Examples include original research outputs, research data, software, source code, workflows and protocols, and digital representations of pictorial and graphical materials [246].

Persistence is one dimension of sustainability; reproducibility is the other [192]. Software should remain functional in the future despite changes in languages, libraries, and hardware—and despite more mundane obstacles such as incomplete documentation [204].

1.2.2 Reproducibility

Digitally designed 'hardware' introduces additional challenges. In digital musical instrument (DMI) design, long-term reuse remains difficult [73]. Hardware projects typically combine electronic schematics, CAD/CAM assets, bills of materials, and assembly or operation documentation; these components must be archived together within a well-structured repository [30]. CAD formats and toolchains themselves pose preservation risks. During the course of this thesis, Autodesk announced the discontinuation of the EAGLE EDA tool [12], effective July 2026. A deliberate decision was made to continue using EAGLE's XML-based format: much as the end-of-life of Python 2 "calcified" that environment for archival purposes [207], EAGLE's stable format remains processable by other tools such as KiCad [33].

Perkel [192] aggregates guidance from the ReScience C ten-year challenge on reviving decade-old research software. Its key recommendations—version control, archival deposition, and explicit documentation—align with broader best practices [225, 230].

All digital assets associated with this thesis are released under the GPLv3 licence, following recommendations to grant permissions as openly as possible [230]. GPLv3 permits copying, distribution, and modification, with the stipulation that derivatives remain under the same licence [81]. Repositories were structured in accordance with guidance from the Software Sustainability Institute and were subsequently reviewed by the Institute at the University of Edinburgh [45].

1.2.3 Case Study: Aurora

During the course of this PhD, Professor Angelo Farina—a prolific acoustics researcher and author of several freely available analysis tools—passed away. Among his contributions, the Aurora suite provides a pertinent case study in software sustainability: it holds enduring value and has supported digital cultural heritage projects for decades [4, 71, 83].

Aurora originated in 1995 [65] as an extension to Cool Edit [244] (later Adobe Audition [70]) and was initially distributed alongside Farina's Ramsete room-acoustics simulator [66] via shareware sites. Its widespread adoption followed the introduction of sine-sweep impulse response measurement [67]. In 2009, Simone Campanini ported Aurora to the open source editor Audacity [31], ending the "Russian roulette" shareware model [68] and making Aurora freely usable.

Aurora remains widely cited [49, 78, 196], and development continued as recently as 2023 [21]. However, the absence of consistent software citation complicates provenance: inferring versions from publication dates is imprecise, and significant code changes may affect the comparability of results. In response, a small conservation effort—in collaboration with

Campanini and Farina—uploaded the Audacity variant's source to a public version-controlled repository, licensed under GPLv3 and assigned a DOI [69], in line with best practice [120, 230].

Technically, Audacity supports extensions through an experimental module system.[6] Modules must be co-compiled with the host source and version-checked at load time. This strategy enabled distribution of a single working editor with Aurora integrated, but it also tightly coupled module and host code, rendering Aurora vulnerable to breaking changes as Audacity evolved—particularly following its 2021 partnership with Muse Group [199]. Consequently, Aurora's long-term availability depends on maintaining build compatibility.

Farina's websites hosted Aurora binaries,[7] but such hosting remains fragile.[8] The Audition-era source code is not public; the current repository is therefore only a partial historical snapshot. This situation is not unique. The YIN pitch-detection code by Cheveigné et al. [34] faces similar challenges: widely used, historically hosted at unstable URLs,[9] and often cited via papers rather than as software artefacts. When the 'software'—not merely the algorithm—is integral to research, the scholarly record should include an accessible, citable source package.

These examples highlight an institutional responsibility: research organisations should host software repositories, assign DOIs, and provide light-touch stewardship for outputs arising from funded projects. Documentation is likewise central to sustainability [192]; even simple steps such as adding a licence can improve community engagement [40]. Lessons drawn from Aurora and YIN inform the project structure, documentation practices, and digital outputs presented in this thesis.

1.3 Free Open Source Software for Acoustics Research

The preceding discussion highlighted the fragility of digital heritage and the responsibilities that follow from creating new digital tools. Having shown how issues of access, licensing, documentation, and long-term stewardship affect the preservation of software itself, it is necessary to consider the broader ecosystem into which such tools are released. This section therefore surveys free and open source software (FOSS) relevant to acoustics research, with particular attention to projects that intersect with heritage practice—whether through analysis, simulation, reconstruction, or measurement of instruments and spaces. The aim is not to catalogue the field exhaustively but to understand the current landscape into which new work is introduced, identify patterns of good practice and recurring shortcomings, and clarify where further development is needed.

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[6] `https://manual.audacityteam.org/man/modules.html`

[7] `https://www.angelofarina.it/Aurora/download`

[8] At the time of writing, Farina's University of Parma site (`http://pcfarina.eng.unipr.it`) is down, though it has been mirrored at `https://www.angelofarina.it`.

[9] `http://www.ircam.fr/pcm/cheveign/sw/yin.zip` (defunct); see also `http://audition.ens.fr/adc/sw/yin.zip`.

1.3.1 Software Documentation

Following Procida [198], four complementary forms of documentation can be distinguished: Tutorials, How-to guides, Explanation, and Reference. These forms naturally divide into two audiences: user-facing and developer-facing. Adapting Procida [198], developer-facing documentation lies in the How-to and Reference categories, while user-facing documentation is found in Tutorials and Explanation. This division is not strict, as the binary of 'user' and 'developer' rarely holds true in practice; rather, audiences exist along a continuum. Reference documentation can be generated from source annotations to avoid duplication and support automation. Across MATLAB, Python, and C++, multiple conventions coexist [99, 206], supported by tooling ecosystems such as Doxygen, Sphinx, and HeaderDoc.[10] Even so, generated API references should not substitute for user manuals [231, Section 6.2], though this is often the case [198].[11]

Best practice emphasises the importance of documentation [225], though it is less prescriptive about form and depth. Write the Docs Community [259] offers comprehensive guidance; a pragmatic rule is that documentation should enable you to still "understand your code in six months" [259], a principle echoed in reproducibility studies [192]. Using the The Software Sustainability Institute's [241] checklist, the core requirements for an open research software project are: publicly available source code, a version control system (VCS), user and developer documentation, an OSI-compliant licence, and persistent identifiers (typically DOIs). A public VCS implies source availability, though the reverse is not guaranteed. Likewise, a DOI implies some level of digital archiving, but a release archive does not necessitate a DOI. DOIs should be assigned both to the software as a whole and to individual releases [225]; licences should be clearly stated and OSI-compliant [121]. To better support complex software citation, Druskat et al. [55] introduced the Citation File Format (CFF), which standardises metadata for software citations and is supported by both GitHub and Zenodo. Recommendations in Fiordelmondo et al. [73] extend this to hardware projects, with tools for citation [228]. Beyond these essentials (contribution policies, issue tracking, codes of conduct), more advanced practices presuppose an active repository. The following subsections examine seven projects in this light.

Aurora

As discussed in Section 1.2.3, Aurora began in 1995 and became fully open only with the 2009 Audacity port [31]. The project now has an OSI-compliant licence and a citable release with a DOI [69]. Developer documentation remains sparse; a user manual exists but is not currently configured for community contribution.[12]

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[10] See the Stack Overflow Data Explorer for indicative tag counts: `https://data.stackexchange.com/stackoverflow/query/1069131/get-all-tags`.

[11] `https://diataxis.fr/reference/`

[12] `https://www.aurora-plugins.com/Package.htm`

ITA Toolbox

The ITA Toolbox emerged around 2010 [53], moved to RWTH Aachen's GitLab in 2016, and adopted an explicit open source model in 2017 [20]. The toolbox can be viewed as a successor to Aurora for measurement and analysis [52]. Developer documentation within MATLAB is extensive, but—as cautioned by Stallman et al. [231]—"doc strings" are not a substitute for a user manual. Public-facing materials correspond mainly to "Tutorials" in *Diátaxis documentation framework* [198]; other forms are limited. Recommended citations are tied to publications; releases are available via the institutional GitLab. The toolbox depends on proprietary MATLAB toolboxes, narrowing its audience. Its BSD-4-Clause variant is not currently OSI-approved.[13] Despite these caveats, it remains a well-maintained institutional open source effort and has been used in heritage case studies [63]. A Zenodo DOI has been suggested [20] but, at the time of writing, not implemented—possibly due to the BSD-4-Clause's non-compliance with Zenodo's licence requirements [263].

ITEMM OpenLab

The ITEMM OpenLab platform[14] provides resources for makers, including datasets, CAD models, and workshop-oriented calculators. Of particular relevance, the *Rigidité de plaques* tool implements McIntyre et al. [159] for plate elastic constants.[15] While accessible after registration, the model is distribution-free rather than open source; code delivered to the browser can be inspected but is not clearly licensed for reuse.[16] Legal terms cover 3D models under CC-BY-SA,[17] but do not explicitly extend to calculators [41]. By contrast, MAGPIE follows an "open first" approach aligned with FAIR principles [254, 255], aiming for sustainability, interoperability, and citability (as defined by Soito et al. [227]). The intent is FLOSS rather than merely "open source" [233]—the inclusion of an explicit 'L' for *libre* to encompass the two meanings of 'free.'

NeSS

The Next Generation Sound Synthesis (NeSS) project at the University of Edinburgh employed GPU acceleration for physically based synthesis of instruments and acoustics, running from 2012–2017. During this thesis, the source was released under the MIT licence on GitHub, with documentation covering build steps and partial structure,[18] and an associated website providing explanations and examples [175]. Given its recent release, citations outside the original project remain limited.

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[13] `https://spdx.org/licenses/BSD-4-Clause.html`

[14] `https://www.openlab-itemm.com`

[15] `https://www.openlab-itemm.com/calculateur-mecanique/rigidite-de-plaques-1/`

[16] See `js/p_w_script.js` and `js/olt_class.js`.

[17] `https://www.openlab-itemm.com/mentions-legals/`

[18] `https://github.com/Edinburgh-Acoustics-and-Audio-Group/ness/tree/main/doc`

PFFDTD

PFFDTD [104] provides open source room-acoustics simulation driven from SketchUp models,[19] using CUDA for GPU acceleration and open languages (Ruby, Python, C) elsewhere. Documentation includes references and installation guidance; a concise how-to guide is also provided. The project suggests a standard citation—a positive step for traceability—though a DOI would further improve citability. Tools of this kind support virtual exploration of cultural heritage spaces [42, 134, 244].

VK-Gong

VK-Gong (ENSTA Paris) simulates nonlinear plates and shells relevant to gongs, cymbals, and bells. MATLAB and C++ sources are hosted via an institutional site, accompanied by an unusually comprehensive MATLAB user manual [8]. The site lists CC-BY-NC-SA-4.0,[20] though the licence text is absent from source files; CC licences are discouraged for software by both Creative Commons and the OSI [41]. No public VCS is used, limiting collaboration and issue tracking. Platform-specific optimisations (Intel SSE intrinsics) hinder portability, particularly to Arm processors; without a VCS, workarounds must be rediscovered by each user. Despite these hurdles, VK-Gong has been used in research [176], though it is more difficult to track compared to other examples.

YIN

The YIN pitch detector [34] is widely adopted, with MATLAB code commonly used in studies (e.g., Bowen et al. [27]). The software lacks a stable URI or DOI and carries a “FOR RESEARCH PURPOSES” restriction,[21] which is not OSI-compliant. Documentation consists primarily of the original paper (*Explanation* in Procida [198]); developer reference is absent. Technical friction arises from MATLAB MEX changes post-R2016a [156], requiring users to rebuild binaries individually.

1.3.2 Summary of Acoustics Software Practice

Across these seven projects, there is a clear movement towards openness, but uneven adherence to best practices. Table 1.3 summarises the status with respect to source availability, version control, documentation, licensing, and persistent identifiers. Two trends stand out. First, persistent identifiers are largely absent; where present, suggested citations help but do not replace DOIs [122]. Second, developer documentation is thin; most projects assume technically experienced users, narrowing adoption outside core acoustics communities. Licensing is generally present, though some projects apply non-OSI licences (or CC variants) in ways that

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[19] `https://sketchup.trimble.com`

[20] `https://creativecommons.org/licenses/by-nc-sa/4.0/`

[21] `https://github.com/mhamilt/yin/blob/main/LICENCE`

Project	Source	VCS	Reference	Manual	Licence	DOI
Aurora	Yes*	Yes*	No	Yes*	GPL-3.0-or-later	Yes
ITA Toolbox	Yes	Yes	Yes	Partial*	BSD-4-Clause†	No*
ITEMM OpenLab	No*	No	No	No	CC-BY-SA-4.0*†	No
NeSS	Yes	Yes	Partial*	Yes	MIT	No
PFFDTD	Yes	Yes	No	Yes	MIT	No
VK-Gong	Yes	No	No	Yes	CC-BY-NC-SA-4.0†	No
YIN	Yes	No	No	Partial*	Bespoke*†	No

Table 1.3: Acoustics FOSS compliance overview. †Not Open Source Initiative—approved. * See relevant project section for discussion.

limit reuse [41, 121]. Finally, software evolves: dual DOIs (project and release) clarify which version underpinned a result and make bugs or behavioural changes traceable in retrospect.

The GNU Software Freedoms [232] can be summarised as the freedom to run, copy, study, and modify FOSS. From Table 1.3 we can see that the freedoms to run, copy, and study are well represented in the research software discussed, but the last—to modify—is the most underserved. Any source code can be modified if it is publicly accessible, but to do so one must first understand it, and bare code rarely provides sufficient information. From the lack of universal version control and reference documentation, we can surmise that there is little or no expectation of external development for the software discussed above. This conclusion is further supported by the absence of DOIs: when software is not 'alive,' there is little reason to cite it directly. Static software, on the other hand, can be referenced through suggested paper citations, as it will function the same as at the time of publication.

The projects presented in this thesis—the keyboard interfaces and MAGPIE—aim to model FLOSS-aligned research practice: public version control, explicit licensing, structured documentation for users and developers, and archival deposition with DOIs. The thesis and associated papers [114, 115] constitute the explanatory documentation, with the remaining forms distributed across repositories [58, 108–112, 116] and online reference manuals [105–107].

1.4 Thesis Outline

This thesis describes two digital projects, each addressing a distinct stage in the digital heritage[22] conservation pipeline (Figure 1.2a). Chapter 2 considers musical heritage once digital conservation has taken place, asking the question: how can interaction with a digitised musical instrument be facilitated? Chapter 3 represents the beginning of the process, focusing on the

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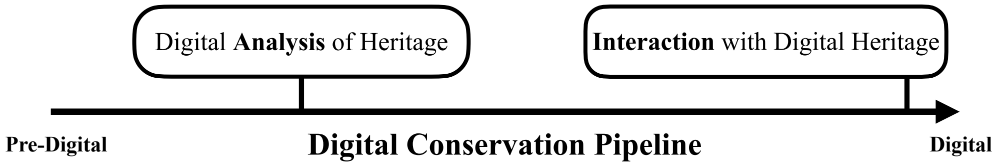
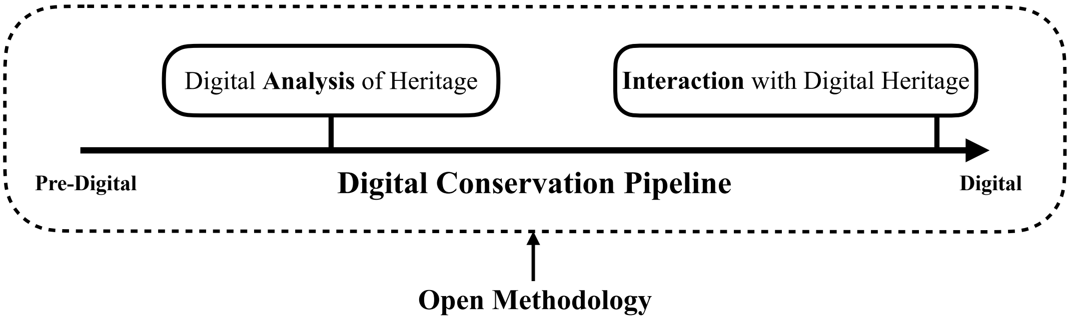
[22] more specifically, musical heritage

(a) A heritage object traverses the digital conservation pipeline, moving from its original, pre-digitisation form (left) to a fully digitised representation (right).



(b) The projects in Chapters 2 (**Interaction**) and 3 (**Analysis**) occupy different points along the digital conservation pipeline. **Interaction** explores interaction with a fully-digitised heritage object. **Analysis** focuses on understanding the materials of a heritage object through digital analysis.



(c) Underpinning both chapters is an open methodology that aligns with FAIR research practices, ensuring the longevity and reproducibility of digital research.

Figure 1.2

analysis of materials—in this case, those of the harpsichord—which can inform subsequent decisions about conservation strategies [15].

Chapter 3 discusses the steps taken to ensure sustainability in a purely software-based project, where both a functional software library and an interface library were developed for the MAGPIE framework. In contrast, for electronic hardware the problem of sustainability is compounded by the inclusion of physical components, their schematics, and assembly processes, alongside the firmware and software required for operation. The process for addressing these challenges is discussed further in Chapter 2.

Binding these projects together is an open methodology (Figure 1.2c): a system of methods, tools, and processes that should be considered integral to any digital cultural heritage project. This thesis aims to demonstrate the considerations necessary to adhere to the FAIR principles—Findable, Accessible, Interoperable, and Reusable—particularly within cross-disciplinary research. All digital assets—whether source code, measurement data, or CAD files—are managed in accordance with these principles.

Given the context outlined in this chapter, how can the principles of Open Science and FAIR be embedded at the core of digital academic research outputs? This thesis explores what FAIR and Open Science aligned research requires in practice across the different stages of the digital conservation pipeline. The digital outputs of this thesis conform to a consistent set of requirements. All assets are maintained under version control using the `git` system, with repositories hosted on GitHub to ensure public access. When a repository release is created, it is automatically archived in Zenodo, which generates a persistent DOI.

Within the context of this thesis, a 'release' refers to any self-contained, functional version of an asset used during the course of research. Digital assets are inherently dynamic: they evolve over time as they transition from one release to the next.

1.4.1 Chapter 2: Interaction

Chapter 2 presents the creation of a model harpsichord interface augmented with an electronic optical sensor system, enabling interaction with digital software instruments. The chapter discusses the design, prototyping, and fabrication stages, as well as the final deployment as part of an exhibition at Museo San Colombano, Bologna [212].

Technological advances have reshaped the ways museums document, present, and interpret their collections. Immersive experiences are now made possible through tools such as 3D printing and virtual reality, yet these technologies can sometimes place a veil between the visitor and the heritage object, distancing rather than engaging them. Although such media can facilitate experiential authenticity, achieving it requires museums to carefully negotiate the balance between preservation and meaningful engagement [194]—a tension that is especially pronounced in historical musical instrument collections [157].

Musical instruments occupy a distinctive position within cultural heritage: they are not only aesthetic artefacts but also functional tools with an inherently tactile dimension [211]. Over time, however, they inevitably deteriorate to the point of being too fragile for handling [187]. This places museums in a persistent dilemma between accessibility and conservation, often restricting how visitors can interact with collections [157, 240]. The key question, then, is how to preserve not only the physical object but also the embodied experience of playing it.

This chapter addresses that question by presenting the design and creation of a replica harpsichord keyboard with a typical early Italian layout, electronically augmented for use in an interactive exhibition. Moving beyond the constraints of the traditional "red velvet cord" [154, 157], the replica seeks to enhance visitor interaction while protecting fragile originals. Rather than pursuing technical novelty, the project demonstrates how digital interventions can foster meaningful engagement with musical heritage, sustaining its relevance within contemporary museum practice.

The resulting exhibition at Museo San Colombano in Bologna provided visitors with a tactile interface to digitised versions of instruments in the collection. It was grounded in the understanding that human perception of music is strongly shaped by visual cues [85–87, 245]. The installation sought to balance historical authenticity, accessibility, and preservation, while contributing to broader debates on the role of technology in museums. The chapter discusses the keyboard's design principles, technical implementation, and implications, highlighting its potential to deepen public engagement and support the long-term preservation of musical heritage.

Chapter 2 begins with a review of related work over the last forty years in the fields of haptic keyboard interfaces and museum-based musical heritage interaction. This specific context is then connected to the broader discussion of digital cultural heritage and musical instrument conservation (as outlined earlier), showing how these considerations informed the interface design process and the constraints that emerged from it. The project is presented in discrete stages, from initial design and prototyping through to the fabrication of two final interfaces: one exhibited at Museo San Colombano, and a second used for continued research within the NEMUS project.

1.4.2 Chapter 3: Analysis

Chapter 3 examines the creation of an open source software tool for plate vibration analysis, material property estimation, and musical acoustics education. Although applications of plate simulation continue to expand, access remains largely restricted to specialised, proprietary software—often prohibitively expensive for students or smaller research groups. This work presents the theoretical background and initial implementation of MAGPIE, an open source platform for simulating plate physics. MAGPIE provides intuitive visualisation tools and a range of analysis methods, making it suitable both as a teaching aid for instructors and as a research tool for academics and industry professionals.

Its functionality includes defining elastic boundary conditions along plate edges, visualising and exporting eigenshapes and corresponding frequencies, running time-domain simulations of the plate equation for sound synthesis, and estimating the elastic constants of experimental plates. This final feature—estimation of elastic constants—forms the basis of a tool for soundboard analysis to assist luthiers and conservators working with historical string and keyboard instruments.

MAGPIE offers a valuable data point, providing insight into the internal condition of wooden plates through their elastic constants in a non-destructive and inexpensive way, without reliance on costly finite-element software. In parallel, MAGPIE seeks to make accessible the scientific tools developed within the NEMUS laboratory, adapting them to simplify their use and lower technical barriers to entry.

Chapter 3 begins with a discussion of existing software for plate analysis and the core mathematical problems that must be addressed. It then traces the development of MAGPIE from an initial proof-of-concept to a structured software library. The chapter concludes with an examination of MAGPIE's implementation across multiple programming languages and the application of the open methodology introduced earlier.

1.4.3 Chapter 4: Future

Chapter 4 explores future directions for the projects presented in Chapters 2 and 3. These developments are considered alongside their implications for each project's design principles and for the broader open methodology. Neither project represents an endpoint; rather, both offer numerous opportunities for expansion, optimisation, and refinement. This chapter discusses selected avenues for development of the interface and of MAGPIE in turn, outlining the technical challenges involved and their potential impact on both the open methodology and adherence to the FAIR principles.

Future developments for the interface are divided between mechanical fabrication and electronic systems. In the mechanical domain, particular attention is given to the design of the jacks and the potential integration of sensor surfaces within them. This is followed by a discussion of the electronics system, focusing on refinements to the sensor circuitry, extensions of functionality, and the resulting implications for project accessibility. The section concludes with a forward-looking discussion on digital musical interfaces as tools for research and musical expression, and the unexplored possibilities that the current system presents.

The final section considers the future of MAGPIE, discussing expanded functionality and changes already underway at the time of writing but not yet consolidated into an official release. The ongoing development of MAGPIE's graphical interfaces is also outlined, with particular emphasis on emerging web technologies that promise to make the software more accessible and sustainable in the long term.

Chapter 2

Interaction

As part of a broader commitment to accessibility, the Museo San Colombano-Tagliavini Collection,[1] situated within Fondazione Carisbo's cultural itinerary in Bologna [167], has undertaken a series of projects aimed at enhancing both cognitive and sensory engagement. Supported by funding from NextGenerationEU,[2] these initiatives seek to leverage the collection's rich holdings to create immersive and interactive modes of encounter with the exhibited heritage. Central to this vision is the reinterpretation of historical musical objects through their tactile and auditory dimensions, making the exhibition more inclusive for blind and partially sighted visitors, as well as the general public. The Tagliavini Collection comprises over fifty historical keyboard instruments, with a particular focus on Italian plucked string instruments. The collection represents a unique resource of interest to musicologists, organologists, and performers. Tagliavini's guiding principle was one of authenticity: instruments were acquired with the explicit aim of restoring them to playing condition with as little intervention as possible. Clearly, the cultural value of such instruments extends beyond their visual presence, encompassing tactile and auditory dimensions of performance [87].

In the museum context, they may be played under carefully controlled conditions, typically by experienced historical keyboard specialists or by students under the close supervision of the curator. Thus, the experiential access remains limited for the general public. As McAlpine describes through the "red velvet cord" metaphor [157], collections such as Tagliavini's prioritise protection of fragile mechanisms by limiting their usage.[3]

This limitation prompted a collaboration between Museo San Colombano and the NEMUS project, aiming to develop an interface to digital representations of historical instruments. The installation (Figure 2.1), conceived for the San Colombano exhibition space, sought to reproduce the haptic experience of a sixteenth-century Italian harpsichord. At its centre was an

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[1] `https://genusbononiae.it/san-colombano-collezione-tagliavini/`

[2] `https://openpnrr.it/progetti/143852/`

[3] McAlpine [157] defines the "the red velvet cord problem" as the situation which arises from curatorial choices to preserve an object of function. For example, a museum exhibiting musical instruments behind a "red velvet cord" that visitors are forbidden to cross, stripping those instruments of their function and thus rendering them "impractical [...] pieces of furniture."

Figure 2.1: Keyboard being installed for exhibition in the Oratory at San Colombano.

electronically augmented keyboard: a replica designed to capture the tactile and kinaesthetic qualities of the original while removing any risk to the artefacts themselves. Shown in Figure 2.1, the replica serves as a controller for a digitally emulated harpsichord, implemented through sampling or physical modelling, with sound delivered to visitors via headphones.

Beyond simple replication, the interface was conceived as an immersive learning environment, a medium through which the instructional value of the Tagliavini Collection could be more broadly accessed. As Oboe [181] observes:

> (the haptic information) allows the player to perceive the "state" of the mechanism being manipulated through the key. By using this knowledge about the state of the mechanism and correlating it with the sound generated, the player learns a strategy to obtain desired tones.

The expressive potential of commercial MIDI interfaces is further limited by their reduction of musical nuance to a single parameter: key attack velocity, which, as Oboe [181] writes:

> constitutes a significant limitation for the musician, who loses expressive control of the instrument and, in turn, of the generated sound.

This chapter presents the development of two digital musical instruments (DMIs). It begins by outlining the motivations, constraints and methodological approach, before following the

Figure 2.2: The McAlpine's [157] Interface for the Benton Fletcher (Left) and Baldwin's [14] Tromba Moderna for the Music Museum, Copenhagen.

design process from early prototypes through to the completed system. The work builds on prior studies of musical heritage [14, 157] and draws on a long history of research into haptic keyboard design. While the immediate goal was to enhance the visitor experience within the museum, the project also responds to a broader challenge: the sustainability of digital research (§§ 1.2, 1.3). The optical sensing approach adapts earlier techniques developed for the piano [161], here reinterpreted for the harpsichord. Thus, the project situates itself within best practices for archiving and long-term reuse [225], engaging with ongoing discussions around the durability of DMIs and electronics hardware [74, 163].

2.1 Related Work and Motivations

The Benton Fletcher Collection at Fenton House in England presents an instructive case of the recurring challenge of providing meaningful interaction with historical instruments while safeguarding fragile originals. McAlpine [157] developed a sampling campaign and a custom MIDI interface (Figure 2.2) to enable public engagement without endangering the instruments. Although successful in preserving access, the commercial weighted keyboards used failed to capture the distinctive feel of historical plucked mechanisms, a limitation common in digital musical instruments [153]. The Tromba Moderna project [14], developed in collaboration between the Music Museum in Copenhagen and a group of researchers from Aalborg University, took a more embodied approach, reconstructing and augmenting a tromba marina replica with embedded sensors and actuators (Figure 2.2). This strategy exemplifies what Cook [43] terms

```
Haptic Feedback
├── Mechanical
│   ├── Tactile
│   │   └── Vibrotactile
│   └── Kinaesthetic
│       └── Force
├── Thermal
├── Electrical
│   └── Electrotactile
├── Ultrasonic
...
```

Figure 2.3: An incomplete, informal taxonomy of haptic feedback.

"remutualising" the interface: restoring a closer relationship between gesture and sound.

In parallel to these museum-focused initiatives, four decades of research have explored haptic keyboard design. The lineage begins with Cadoz's [28] modular feedback keyboard, which introduced tactilo-proprio-kinesthetic elements through polarisation magnets and flat coils, originally intended for applications in teleoperation and virtual reality. Gillespie et al. [97] advanced the field with a single-key linear motor prototype, later simplified to enable more realistic emulation of keyboard performance [95]. These efforts culminated in the MIKEY project, a multi-modal interface capable of reproducing piano, harpsichord and organ actions [181]. Subsequent explorations have included magneto-rheological actuation [150], ultrasonic haptics combined with virtual reality [126], and multibody-based designs using low-cost electronics while preserving key mechanics [242].

Despite their variety, these systems share a common limitation: they are generally restricted to a single key or a small number of keys. Similar work exists in haptics studies of other musical instruments, such as the violin e[98, 177, 183, 256]. To emulate bowing actions, these studies typically employ general-purpose six-DoF haptic interfaces (3D Systems Touch/Touch X; Delft Haptics Phantom Omni). The high cost of these artificial actuation devices imposes financial constraints, while their proprietary nature limits alignment with FAIR principles. The interfaces described in this chapter align more closely with the approach of Nichols [177], which utilized a bespoke device. For heritage applications such as the Tagliavini collection, an interface must span 38–53 keys to match historical harpsichords [237]. The present project, therefore, builds directly on both museum precedents and haptic keyboard research. It diverges, however, by adopting an aesthetics-forward approach: electronics are concealed, serving only as a transparent link between mechanical action and digital sound, so that the tactile and kinaesthetic qualities of the instrument remain central to the visitor's experience.

2.1.1 Haptics Terminology

There is some confusion in the usage of terminology around haptic interfaces, as seen in the DMI communities, such as NIME.[4] Much of this terminology takes its cues from the field of Human-Computer Interaction (HCI), where terms such as *haptic*, *tactual*, *tactile*, *vibrotactile*, *kinaesthetic*, *proprioception*, and *force feedback* are all in circulation, often without strict or consistent definition. This section, therefore, seeks to define the relevant terms as they apply to musical instrument interfaces, to bring clarity to the remainder of the thesis.

The archive of DMIs available from the NIME conference will serve as the primary source of definitions and examples of usage, made possible by its open-access status under the Creative Commons Attribution 4.0 International License (CC BY 4.0).[5]

For this thesis, *feedback* refers broadly to physical sensory feedback: the sense of forces, movement, position, and pressure as perceived by the human body. The following subsections outline specific terms.

Haptic Feedback: Physical feedback that engages the sense of touch, including tactile and kinaesthetic sensations. The term is sometimes substituted for *tactual* when referring to cutaneous feedback (i.e. sensed by the skin [25, 229]). Its etymology traces to the Greek *haptikos*, meaning a "sense of touch" [46]. The *Oxford English Dictionary* defines haptics as: "Relating to the sense of touch, in particular relating to the perception and manipulation of objects using the senses of touch and proprioception."

Within the DMI literature, O'Modhrain [180] describes haptics as the combined feedback from tactile sensors in the skin and kinaesthetic sensors in muscles and joints. Similarly, Rovan et al. [208] refers to "sensory and motor modalities under one unified umbrella." Finally, Cook [43] defines haptics as the "combined senses of touch, including skin vibration and pressure, and the muscle senses of motion, position, and force." From these accounts, vibration or texture felt directly by the skin, as well as forces felt by the muscles, can all be understood as haptic feedback.

Mechanical Feedback: Haptic feedback achieved through physical movement or structures that apply forces or constraints. Rovan et al. [208] sometimes uses the terms *haptic* and *mechanical feedback* interchangeably. For example, Hayes [118] refers to "an actuator or mechanical device." However, in the DMI context, the distinction is not particularly useful, since virtually all haptic feedback is 'mechanical.' The term can informally be summarised as force-feedback derived from a physical mechanism [168] or *passive* feedback that is not reinforced by an *active* system [43] (e.g., as the term is used in Montag et al. [172]). 'Mechanical feedback' becomes more meaningful a term in contrast to thermal [171], ultrasonic [126], or electrical [6] forms of feedback.

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[4] `https://nime.org`

[5] `https://creativecommons.org/licenses/by/4.0/`

Tactile Feedback: A subset of haptic feedback perceived through direct contact with the body, encompassing sensations such as pressure, texture, and vibration. Rovan et al. [208] defines tactile as "discriminative touch as in the perception of surfaces." The terms *tactile*, *tactual*, and *haptic* are sometimes used interchangeably, though not always consistently. Bongers [25] and Srinivasan et al. [229] define *tactual* as cutaneous sensation, including kinaesthetic feedback, though in practice the term is rarely used in the DMI community. For example, in the NIME archive, 'tactual' appears in only four papers [72, 102, 186, 189], whereas 'haptic' appears in roughly 300 papers. As such, within this thesis, haptic and tactual can be considered largely interchangeable.

Vibrotactile Feedback: A subset of tactile feedback achieved specifically through vibration, typically in the range of 10–500 Hz [131]. Rovan et al. [208] describes this as "vibrating at a given frequency, in contact with the skin at one or several locations."

Kinaesthetic Feedback: Haptic feedback that relates to the awareness of body position and movement. Definitions include "the awareness of the body state, including position, velocity and forces supplied by the muscles" [185], "position and motor control of muscles and joints" [118], and "the movement principles of the body" [24]. Berthoz [19][pp 26–32] further distinguishes kinaesthesia ("the sense of movement") from proprioception, which they treat as a subset of kinaesthesia. In the NIME archive, kinaesthetics appear in approximately 30 papers, usually discussed alongside somatic practice and proprioception. For this thesis, kinaesthetic feedback is defined as the way an interface influences movement and encourages specific bodily gestures during use.

Force Feedback: A subset of kinaesthetic feedback derived from physical impedance [98] or forces perceived by muscles and joints. It allows users to feel weight, resistance, or motion. Examples in DMIs include the FireFader [18] and the TorqueTuner [137].

Beyond these subsets, Cook [43] distinguishes between *passive* and *active* haptics. Passive haptic feedback is achieved by purely mechanical means, without actuators or motors—for example, weighted piano keys or the mechanical jacks of a harpsichord. Using the taxonomy of Figure 2.3 and Cook's distinction, the interface described herein can be categorised as a passive haptic, force-feedback, tactile interface. For brevity, the term 'haptic' will be used.

Finally, it is worth reflecting that all musical instruments involve physical interaction and could therefore be described as inherently haptic. Even the theremin, often cited as an exception, requires specific bodily movement, which may be interpreted as a form of kinaesthetic feedback. While this thesis avoids the ontological implications of such claims, the term 'haptic feedback' is used here to describe design intent.

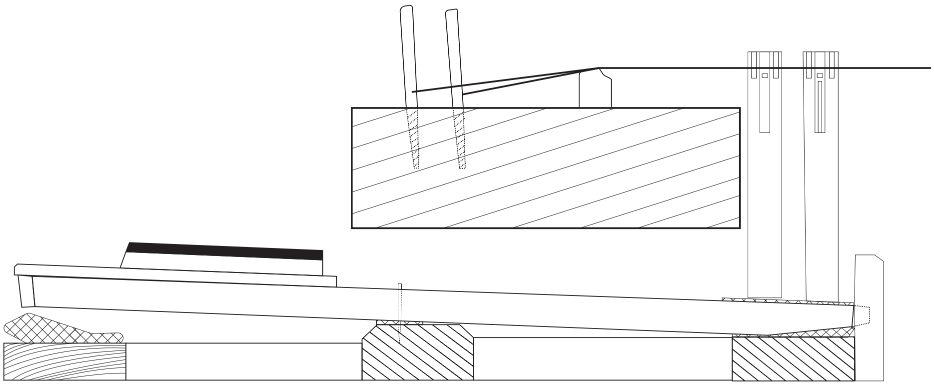

Figure 2.4: Single–manual, two–register action as used on the 1547 Alessandro Trasuntino and on the model interfaces.

2.2 Harpsichord Mechanics

The harpsichord emerged in the latter half of the fourteenth century, its design partly derived from what contemporary sources termed the “eschaquier” or “eschequier” [51, 141], and from the plucking action of the psaltery [32].

At the core of the instrument lies a simple plucking mechanism (Figure 2.4) based on a second–class lever: depression of the key lifts a *jack*, which drives a plectrum upward to pluck a string. Historically, plectra were most often made of quill, though leather was also used. Each jack is a two–part wooden element consisting of a *body* and a pivoting *tongue*. The plectrum is wedged into a slot on the tongue, which is attached to the body by a pin. A tapered tongue and a correspondingly tapered recess allow the tongue to return to an upright position against a spring—commonly a strip of brass, though quill or boar hair were sometimes employed [237]. As the jack rises, the plectrum presses laterally against the string until it slips past and releases it. The resisting force of the plectrum is relatively constant, so the amplitude of the pluck—and therefore the volume of the note—is largely fixed, a defining characteristic of the harpsichord’s dynamics.

Table 2.1: Design constraints for the augmented harpsichord keyboard and their immediate implications.

Category	Constraint	Immediate Implications
Mechanical interface	**Faithfulness**: Preserve the authentic feel and behaviour of a sixteenth-century harpsichord.	No mechanical ‘improvements’ to the action; electronics must observe rather than alter jack behaviour.
	Robustness: Withstand frequent public use; allow maintenance by non-specialist staff.	Preference for durable materials and serviceable assemblies; tolerance for minor misalignments.
	Concealment: No visible electronics, except headphones and a small display.	All sensing, cabling, and control hardware are internal/hidden; external aesthetics remain historical.
	Compactness: Minimal footprint in the gallery.	Rectilinear casework and tight internal packaging; no external modules or frames.
Electronics	**Non-invasiveness**: No modifications to visible historical parts.	Sensors mounted off key surfaces; use of add-on targets and internal fixtures instead of altering the action.
	Low latency: End-to-end read/process budget $< 10\,\text{ms}$ for 49 keys [129].	Efficient multiplexing; lightweight filtering; avoidance of heavy interrupt schemes that conflict with monitoring.
	Reliability: Readings respond only to jack motion; minimal drift/noise.	Controlled illumination and shielding; avoidance of ambient-light sensitivity; robust calibration storage.
	Scalability: Economically extend from a three-key rig to a 49-key keyboard (and beyond).	Modular PCBs and looms; repeatable alignment features; component choices that tolerate mass assembly.

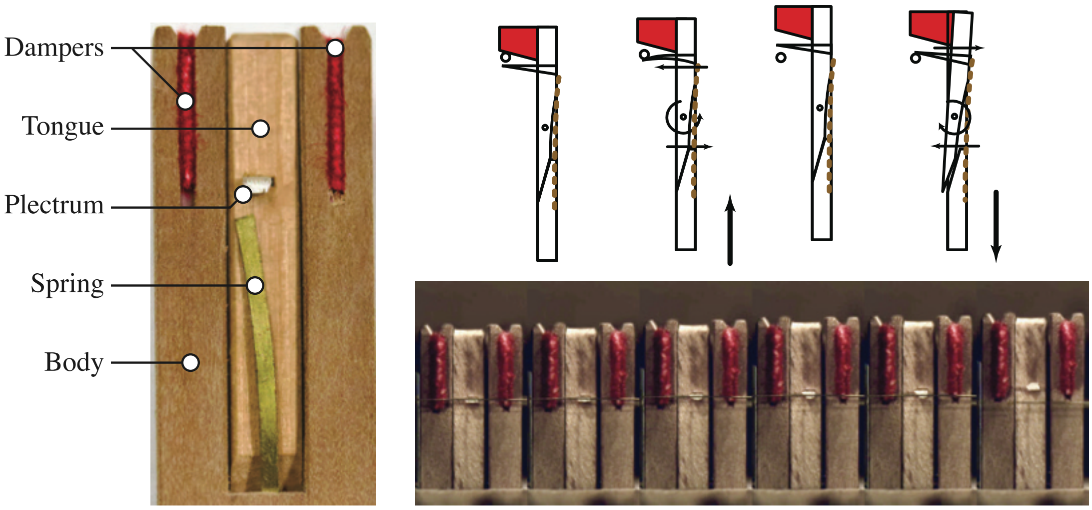

Figure 2.5: Forces acting on the jack during plucking and release (adapted from Perng [193, Figure 1.7]) alongside a high–speed photo series (1000 fps) of jack displacement.

By the sixteenth century, it was common for Italian harpsichords to employ more than one string per key, each with its own jack. These jacks were arranged in rows and staggered in height so that, over the key's travel, each register was plucked sequentially rather than simultaneously [248]. Accurate detection of the plucking event, therefore, requires measuring the displacement of each jack individually, rather than only the key motion, owing to subtle hand–crafted variations across the keyboard. Fig. 2.5 depicts snapshots of the plucking mechanism, highlighting the jack mechanics and the jack-string interaction.

2.3 Design Constraints

The augmented replica keyboard for the Museo San Colombano was steered by two interlocking sets of constraints: one governing the *mechanical interface* (how the instrument should look, feel, and behave), and one governing the *electronic sensor system* (how motion is detected, processed, and conveyed to sound synthesis). These constraints simultaneously served as design principles and evaluative criteria throughout the prototyping and deployment phases. To orient the reader before the detailed discussion that follows, Table 2.1 summarises the key requirements and their immediate implications for the rest of the chapter.

2.3.1 Mechanical Interface

At the mechanical level, the instrument needed to *read as* a sixteenth-century Italian harpsichord in both appearance and feel. This implied, first of all, a commitment to *faithfulness*: the replica had to reproduce the characteristic behaviour of a historical plucked action—the resistance of plectrum against string, the sequencing of registers, and the subtle asymmetries inherent to hand-built components. The electronic system was therefore conceived as an

Figure 2.6: Gradient stickers applied to the jack body to provide a concealed optical target.

observer rather than an active agent; actuator-based haptic solutions that impose forces on the key were excluded, since they risked compromising authenticity and would have required substantial mechanical intervention [96, 242]. Equally important was *robustness*. As a public exhibit, the interface had to withstand repeated handling, minor misalignments, and basic servicing by museum staff. Fasteners, brackets and wear surfaces were specified for durability, and tolerances were chosen so that minor adjustments could be made without specialist tools. A further concern was *concealment*. All electronic elements—sensors, wiring, and controllers—were placed inside the case, leaving visible only a discreet headphone socket and a compact display for audio parameters. This preserved the visual integrity of the instrument and avoided the perceptual bias that overt technology can introduce in a heritage context. Finally, the instrument had to respect the spatial limits of the gallery. The overall envelope was therefore kept deliberately compact, with internal cavities planned from the outset so that electronics could be accommodated without external modules or frames.

Taken together, these considerations pointed towards an optical approach in which each jack carries a concealed, high-contrast target read by an adjacent sensor (Figure 2.6). This strategy preserves the original action geometry while allowing precise displacement measurements. Although the current implementation uses thresholding to trigger MIDI events, the continuous data remain available for analysing subtler aspects such as pluck staggering and resistance profiles across the keyboard compass [164, 248].

2.3.2 Electronics

At the electronic level, the design was shaped by four complementary constraints that informed sensor selection, signal conditioning, and firmware development. Foremost among these was *non-invasiveness*: the historical geometry of keys, jacks, and casework had to

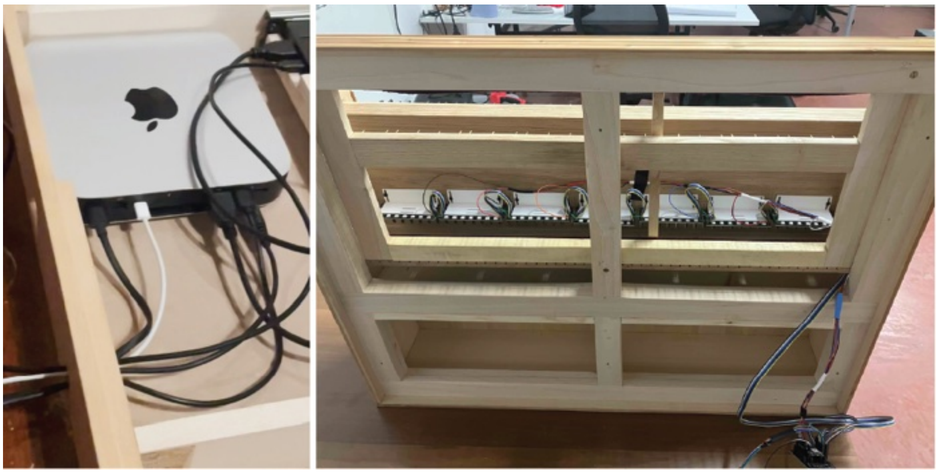

Figure 2.7: Underside of the keyboard showing optical-sensor PCBs mounted beneath the wrest plank.

remain untouched. Sensors were therefore mounted on custom printed-circuit boards concealed beneath the wrest plank, with reflective targets applied to the hidden face of each jack. This arrangement avoided irreversible alterations and kept every intervention reversible. A second priority was *low latency*. To maintain a convincing link between haptic gesture and sound in a museum setting, the full read–process cycle across all keys needed to remain comfortably below approximately 10 ms [129]. Meeting this requirement favoured lightweight analogue multiplexing, modest smoothing filters, and a polling strategy designed to coexist with diagnostic serial output without compromising timing. Equally important was *reliability*. Sensor output had to respond exclusively to jack displacement, resisting interference from ambient light or neighbouring channels. The final configuration, therefore, combined controlled, local infrared illumination with 3D-printed baffles that suppress optical cross-talk. Calibration values are stored in non-volatile memory so that thresholds remain stable between sessions and can be reloaded after servicing. Finally, the system needed to be *scalable*. Techniques proven on the three-key rig had to migrate cleanly to a full forty-nine-key instrument. This was achieved by modularising the electronics into repeatable seven-sensor boards and a single controller PCB, fixing the pitch between sensors and standardising the wiring harness so that assemblies could be prepared off-site, installed quickly, and serviced in sections.

Together, these considerations materialised as a chain of sensor boards mounted under the wrest plank (Figure 2.7), each integrating illumination, sensing, and simple aggregation logic. Through-hole technology (THT) components were used wherever possible to facilitate easier soldering and rework, while socketed microcontrollers and detachable looms ensured serviceability. The resulting design balances accessibility and cost with the open source ethos of the project, adapting established piano-tracking techniques [161] to the idiosyncrasies of a plucked harpsichord action, where discrete pluck and release events dominate but continuous motion remains observable.

2.4 Summary of Informed Design Choices

The preceding section outlined the mechanical and electronic constraints that guided the development of the augmented keyboard. Before describing the prototypes in detail, it is helpful to summarise how these requirements informed specific design decisions. Table 2.2 anticipates the results by linking each constraint to the principal strategies adopted in the final system. This mapping clarifies the rationale behind the hardware architecture and highlights how apparently competing demands—historical fidelity, robustness, the invisibility of electronics, and scalability–were reconciled.

The table highlights that the same design element often answered several constraints: for instance, the optical gradient not only met the non-invasiveness requirement but also enabled reliable and low-latency sensing, while the modular PCB architecture simultaneously supported maintenance and scalability. Presenting these links up front clarifies why apparently modest details—sensor orientation, baffle geometry, choice of soldering technology—were decisive for meeting the project's broader aims.

2.4.1 Visual Aesthetics

From the outset, one guiding principle of the hardware design was that the keyboard must *look* as authentic as it felt. Beyond the functional demands already outlined in Section 2.3, the instrument's external form had to sustain the visual language of a sixteenth-century harpsichord so that visitors would immediately read it as part of the collection rather than as an electronic artefact. This requirement introduced an additional layer of restriction: every sensing or control element needed to be concealed or visually reconciled with historical practice, while the overall proportions and detailing had to echo Italian models of the period.

The physical and visual presentation of an instrument might not be the primary concern for a performer, but in the context of a museum exhibition, it is vital to the visitor experience, as demonstrated by McAlpine [157]. Since the Tagliavini collection hosts primarily early plucked stringed keyboards of Italian origin, the keyboard layout was deliberately modelled after early Italian harpsichords. The aesthetics of the instrument were therefore carefully considered during the design process.

In contrast, many haptic DMI projects place most of the effort into the design and functionality of electronic components, while paying comparatively little attention to visual stimulus. For keyboard interfaces, this is in part due to the limited scope of key modelling [96, 149, 242], whose form already diverges significantly from performer expectations. For actuated haptic systems, there is also a question of where to place the electronics. A combined approach of realistic haptics and aesthetics presents a challenge: commercial MIDI keyboards are differentiated from acoustic keyboards by the absence of strings, while the interfaces presented here employ strings as both functional haptic mechanisms and visual features. Even if strings were no longer required mechanically, their presence would still be necessary as a

Table 2.2: Design constraints and corresponding design choices for the augmented harpsichord keyboard.

Constraint	**Design choice(s)**
Faithfulness to historical action	Replicated jack and key geometry from sixteenth-century models; avoided actuators or motorised force feedback [96, 242]; optical sensing chosen for non-contact measurement of jack travel.
Robustness and maintainability	Mechanical frame built with traditional woods (walnut, cypress, boxwood) and brass springs; electronics mounted on modular PCBs with replaceable sensors and LEDs; Through-hole components are used where possible to simplify repairs.
Concealment of electronics	All sensors, PCBs, and wiring installed in cavities beneath the wrest plank (Figures 2.6, 2.7); Only headphones and a small display are visible to visitors.
Compact footprint	Adopted a rectangular frame inspired by historical harpsichords but shortened to 49 keys; electronics stacked vertically within two internal chambers, preserving gallery space.
Non-invasive sensing	Infrared reflectance sensors (QRE1113) reading a printed gradient on each jack; No alterations to visible parts of the mechanism.
Low latency	Firmware optimised to sample all 49 sensors within ~2 ms, comfortably below the 10 ms limit from Jack et al. [129].
Reliability of data	Matte 3D-printed baffles around sensors to prevent optical cross-talk; adhesive vinyl gradients resistant to curling; calibration thresholds stored in FRAM for persistence.
Scalability (3-key to 49-key)	Seven-sensor PCBs daisy-chained by ribbon cables; identical board layout for both registers; prototypes validated on a three-key rig before full-scale build.

Figure 2.8: McGurk Effect as demonstrated on *Horizon: Is Seeing Believing?* The left-hand side of the video shows the mouth movements for "fa" and the right-hand shows "ba". Copyright BBC (2010).

visual differentiator; otherwise, the interface risks resembling existing commercial offerings. This then raises the practical issue of electronic footprint, as haptic systems and actuators often require components that extend beyond the confines of the instrument body [162, 214].

The importance of visual stimulus should not be underestimated, particularly for musicians. Studies by Fritz et al. [85–87] (see Section 1.1.3) show that visual stimuli can bias auditory perception and therefore should be carefully restricted in experimental settings. Tsay [245] further asserts that visual appearance influences quality assessment by both "novices and experts." In all these studies, the visual stimulus was treated as an undesirable influence. This phenomenon, akin to a 'musical instrument McGurk effect' [158], is one reason why the electronics in this project were deliberately concealed from view.

The McGurk effect is a well-known example of cross-modal perception. It typically manifests as an aural illusion: when two videos show a mouth pronouncing "ba" and "fa" but the audio always contains "ba," the sound heard depends on the mouth movement observed [11] (Figure 2.8).[6]

The effect has been proposed to extend beyond speech into the domain of musical visual cues [210]. Its relevance to musicians remains debated: while Proverbio et al. [200] and Alsius et al. [5] argue that musicians are less susceptible, Politzer-Ahles et al. [195] refutes this, concluding that musicians may be equally or even more vulnerable. Taken together with Fritz et al. [85–87] and Tsay [245], these results highlight the non-negligible influence of visual cues on auditory perception.

Instead of attempting to suppress this influence, the present design seeks to leverage it.

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[6] Timestamp 00:12:54 of Austin [11]

Figure 2.9: Three-key model harpsichord mechanism.

Given the extensive research into modelling and recreating piano action [28, 96, 149, 242], the visual component may provide the final persuasive element necessary for acceptance, much like how visual perception shapes judgments of musical performance. The aesthetics of the interface thus enhance its likelihood of being perceived as an 'authentic' musical instrument. Building on the observations of McAlpine [157], the design asks to what degree visual stimuli can be used to "sell" the experience of playing a DMI. When combined with a passive haptic response, aesthetics may provide sufficient influence to shape the player's perception and lower the barriers to a convincing musical experience.

2.5 Staged Development Overview

We first received a *three-key prototype* and used it for several months to test sensing approaches and electronics at a small scale. Next, we received the *full keyboard* and, within one week, scaled the system to 48/49 keys and delivered it to San Colombano (*Mark I*). At delivery, *Mark I* ran a single register with simple thresholding (no hysteresis). After installation, development returned to the three-key rig, where we added a *second register* and *force sensors* to detect plucks. Finally, a *second full keyboard* (*Mark II*) was built, in which we implemented the dual-register PCBs and the refined electronics/firmware. See also Fig. 2.10.

The prototyping was staged with ever-increasing complexity to solve jack-displacement sensing in the simplest controllable case before scaling up: single action → multi-register action → multi-key interface. The system evolved from simple threshold tests to a multi-sensor interface capable of triggering MIDI events. The four development stages are now reviewed in detail. For reference, Fig. 2.11 shows a timeline of all four stages.

2.6 Stage 1: Three-key prototype

The initial question was whether sensor data could reliably trigger MIDI playback. The custom three-key mechanism (Figure 2.9) formed the basis of our tests. This mirrors the methodology in the Timmermans et al. [242] *Haptic Key* project: iteratively validate sensor placement, signal processing, and mechanical tolerances on a compact model before scaling to multiple octaves. Our approach follows single-action test beds in haptics [96] and harpsichord-specific rigs assembled from luthier parts [193]. The open-sided construction of the three-key model offered direct access to the key lever and jacks, making it straightforward to mount and align sensors. Multiple keys and registers on the same model enabled more complex iterations (such as sequencing and staggering) without requiring a second rig, while also meeting the visual/aesthetic requirements outlined in our design principles.

2.6.1 Sensor Trials

A range of sensing strategies was explored against the project's constraints of non-invasiveness, concealment, reliability, and scalability.

IMU A six-DoF Inertial Measurement Unit (IMU) (accelerometer + gyroscope) mounted on a single key yielded a recognisable 'fingerprint' for each gesture, but the resulting features were not sufficiently separable across neighbouring keys, and the per-key cost remained high even at scale.

Magnetic (reed / Hall) Reed switches and Hall sensors were tested with small magnets embedded in the jacks. Both provided repeatable threshold detection, yet each introduced difficulties: reed switches placed calibration entirely in the mechanical domain and scaled poorly; Hall sensors demanded precise positioning and per-key software trimming. Limited internal space made such adjustment impractical, and embedding magnets in the jacks was neither non-invasive nor low-risk.

LDR near the jack rail Light-dependent resistors (LDR) placed at the rail (above the jacks) produced a usable signal—less light as the jack rose—but were highly sensitive to ambient illumination. Mitigating this would have required continual re-balancing or a dedicated light-balance circuit. Mounting the devices outside the cavity also conflicted with the requirement for concealment. Nevertheless, these trials suggested that a *local* light source, if fully enclosed, could be viable.

Optical reflectance (final choice) Building on McPherson [161] and Moro et al. [173], we adopted the Fairchild QRE1113[7] infrared reflectance sensor in a simple voltage-divider circuit (Figure 2.12). Unlike earlier key-displacement systems [161, 173], we needed to sense the motion of the *jack* while keeping hardware invisible. The solution was to rotate the geometry: each sensor looked sideways onto a *grey-scale reflectance gradient* applied to the jack body

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[7] Fairchild, now ON Semiconductor, QRE1113 datasheet `https://www.onsemi.com/download/data-sheet/pdf/qre1113-d.pdf`

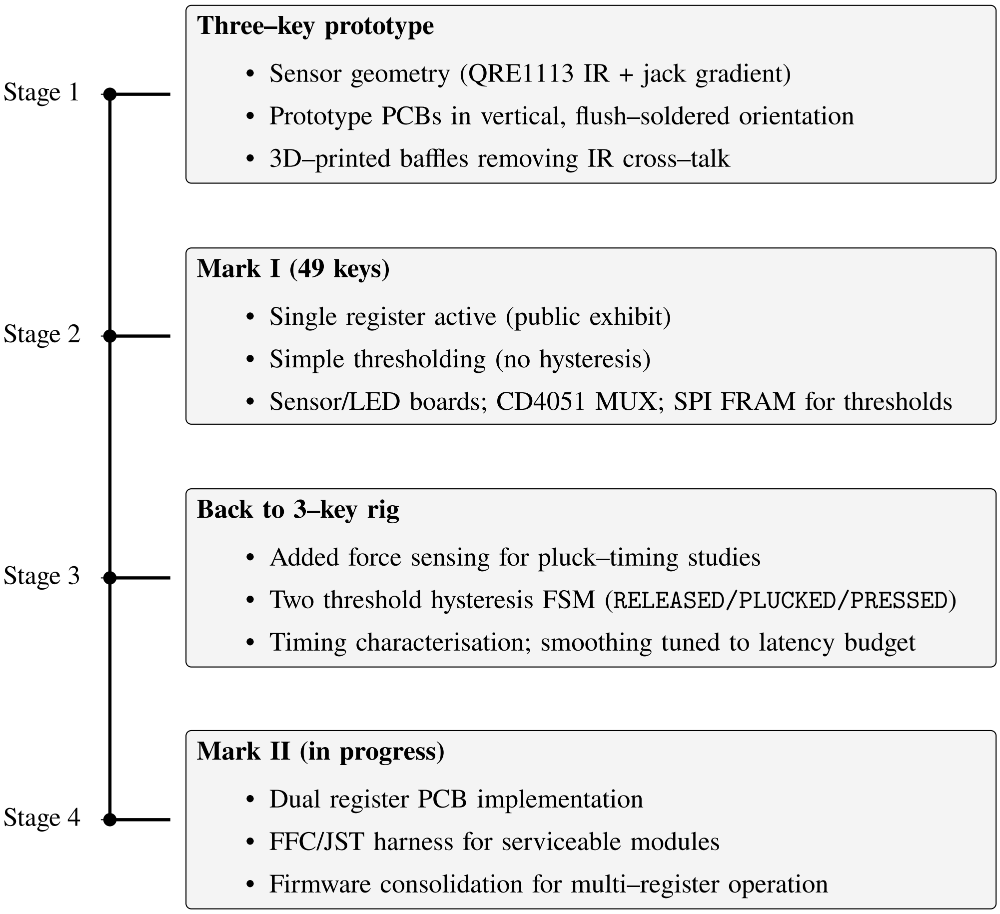
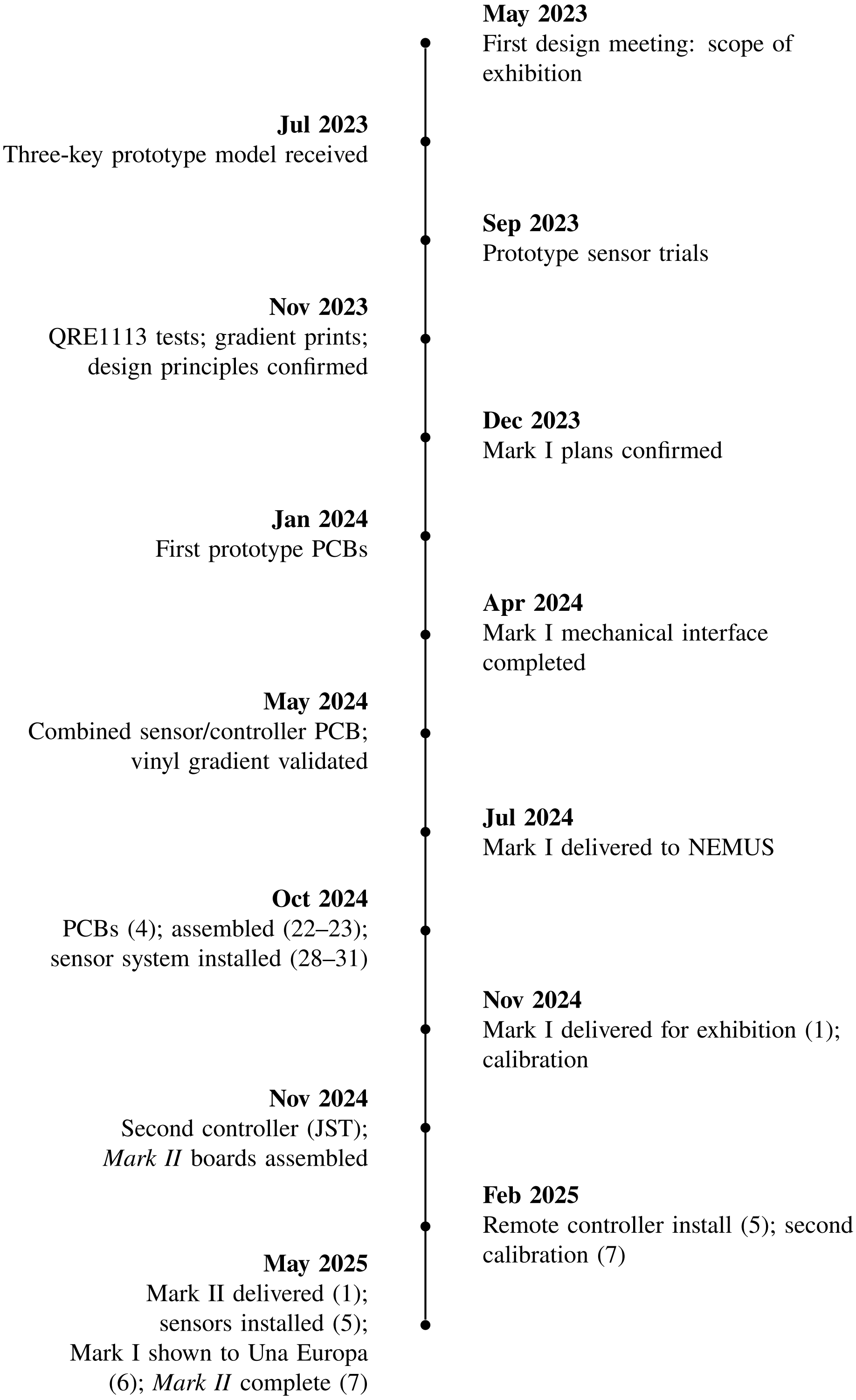


Figure 2.10: Four-stage development timeline and milestones.



May 2023
First design meeting: scope of exhibition

Jul 2023
Three-key prototype model received

Sep 2023
Prototype sensor trials

Nov 2023
QRE1113 tests; gradient prints; design principles confirmed

Dec 2023
Mark I plans confirmed

Jan 2024
First prototype PCBs

Apr 2024
Mark I mechanical interface completed

May 2024
Combined sensor/controller PCB; vinyl gradient validated

Jul 2024
Mark I delivered to NEMUS

Oct 2024
PCBs (4); assembled (22–23); sensor system installed (28–31)

Nov 2024
Mark I delivered for exhibition (1); calibration

Nov 2024
Second controller (JST); *Mark II* boards assembled

Feb 2025
Remote controller install (5); second calibration (7)

May 2025
Mark II delivered (1); sensors installed (5); Mark I shown to Una Europa (6); *Mark II* complete (7)

Figure 2.11: Keyboard project timeline.

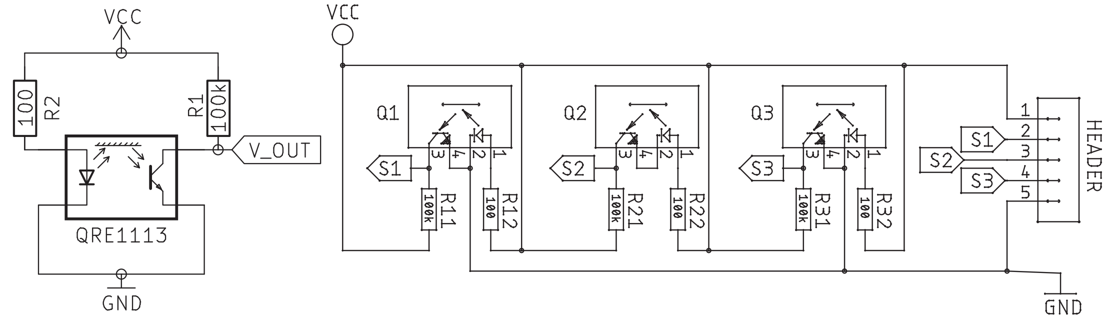


Figure 2.12: Optical sensor in a simple voltage-divider circuit (Left) and its application in the prototype sensor board schematic (Right).

(Figure 2.6). This borrowed the controlled-contrast approach of line-following robots [202], giving a smooth, monotonic response without exposing the emitters.

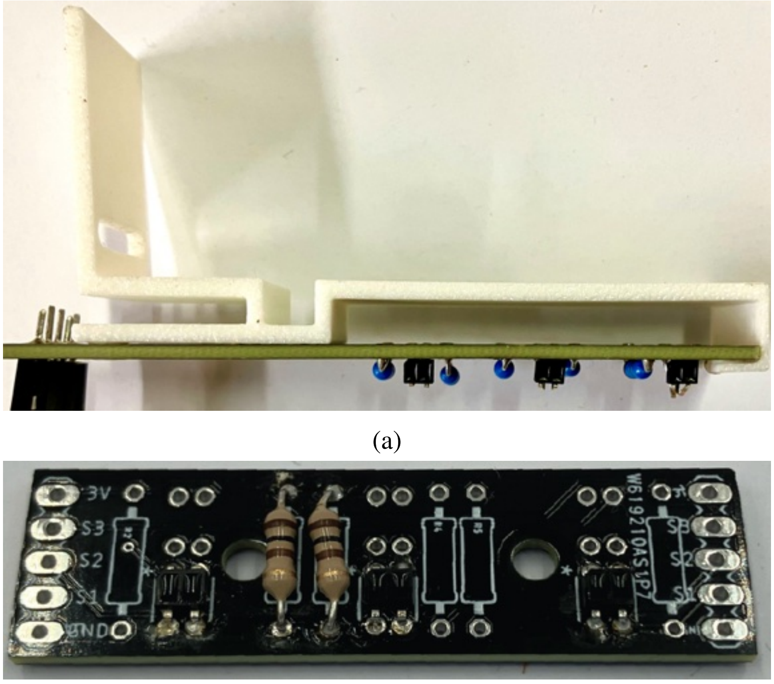
To prototype the target surface, gradients were initially printed on paper and taped to the jacks. For production, they were rendered as full-length vinyl stickers using an HP Latex 115 and cut on a Summa 150 from vector outlines. The print-and-cut process scaled cleanly from six prototype jacks to the ninety-eight required for Mark I, satisfying the scalability criterion. Short ‘gradient-only’ strips sometimes curled at their ink edges or caught against neighbouring parts; full-length stickers provided greater adhesion and kept heavy ink away from the edges, eliminating binding.

Early optical trials also revealed cross-talk: infrared light reflected from adjacent jacks contaminated nearby sensors. We designed matte, dark-pigmented PLA baffles to wrap each device and block stray light. Printed on a Bambu X1, these baffles (Figures 2.19) removed interference entirely and became part of the standard mounting.

2.6.2 Prototype PCB

A small EAGLE PCB (Figure 2.12) provided simple divider wiring, power, and header breakout to a microcontroller, primarily to validate mounting and pitch spacing. The original plan was a right-angle mount (bending leads; Figure 2.13a) so the board could sit on an adjustable 3D-printed bracket at the wrestplank side, setting the sensor–gradient gap. In practice, the optical leads were fragile, and an end-mount approach à la McPherson [161] was too alignment-sensitive on the jack’s 4.30 mm edge: tiny angular errors produced large signal differences. We therefore switched to sensors soldered *flush* to the PCB and oriented the PCB vertically.

The vertical redesign (Figure 2.13b) doubles the sensor layout to accommodate wiring from a single side on the three-key rig, while keeping identical vertical positioning for the front and rear registers. This minimises signal-range differences and avoids separate offset gradients or separate PCBs. A two-piece 3D-printed bracket holds the board vertically and provides coarse gap adjustment.



(a)

(b)

Figure 2.13: (a) Prototype PCB attached to 3D-printed adjustment bracket. (b) Vertically oriented prototype sensor PCB.

2.7 Stage 2: Mark I

After the initial prototyping, the first complete interface, *Mark I*, was completed for delivery to the Tagliavini collection. Development proceeded modularly (mechanical hardware, electronics, audio software; and within electronics, hardware vs. firmware), allowing mechanical construction while electronic prototyping continued.

2.7.1 Keyboard design

The mechanical design was developed in close collaboration with luthier Roberto Livi and curator Catalina Vicens, guided by the priorities outlined in Table 2.2: faithfulness to sixteenth-century practice, robustness for public use, and a compact footprint. Livi fabricated the instrument in his Pesaro workshop, adopting a restrained rectangular frame (Figure 2.15) that answered the gallery's spatial limits while leaving generous internal cavities for the sensing system (Figure 2.14).

Traditional materials were employed throughout: a walnut wrestplank, chestnut key levers, boxwood and ebony key covers, and a cypress case and soundboard; the jacks were beech with brass springs and seagull-feather plectra. The design drew on the 1547 Alessandro Trasuntino harpsichord at San Colombano–particularly its two eight-foot choirs–while replacing the historical short octave with a standard layout, as requested by the curator, to simplify mapping

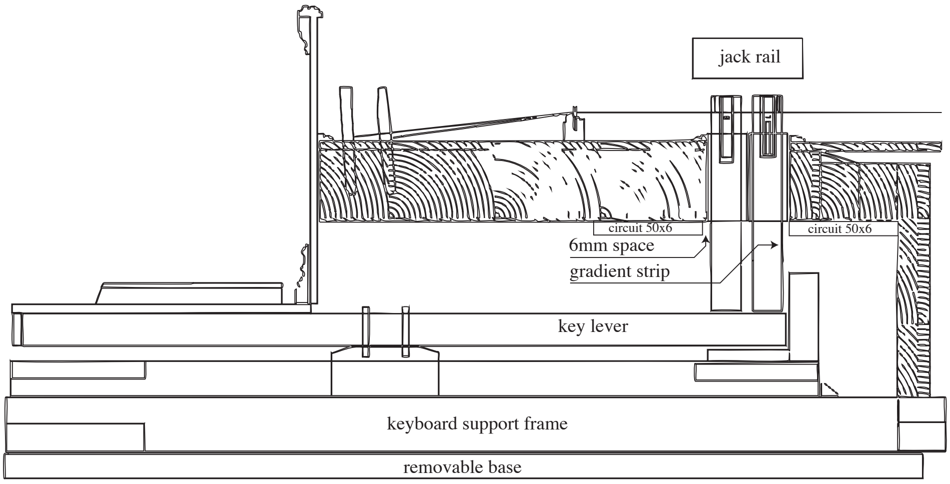


Figure 2.14: Cross-section of keyboard mechanics by Roberto Livi. The original design reserved space for a horizontal circuit board of 50 mm × 6 mm.

to sampled sounds. This modernised geometry, combined with the rectangular poplar frame, also eased installation of optical sensors beneath the wrestplank without compromising tactile or visual authenticity (see Figure 2.7). Two brass choirs were tensioned to reproduce plucking resistance, and felt strips were added to damp residual vibration.

2.7.2 Electronic Components

This section summarises the components used in the final circuit design and the rationale for each choice.

Microcontroller All signals terminate at a microcontroller that samples analogue inputs and controls peripherals. We chose the Arduino Nano 33 BLE. The Nano form factor allowed early substitution among models while requirements were still unclear. An initial Nano 33 IoT revealed ADC issues on channels 4–5 [10], effectively limiting usable inputs to six; the BLE variant exposes eight ADC channels, so it replaced the IoT with minimal firmware/circuit changes. Nanos provide native USB-MIDI (with BLE-MIDI fallback). The BLE's 12-bit ADC also provided headroom if 10-bit resolution proved marginal.

Non-Volatile Memory (NVM) Per-key pluck and release thresholds must persist across power cycles. The Nano BLE lacks a convenient NVM for this; we therefore used a Fujitsu MB85RS64 SPI FRAM [88]. I^2C pins were reserved for ADC expansion, so SPI was preferred. Alternatives (SD card or host-stored calibration) would complicate access, reliability, and portability, undermining the 'plug-and-play' advantages of MIDI.

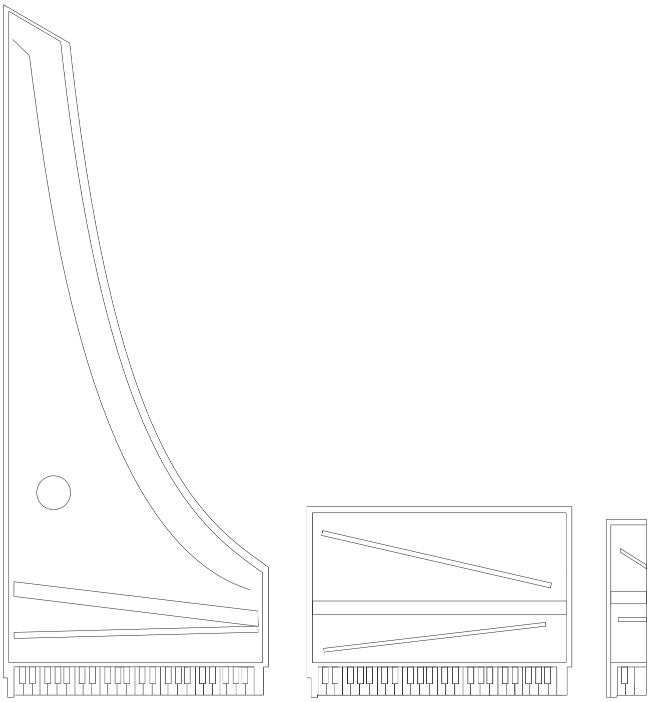


Figure 2.15: Scale comparison: (left to right) the 1547 Trasuntino, 49-key *Mark I* model, and the three-key prototype. The Trasuntino shows the traditional 'logarithmic' outline.

RGB LEDs Scaling from six to 98 jacks introduced 'problems of scale': tracking which key is being calibrated and spotting out-of-range sensors. Addressable WS2812 LEDs were aligned to keys and driven programmatically; colour states (Figure 2.16) provided immediate visual feedback to the user during calibration and debugging. We avoided separate drivers (e.g., `TLC5940` in McPherson [161]) to reduce assembly complexity. While chain failure can cascade past a dead LED, LEDs are hidden in regular operation and non-critical to playability. Replacing the affected PCB remains the practical remedy should an LED fail and disrupt the signal chain.

Multiplexer The Nano exposes eight ADC channels; *Mark I* required 98 sensors. We therefore added `CD4051BE` 8:1 multiplexers. A MUX routes a common pin to one of eight inputs; GPIO lines select the channel. This duplicates the internal ADC muxing [179], yielding a two-stage cascade. We used seven channels per board to match seven sensors per PCB and seven PCBs per register (49 jacks/register). Two microcontrollers split the load across the two registers (14 sensor boards total), balancing noise, timing, and wiring complexity.

Printed Circuit Boards Two PCBs were designed to stabilise connections, minimise footprint, and fix sensor pitch to the jacks: (i) a *sensor board* and (ii) a *controller board*. Figure 2.17 shows the macro-level connections.

Figure 2.16: Mark I demonstrating the addressable RGB LED array.

Sensor Board Each board measures vertical jack displacement. Distributing sensors across multiple boards reduced cost, eased installation, and allowed coarse adjustment in both stand-off and lateral centring over seven jacks. We kept sensor–MUX traces short to minimise noise. Per board:

- 7 QRE1113 optical sensors
- 7 100 Ω resistors and 7 10 kΩ resistors (later reduced to one shared resistor per board)
- 1 Texas Instruments `CD4051BE` multiplexer
- 7 WS2812 RGB LEDs

Figure 2.20 shows the sensor board schematic. The analogue `SIG` output is routed through the MUX but returns separately to the controller in v1 (to reserve board space for an unused MUX interrupt `INT`). MUX select lines `A`/`B`/`C` implement 3-bit encoded channel selection.

Ribbon cables linked `Input`/`Output` between boards prior to installation; the assembly was fitted as a single chain. Each board's `SIG` was brought separately to the controller (Figure 2.20). The same 3D-printed baffles used on the prototype eliminated cross-talk (Figure 2.19). As

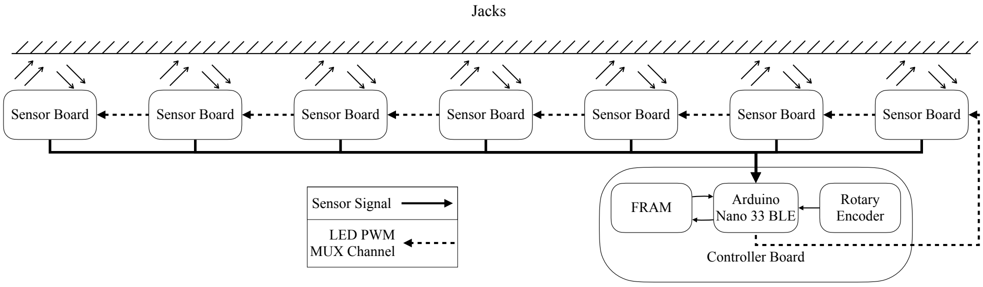


Figure 2.17: Block diagram of PCB connections. Each sensor board's analogue signal (`SIG`) returns individually to the controller; LED and MUX control lines are daisy-chained.

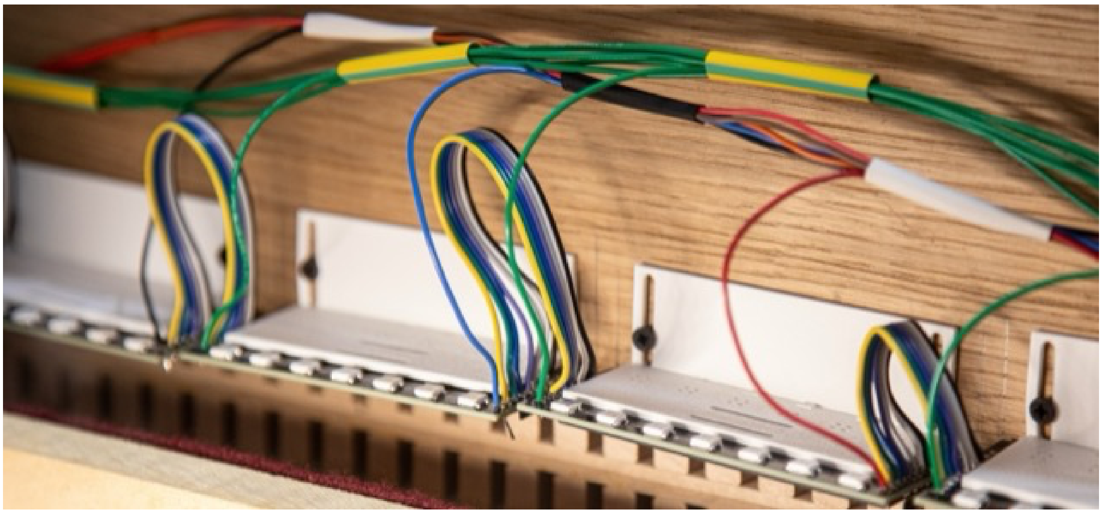


Figure 2.18: Sensor boards *in situ*. Daisy-chain ribbon cables connect `Input/Output` headers (Figure 2.20). The multicoloured cable loom carries each board's `SIG`; the green loom is the unused `INT` later tied to `GND`.

shown in Figure 2.19, the baffles, an adjustment plate, and a vertical back plate form a three-part bracket. Push-fit dovetails allow off-site printing and on-site assembly; two 3 mm holes in the PCB allow it to be sandwiched between back plate and baffle.

Controller Board The controller board reliably connects all components to the Nano BLE (Figure 2.20).

The controller board is comprised of the components:

- 1 Arduino Nano 33 BLE
- 1 Fujitsu MB85RS64 SPI FRAM
- 1 EC11 rotary encoder with integrated tactile switch

Figure 2.19: Sensor board front with baffles.

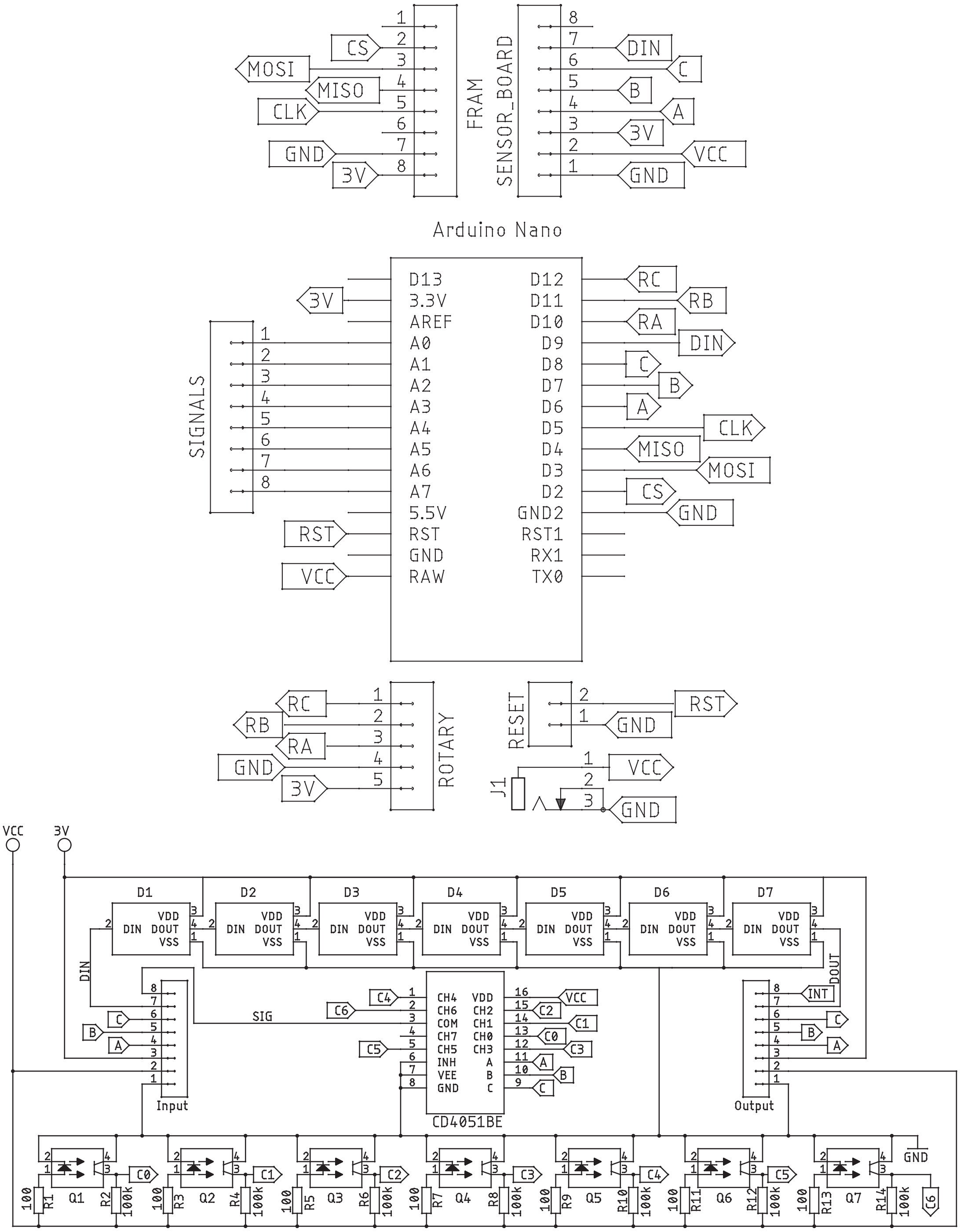


Figure 2.20: Mark I controller board (Top) sensor board (Centre) schematics and the sensor boards *in situ* (Bottom). ‘`D`’ = RGB LED; ‘`Q`’ = optical sensor; ‘`C`’ = MUX channel. Labels indicate current direction. Daisy-chain ribbon cables connect `Input`/`Output` headers (Figure 2.20). The multicolour loom carries each board’s `SIG`; the green loom is the unused `INT` later tied to `GND`.

Figure 2.21: Mark I keys after milling and re-finishing.

- 1 momentary reset switch

Power enters via barrel jack `J1`. Headers separate `RESET`, `ROTARY`, and `FRAM`; sensor connections are split as analogue `SIGNALS` and `SENSOR_BOARD` (power, MUX select, LED data). The Nano BLE is socketed to permit rapid swap if a unit fails or needs reflashing (no reliable museum internet). The front reset switch provides a reachable hard reset without power-cycling.

Estimated power draw is ~1.1 A at 5 V with inrush variation. Sensors stayed continuously powered in v1; future designs may modulate emitters dynamically [161].

2.7.3 Installation

Once fabricated, the electronics were fitted to the instrument as a bespoke installation, with brackets and enclosures added to ease future servicing without constraining the design. Some of the geometry inevitably evolved during fitting—most notably the shift from horizontal to vertical sensor boards—showing how fabrication and assembly remained in dialogue until the last moment.

Pre-assembly took place in Edinburgh, while the final build was completed in the NEMUS Lab in Bologna during the last week of October 2024; delivery and exhibition followed in the first week of November. Power and data were carried through a daisy-chained loom, while the `SIG` lines ran separately to reduce noise. Ribbon cables were hand-cut to length so they could be repositioned later, a decision that improved flexibility but added time—an insight folded into *Mark II* through the adoption of flat-flex cabling. The controller's location was revised when the rear-chamber dimensions proved tighter than those assumed for the Mac mini housing the sampler.

Fitting the keyframe required temporarily removing the keys. Brackets were secured to the underside with round-head self-tappers and left slightly loose for coarse positioning; final alignment was completed in firmware. Each jack was prepared with a varnished short side for better sticker adhesion, the gradients were trimmed to length, and the free travel of every jack was checked. Preliminary calibration took place before the keys were replaced, with outliers traced and corrected. A single clearance error blocked key travel entirely, forcing a 10 mm ×

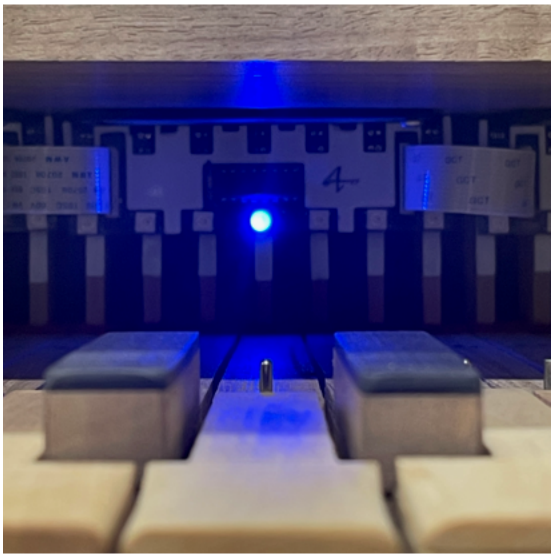


Figure 2.22: RGB LEDs behaviour in calibration mode. LEDs are aligned with the keys and colour-coded for quick identification or the jack being calibrated and its state.

15 mm recess to be milled into each key (Figure 2.21) and the leather pads refitted—an extra day's work, but one that informed later geometry and cabling changes adopted in Mark II.

For the first exhibition, a harpsichord sample library ran in Kontakt[8] on a Mac mini housed in the lower compartment; cables were routed through hidden holes (Figure 2.7). An iPad exposed controls for tuning, voicing, and stop selection.

2.7.4 Calibration

The rotary encoder is used to select a key, edits thresholds, and save new threshold values to FRAM. Defaults are mid-range; each sensor is plotted against its threshold (Figure 2.24) and adjusted until the threshold is crossed only at the pluck. LEDs identify the active key and report state; red indicates readings near ADC rails (misalignment/fault).

2.8 Stage 3: Return to Three-Key Rig

With *Mark I* delivered and installed for the San Colombano exhibition, development returned to the three–key prototype to address a weakness that had become apparent during calibration. In the first full instrument, key events were detected by a single threshold with no hysteresis: simple to implement, but prone to chatter near the decision point and awkward to calibrate across forty–nine keys. The smaller rig offered a controlled setting in which to rethink the detection pipeline and firmware before committing changes to a second full build.

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[8] Kontakt webpage (Accessed: 31 Jan 2025)

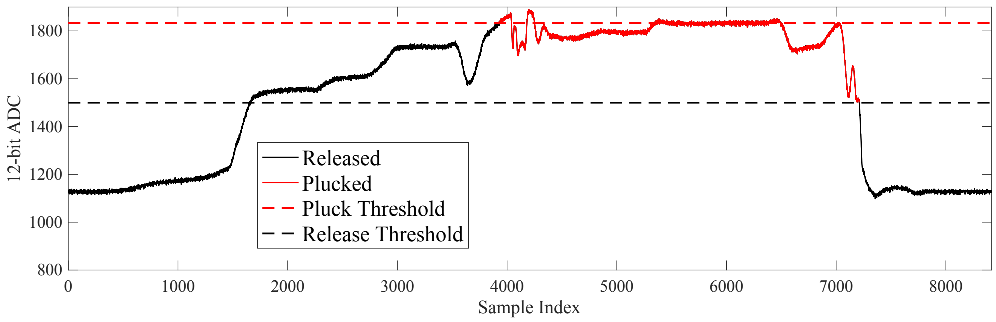

Figure 2.23: Two-threshold hysteresis: full press–release on an Arduino Nano 33 BLE (12-bit ADC). `PLUCKED` begins at `pluck_threshold`; `RELEASED` returns at the lower `release_threshold`.

Force sensing and firmware We added force sensors to the three–key action and redesigned the firmware around a clearer separation between *Calibration* and *Operation*. On boot, the microcontroller configured its GPIO lines and verified the presence of SPI FRAM, then entered one of the two modes according to the state of the rotary encoder. During normal play, sensors were read in groups of seven; a 3-bit address (`A`, `B`, `C`) advanced the multiplexer through its eight channels.

Hysteresis and timing Central to the revision was a two-threshold finite-state machine (FSM) with states `RELEASED`, `PLUCKED`, and `PRESSED`. A note was triggered only when the signal rose above the `pluck_threshold` from `RELEASED`; it returned to `RELEASED` only when falling below a lower `release_threshold` (Figure 2.23). This modest change eliminated chatter around a single boundary and allowed per-key pluck and release points to be tuned independently. A four-sample moving average suppressed high-frequency noise. Across 10 000 iterations, the sampling loop (including multiplexing and filtering) averaged 1.7 ms with ±0.2 ms jitter—comfortably inside the 10 ms latency budget reported by Jack et al. [129].

Threshold storage Pluck and release thresholds were stored in non-volatile FRAM so that calibration survived power cycles. The layout adopted a RIFF-style chunk structure [127], shown in Table 2.3. On startup, the firmware checked the identifiers at `0x00` and `0x66` (“MAXI” and “MINI”); if absent, memory was initialised with default values. A lightweight wrapper around the Adafruit SPI-FRAM library[9] simplified read/write operations.

Calibration workflow During calibration, the selected key streamed raw values over the serial connection (Figure 2.24) while the encoder adjusted thresholds in real time. Addressable LEDs echoed the current state—green for `PLUCKED`, orange for `PRESSED`, blue for `RELEASED`, and red when approaching ADC limits. An initial pass was performed at NEMUS using the Arduino

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[9] Adafruit SPI FRAM Driver v2.6.2
`https://github.com/adafruit/Adafruit_FRAM_SPI/releases/tag/2.6.2`

Figure 2.24: Calibration using the Arduino IDE Serial Plotter (10-bit mode). The live sensor (`K32`) is plotted against its threshold (`T32`); `M`/`m` commands normalise the plot range.

serial plotter and MIDI Monitor,[10] followed by fine adjustments *in situ* with guidance from the curator-performer.

2.9 Stage 4: Mark II

Building on the lessons of *Mark I*, a second interface—*Mark II*—was commissioned by NEMUS for laboratory research with numerically simulated physical models and whole multi-register operation. Where the first build prioritised public robustness and single-register clarity, the new instrument consolidated the sensing and firmware refinements developed in Stage 3 and set out to demonstrate a complete dual-register system. Parametric Python scripts generated EAGLE footprints from the measured jack pitch, speeding the layout of new circuit boards.

Mechanically, *Mark II* adopted forty-five keys rather than forty-nine, following the short-octave layout found in Italian plucked keyboards of the sixteenth to eighteenth centuries [237, p. 46]. The mapping is handled in firmware, allowing the hardware to retain historical proportions without constraining later experiments with tuning or sample mapping.

Address	**Field Name**	**Size**	**C Type**
`0x00`	Pluck Chunk ID	4	`uint32_t`
`0x04`	Pluck Threshold Chunk	98	`uint16_t[49]`
`0x66`	Release Chunk ID	4	`uint32_t`
`0x6A`	Release Threshold Chunk	98	`uint16_t[49]`

Table 2.3: Calibration data layout in non-volatile memory.

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[10] `https://github.com/krevis/MIDIApps`

Figure 2.25: *Mark II*: overall view (top) and front-register sensor boards behind the nameplate (bottom).

Electronics were redesigned with maintainability in mind. The new controller (Figure 2.26, Page 51) introduces keyed JST-PH ports for the FRAM, encoder, and reset switch, alongside flat-flex (FFC) headers for the sensor harness. Both connector types are asymmetric, preventing accidental reversal; the FFC ribbons also route neatly between the frame and outer case, making installation faster and tidier than in the previous loom-based arrangement.

Sensor boards retained the seven-sensor pitch of *Mark I*, a compromise that maximises firmware reuse and avoids wasting multiplexer channels. Boards at the ends of a register can simply leave unused sensors unpopulated rather than adopting a different geometry.

A small but significant refinement lies in the solder-pad junction on each board (Figure 2.26), which routes the multiplexed `SIG` to a defined ADC line via the FFC. Coupled with keyed connectors, this allows any faulty board to be swapped *in situ* without desoldering or disturbing its neighbours—an operation that in *Mark I* often meant dismantling an entire loom. Together, these changes transformed the sensing assembly into a set of serviceable modules, suitable for research environments where components can be replaced or reconfigured between studies.

2.10 Discussion

The development of the interface culminated in its public installation, research deployment, and dissemination strategy. Each aspect was shaped by the principles articulated at the outset of

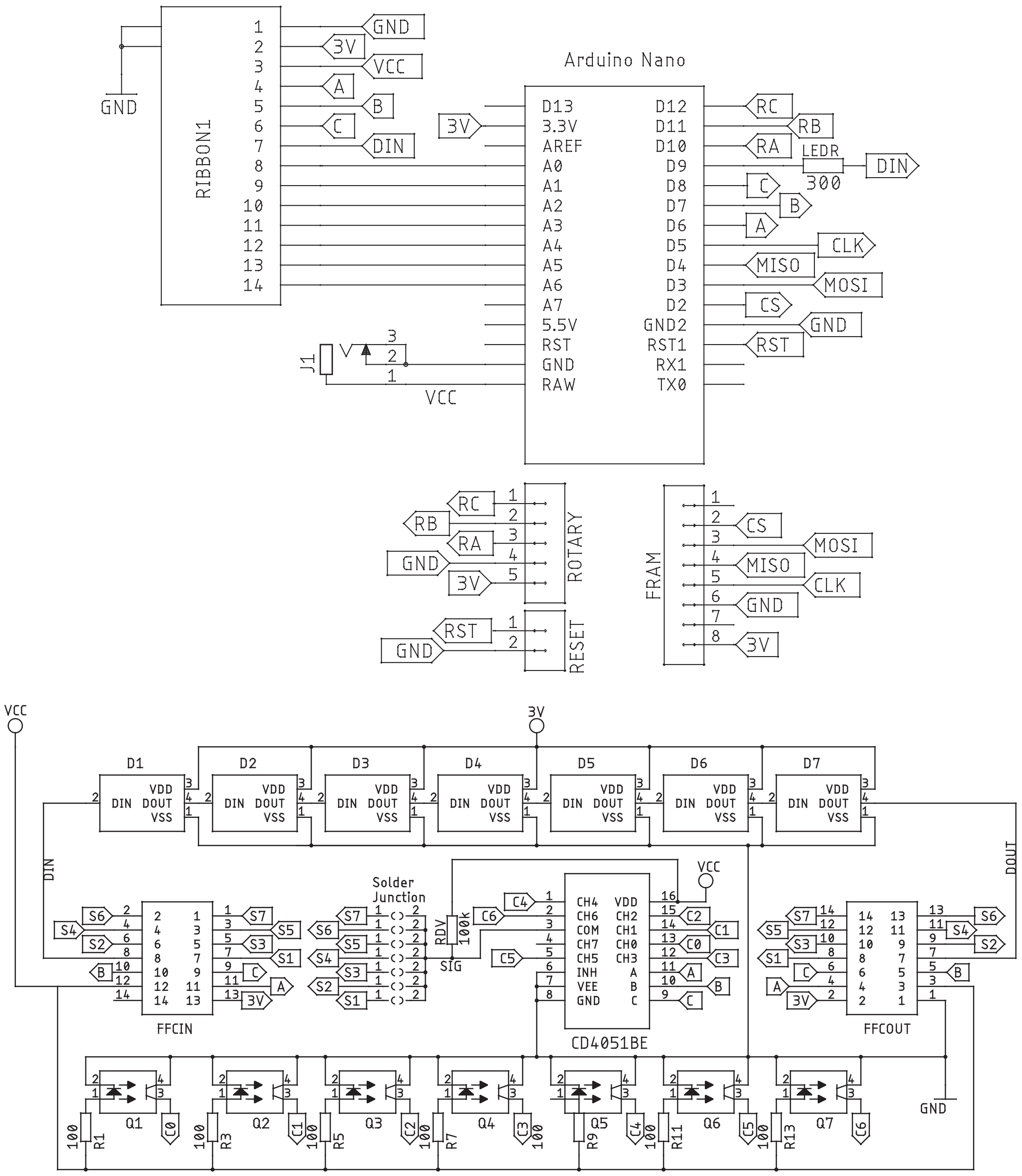

Figure 2.26: Updated controller board (Top) and sensor board (Bottom) schematics for *Mark II*. RGB LEDs (`D`); optical sensors (`Q`); signal routing (`S`). The solder-pad junction on the sensor board assigns the muxed `SIG` to an `S` channel on the FFC.

Figure 2.27: The keyboard installed in the *Oratory* at San Colombano, and a visitor playing with headphones.

this chapter (Tables 2.1 and 2.2): fidelity to sixteenth-century practice, robustness for repeated use, concealment of electronics, compactness, and openness of method. What began as a set of abstract constraints evolved, through staged prototypes, into an instrument capable of engaging visitors while providing a platform for scholarly experimentation.

Embodiment and Public Encounter When *Mark I* was installed in the Oratory at San Colombano, alongside the 1547 Trasuntino harpsichord and the 1540 spinet by the same maker,[11] the emphasis on historical appearance and tactile plausibility paid dividends. Visitors could approach the keyboard without encountering cables, displays, or other cues that might mark it as 'technology.' Reports of the "disconnect" between action and sound noted by McAlpine [157] were absent among staff, surveillance personnel, and trained visitors (approximately twenty participants). The instrument's restrained frame and hidden sensors (Figures 2.27, 2.18) enabled an experience in which haptic response and sonic result felt coherent.

Expert feedback nonetheless identified two limits. First, per-key calibration occasionally introduced a slight temporal mismatch between the felt pluck and the onset of sound, suggesting the need for refined hysteresis and better tools for field adjustment. These limitations have been entirely overcome through the Stage 3 design. Second, while the hardware senses both 8-foot registers independently, the commercial sampler used for the first exhibition exposes only one MIDI note per key; activating both stops would require either multiple sampler instances or a dedicated user interface. For simplicity, the gallery version currently operates on single jacks, with future work directed towards a bespoke library and interface.

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[11] Trasuntino harpsichord – Fondazione Carisbo

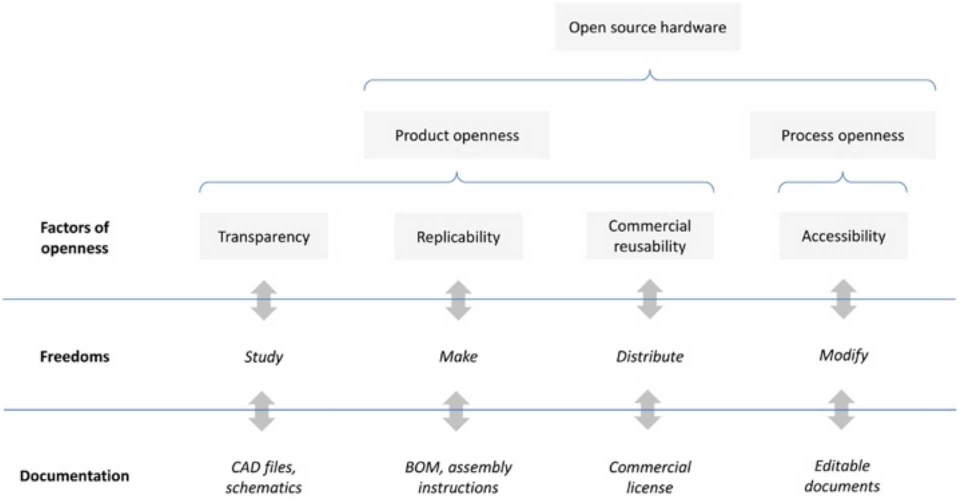

Figure 2.28: Taxonomy of openness from Bonvoisin et al. [26, Figure 1].

A second, informal survey (~50 postgraduate visitors) revealed that some assumed the keyboard was off-limits, an "aesthetic success" in that it conveyed authenticity, but also a reminder that museum interfaces benefit from clear interaction cues.

Open Source Practice There has been a concerted effort to address the problem of archiving and open-sourcing of DMI over the past 10 years [73, 74, 163]. This is not a challenge constrained to just DMI, but is also being addressed as part of the growing open hardware movement. Open hardware, like open software, is the provision of making electronics designs accessible allowing fabrication outside of a central manufacturer. McPherson et al. [163] and Calegario et al. [30] outline largely the same principles as that of the Open Source Hardware Association in 2013 [184], that unlike software, open hardware cannot be simply distributed as a licence and set of source files (Figure 2.28), lest it fall afoul of "openwashing."[12]

Open source hardware has great potential benefits for use in academia [182] and those same benefits can extent to the heritage sector. McPherson et al. [163] rightfully raises concerns of tackling hardware obsolescence and how that is tackled as part of the archiving process. Proprietary systems limit the potential for innovation or reproducibility and, when these systems fail, repairs rely on the original manufacturer who may have ceased support or production of replacement parts [182]. To facilitate reproduction of hardware, it should be self-evident but, any form of archiving and provision of access to source material makes the task much more feasible. Reproduction is made even easier by incorporating open hardware.

This highlights a core problem with digital cultural heritage, which is if we rely on proprietary system for digital conservation, then they will be locked in an ecosystem which is designed to chase change. If heritage institutions are using proprietary digital systems

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[12] when a project "is claimed to be open source whereas no intention to publish product-related information is given" [26].

[128] they should be aware of their choice of digital infrastructure and the implications that will have on a project's longevity. As Bonvoisin et al. [26] coined "openwashing" likewise with digital conservation we run a risk of "heritagewashing" where digital projects claim to serve the conservation of cultural heritage, but are in fact ephemera. That is not to say that ephemeral heritage projects are forbidden, but this should be a conscious choice made at a project's inception and not one applied at a point in the future when the task of archiving a work becomes too great. An open methodology needs to be 'baked-in' to the research process and it is not something trivially applied after the fact. It is of course better to do it afterwards than not at all, but the information at stake also constitutes the development process, not just the end product. The point at which a project is abandoned is not the key point of record–which, given their 'living' status, is likely to have undergone some further modifications.

Both McPherson et al. [163] and Fiordelmondo et al. [73] approach hardware archiving in a repository format. McPherson et al. [163] proposed a workshop with the intention to create a a central repository (or database) for DMI designs. Part of that workshop's primary eight goals were the FAIR adjacent aims of encouraging reproducibility, open access and encouraging a normalised practice of documentation. Both McPherson et al. [163] and [73] raise the issue of repository structure with the latter proposing a a prescriptive measure which can be applied to any DMI project. Research output in the form of open hardware or open software can and should take advantage of the platforms available for distribution of the work,[13] but the work still needs to be citable [225], and cross-reference-able [230] if it is to be built upon.

The limitation here is assuming that the constituent parts of a DMI are a collective to archive and version controlled. This is true to some degree, there is a complete artefact to be documented, but it is very much made of constituent parts that develop and are swapped out. There is the interface, the electronics, and the firmware, whose versions current and old can be used in all number of combinations of versions. Keeping these components contained to a single version control repository limits their modularity and potential for reuse.

Parallel to the physical design, attention was given to documentation and dissemination. Following DMI documentation guidelines [30] and open-science practice [230], the entire project was archived: source code, firmware, bill of materials, CAD schematics, STL models, photographs, and build instructions were placed in public repositories. The material is organised into three submodules—*Firmware* [109], *CAD* [108], and *Model Data* [110]—combined via a meta-repository (Figure 2.29). This structure allows individual components (e.g., a PCB or an optical sensor) to be reused or substituted without restructuring the entire system.

Archiving exposed a few practical challenges. Zenodo's GitHub integration does not yet handle meta-repositories, requiring separate DOIs for each submodule with cross-references [262]. Likewise, the future of CAD data is tied to software sustainability: the discontinuation of Autodesk EAGLE [12] effectively freezes its XML format, though conversion to KiCad remains available [33]. These lessons emphasise that openness depends not only on licensing but also

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[13] such as GitHub, GitLab for source code or Thingiverse for 3D models [184].

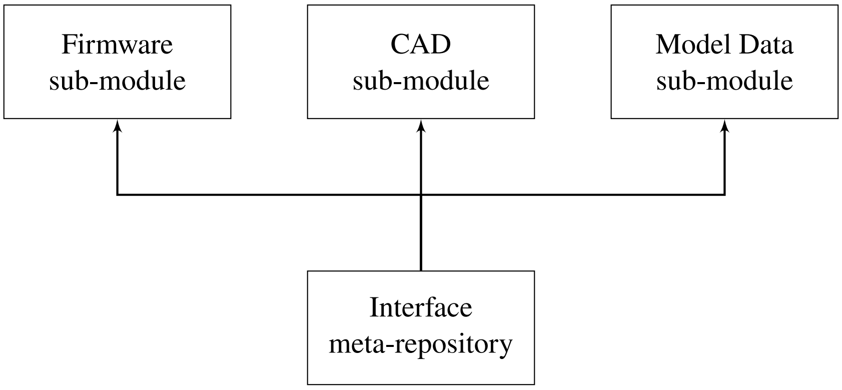

Figure 2.29: Interface git repository and its submodules.

on the careful selection of formats and hosting infrastructure.

Final remarks From the first three–key prototype, through the 49–key gallery instrument, to the laboratory-oriented *Mark II*, the project followed a staged path in which each step resolved a specific set of constraints. The optical sensing system—hidden, inexpensive, and mechanically unobtrusive—met the museum brief without resorting to high-force actuation or unnecessary complexity [28, 96, 242]. Placing digital measurement behind historically derived mechanics and materials [154] allowed the interface to operate as a credible harpsichord in a public setting while still supporting data capture.

Beyond its role as an exhibit, the hardware exposes a level of control that goes beyond a conventional MIDI keyboard. Continuous jack displacement, per-register sensing, and hysteretic event logic make it suitable for engines that aim either at historical reconstruction or at new modes of synthesis. *Mark II* integrates these features into a dual-register platform for research with physically informed models [247], extending the original design without compromising its underlying assumptions.

Seen as a whole, the implementation, public deployment, and open source release confirm that the design values set out at the beginning of the chapter were operational rather than aspirational. They provided a frame within which the instrument could be simultaneously a playable artefact, a museum exhibit, and a reproducible research tool.

Chapter 3

Analysis

This chapter introduces MAGPIE, a free/libre, open, and citable toolkit for the analysis, visualisation, and pedagogical use of plate vibration models in musical acoustics. Whereas the previous chapter centred on *user interaction* with digital reconstructions of cultural heritage—through the San Colombano keyboard project—our focus here shifts to *analysis*, in particular the determination of wood properties that underpin conservation practice. The ability to extract elastic constants from non-intrusive vibration measurements addresses a persistent challenge in instrument making, whether for preservation practices or otherwise. Within the broader framework of NEMUS, MAGPIE aims to extend the project's goals by providing curators, conservators, and instrument makers with an accessible, open source environment in which plate models can be simulated, visualised, and compared to experimental data.

For both the conservation of historical instruments and the making of new ones or faithful copies, reliable material parameters are indispensable. In wooden soundboards and plates, the elastic behaviour is orthotropic, with distinct properties along and across the grain. Conventional destructive or quasi-destructive tests (bending, tensile, compression) are impractical for whole instruments and generally incompatible with curatorial practice. Conversely, vibration-based measurements—e.g., eigenfrequency / eigenshape identification and Chladni visualisation—offer a less invasive alternative. Recent work in NEMUS has produced a practical inverse-modelling method to estimate the rectangular orthotropic plate elastic constants from measured modes and Chladni patterns via a linear least-squares formulation [56, 57]. This approach is robust to boundary condition choices, yields a transparent matrix inversion for the constants, and is well-suited to workflows requiring repeatable, low-risk procedures, such as in a luthier workshop. In this chapter, we package, document, and expose this capability to non-specialists through MAGPIE, with particular attention to reproducibility and ease of use in a web browser.

Plate simulations, eigenshape rendering (including Chladni plots), modal parameter estimation, and impulse-response synthesis are often available only in proprietary software stacks or bespoke research scripts, which usually have steep learning curves. The immediate need is for an open, well-documented toolchain that implements standard thin-plate models (e.g., Kirchhoff–

Love and variants), supports inverse estimation of orthotropic constants from measurements, and lowers the barrier to entry via an interactive browser interface. MAGPIE addresses this gap by consolidating numerics (sparse finite-difference biharmonics, eigenanalysis), analysis utilities (mode sorting, Chladni rendering), and inversion routines into a coherent, cross-language codebase released under a permissive licence and distributed on GitHub[1] through the NEMUS project.

To ensure that MAGPIE is not just *available* but *reusable* in the long term, we align the project with the FAIR Guiding Principles (Findable, Accessible, Interoperable, Reusable) [254, 255]. In practical terms, this means:

1. Assigning persistent identifiers (e.g., DOIs via archival services) to code, releases, and datasets.
2. Providing machine- and human-readable metadata, explicit licences, and provenance.
3. Maintaining stable, versioned APIs and minimal, well-specified dependencies.
4. Supplying rich documentation, examples, and curated notebooks that demonstrate museum-focused workflows (from data capture to inversion to reporting).

Complementarily, we adopt the FORCE11 Software Citation Principles so that MAGPIE and its companion assets can be cited like any other research output, enabling credit and traceability for developers and curators alike [225].

MAGPIE is also intended as a teaching aid. Plates are a canonical gateway into structural acoustics: their eigenshapes are visually compelling and highly informative, and Chladni patterns are a familiar, laboratory-friendly way to connect theory and measurement. By offering easy mode visualisation, the tool enables students to explore how boundary conditions, thickness, and rigidity influence spectra and modal topology. In this sense, MAGPIE serves both as an analysis workbench and as a pedagogical tool.

Scope of the chapter The remainder of the chapter develops the design choices behind MAGPIE and their implications for conservation, lutherie, and education. We:

1. Situate the model choices and numerical methods, with an emphasis on transparent sparse operators suitable for inverse workflows.
2. Describe the cross-language architecture and the web-facing interface, designed for user deployment.
3. Demonstrate a representative case study: estimation of elastic constants from measured modes and Chladni patterns on a rectangular plate.

Throughout, we prioritise reproducibility (scripts and notebooks) and citable artefacts (software, datasets, configurations).

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[1] MAGPIE repositories

3.1 Methodology

The modelling strategy underpinning MAGPIE rests on classical thin-plate theory, discretised through finite differences and extended to cover generalised boundary conditions. This section aims to summarise the governing equations, the energy framework, and the semi-discrete formulation that lead naturally to modal analysis and time-domain simulation. It is anticipated that the fully isotropic case will be considered here. For this specific case, cross-language implementations are available in MATLAB, Python, and C++, along with a graphical user interface developed as a Jupyter notebook. The fully orthotropic model, more closely connected to instrument making, will be illustrated as a case study at the end of the chapter.

3.1.1 Kirchhoff–Love framework

The Kirchhoff–Love model describes thin plates undergoing bending deformation [148]. For a homogeneous isotropic plate of thickness ζ and uniform density ρ, the transverse displacement $u = u(x, y, t)$ over a rectangular domain $\mathcal{D} = [0, L_x] \times [0, L_y]$ satisfies the following partial differential equation [23, 100]:

$$\rho\zeta \frac{\partial^2 u}{\partial t^2} = -D\Delta\Delta u - 2\rho\zeta\sigma \frac{\partial u}{\partial t} + \delta(x - x_p)\delta(y - y_p) f(t), \tag{3.1}$$

where $D = E\zeta^3/[12(1 - \nu^2)]$ is the flexural rigidity in terms of Young's modulus E and Poisson's ratio ν, and σ is a damping coefficient. The forcing is represented as a point excitation at (x_p, y_p) with temporal profile $f(t)$, distributed spatially by a double Dirac delta. The operator Δ denotes the two-dimensional Laplacian

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}, \tag{3.2}$$

so that $\Delta\Delta$ is the biharmonic operator. Equation (3.1) can be derived from an energy balance. For smooth functions f, g on D, define the inner product and associated norm as

$$\langle f, g \rangle = \int_D f g \, dxdy, \qquad \|f\| = \sqrt{\langle f, f \rangle}. \tag{3.3}$$

In addition, introduce the bilinear form

$$L(f, g) = \frac{\partial^2 f}{\partial x^2}\frac{\partial^2 g}{\partial y^2} + \frac{\partial^2 f}{\partial y^2}\frac{\partial^2 g}{\partial x^2} - 2\frac{\partial^2 f}{\partial x \partial y}\frac{\partial^2 g}{\partial x \partial y}. \tag{3.4}$$

With this notation, the total energy of the system is

$$H = \frac{\rho}{2}\left\|\frac{\partial u}{\partial t}\right\|^2 + \frac{D}{2}\left(\|\Delta u\|^2 + (\nu - 1)\langle L(u, u), 1\rangle\right). \tag{3.5}$$

Its rate of change is given by

$$\frac{dH}{dt} = -2\rho\zeta\sigma \left\| \frac{\partial u}{\partial t} \right\|^2 + \frac{\partial u}{\partial t}(x_p, y_p, t) f(t). \tag{3.6}$$

In the absence of losses and external forcing, energy is conserved. Boundary terms, involving shear forces and bending moments, are chosen so that energy conservation is maintained. Along an edge normal to the x-axis, the force and the moment per unit length are given by:

$$F_x = D\left(\frac{\partial^3 u}{\partial x^3} + (2-\nu)\frac{\partial^3 u}{\partial x \partial y^2} \right), \tag{3.7a}$$

$$M_x = -D\left(\frac{\partial^2 u}{\partial x^2} + \nu\frac{\partial^2 u}{\partial y^2} \right), \tag{3.7b}$$

and the corresponding boundary contributions are:

$$B_{x=L_x} = \int_0^{L_y} \left(\frac{\partial u}{\partial t} F_x + \frac{\partial^2 u}{\partial t \partial x} M_x \right)\Big|_{x=L_x} dy, \tag{3.8a}$$

$$B_{x=0} = -\int_0^{L_y} \left(\frac{\partial u}{\partial t} F_x + \frac{\partial^2 u}{\partial t \partial x} M_x \right)\Big|_{x=0} dy. \tag{3.8b}$$

At free edges, $F_x = M_x = 0$; at clamped edges, $u = \partial_x u = 0$; at simply supported edges, $u = M_x = 0$. An additional compatibility condition occurs at the intersection of two free sides:

$$\frac{\partial^2 u}{\partial x \partial y} = 0. \tag{3.9}$$

To interpolate between the classical edge conditions, elastic supports may be added at the boundaries. Each edge is coupled to springs that resist both displacement and rotation, with stiffness constants $K_\circ$ and $R_\circ$. For example, at $x = 0$ and $x = L_x$ the conditions read

$$K_{x=L_x} u(L_x, y, t) = F_x(L_x, y, t), \tag{3.10a}$$

$$R_{x=L_x} \frac{\partial u}{\partial x}(L_x, y, t) = M_x(L_x, y, t), \tag{3.10b}$$

$$K_{x=0} u(0, y, t) = -F_x(0, y, t), \tag{3.10c}$$

$$R_{x=0} \frac{\partial u}{\partial x}(0, y, t) = -M_x(0, y, t). \tag{3.10d}$$

Analogous expressions hold along the y-edges. In the limits $K_\circ \to 0$ or $R_\circ \to 0$, one recovers free boundaries, whereas $K_\circ \to \infty$ or $R_\circ \to \infty$ enforces zero displacement or zero slope, respectively. Note that eight such constants, two per edge, must be specified, as per Figure 3.1.

3.1.2 Finite-difference discretisation

The finite difference method can be used to approximate (3.1) along with the boundary conditions of elastic type (3.10). The first step is to discretise the spatial domain by introducing

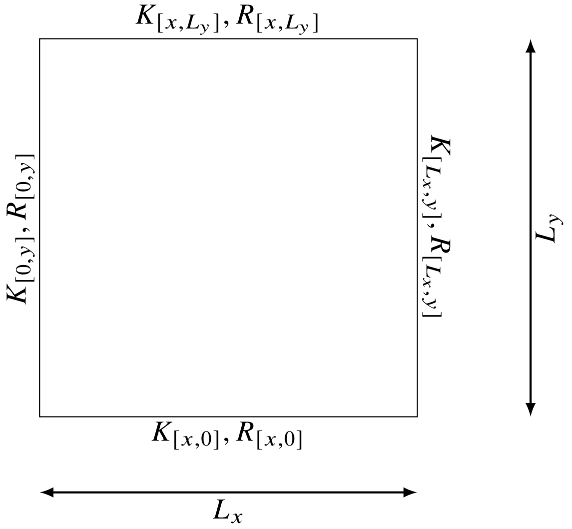


Figure 3.1: Representation of the eight edge elastic constants.

a uniform grid along the x and y directions, with grid spacing h. The domain $\mathcal{D}$ is then represented by a two-dimensional grid containing $N := (N_x + 1)(N_y + 1)$ points, where N_x and N_y denote the number of subintervals along the x- and y-axes, respectively. The continuous displacement $u(x, y, t)$ is replaced by the grid function $u_{l,m}$ at the grid locations $x = lh$, $y = mh$. Derivatives are approximated using centred differences [236]:

$$\delta_x u_{l,m} = \tfrac{1}{2h}(u_{l+1,m} - u_{l-1,m}) \approx \partial_x u, \tag{3.11a}$$

$$\delta_{xx} u_{l,m} = \tfrac{1}{h^2}(u_{l+1,m} - 2u_{l,m} + u_{l-1,m}) \approx \partial_{xx} u, \tag{3.11b}$$

$$\delta_{xxxx} u_{l,m} = \delta_{xx}(\delta_{xx} u_{l,m}) \approx \partial_{xxxx} u, \tag{3.11c}$$

with similar definitions in y. Boundary conditions are enforced by direct discretisation of (3.10). As an example, for the edge at $x = 0$, one has:

$$K_{x=0} u_{0,m} = -D(\delta_{xx} + (2-\nu)\delta_{yy})\delta_x u_{0,m}, \tag{3.12a}$$

$$R_{x=0} \delta_x u_{0,m} = D(\delta_{xx} + \nu\delta_{yy}) u_{0,m}, \tag{3.12b}$$

with analogous discretisations enforced at the other edges. The corner condition (3.9) is discretised as:

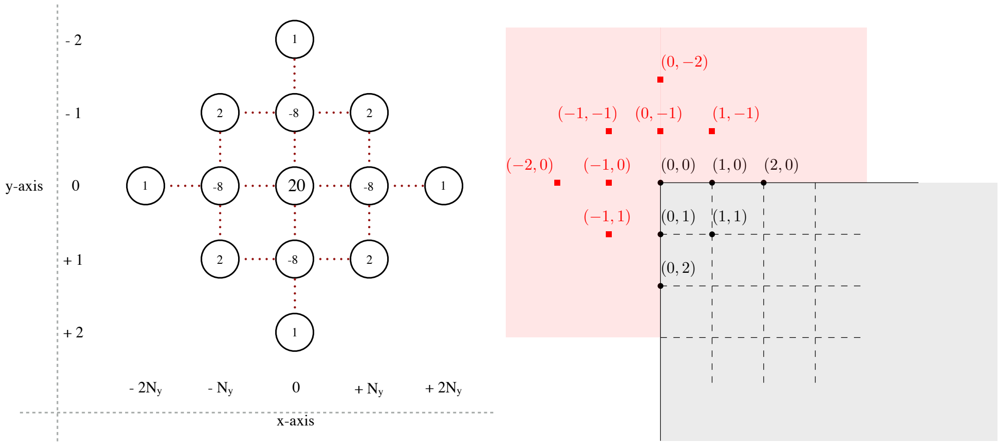
$$\delta_x \delta_y u_{0,0} = 0. \tag{3.13}$$

The biharmonic operator is then approximated as:

$$B := (\delta_{xx} + \delta_{yy})^2 = \delta_{xxxx} + 2\delta_{xx}\delta_{yy} + \delta_{yyyy} \approx \Delta\Delta. \tag{3.14}$$

The 13-point, two-dimensional stencil is reported in Figure 3.2a.

Computationally, the two-dimensional problem is never really encoded as such. It is



(a) (b)

Figure 3.2: a discrete biharmonic stencil. (b) ghost points resulting from application of the biharmonic stencil to the top-left corner of the plate.

convenient to recast the two-dimensional grid function $u_{l,m}$ into a column vector $\mathbf{u}(t)$ of length N. As illustrated in Figure 3.3, this vectorisation is obtained by stacking successive strips of grid points with the same index l. The biharmonic, then, becomes the matrix $\mathbf{B} \in \mathbb{R}^{N\times N}$. The central block of the biharmonic matrix is composed of sub-blocks, as per Figure 3.4. Near the boundary, however, the form of the biharmonic operator coefficients must be specialised. As an example, consider Figure 3.2b: application of the biharmonic stencil to the upper-left corner results in seven "ghost" points whose value must be pre-determined by applying the numerical boundary conditions (3.12).

Although generally non-symmetric, for sufficiently fine grids, the biharmonic matrix $\mathbf{B}$ admits a complete set of eigenvectors with real eigenvalues bounded as

$$0 \lesssim \lambda_{\mathbf{B}} \leq (64 + O(\max(R_\circ, K_\circ)))h^{-4} \tag{3.15}$$

Writing $\mathbf{B} = \mathbf{Q}\boldsymbol{\Lambda}\mathbf{B}^{-1}$, the modal angular frequencies result as:

$$\boldsymbol{\Omega} = \sqrt{\frac{D}{\rho\zeta}\boldsymbol{\Lambda}}. \tag{3.16}$$

Hence, semi-discrete form of Equation (3.1) is:

$$\rho\zeta\ddot{\mathbf{u}}(t) = -D\mathbf{B}\mathbf{u}(t) - 2\rho\zeta\sigma\dot{\mathbf{u}}(t) + \mathbf{J}f(t), \tag{3.17}$$

with $\mathbf{J}$ a sparse spreading operator approximating the two-dimensional Dirac delta appearing in (3.1). Transforming with $\mathbf{w}(t) = \mathbf{Q}^{-1}\mathbf{u}(t)$ yields a diagonal system of forced oscillators,

$$\ddot{\mathbf{w}}(t) = -\boldsymbol{\Omega}^2\mathbf{w}(t) - 2\mathbf{C}\dot{\mathbf{w}}(t) + \rho^{-1}\zeta^{-1}\mathbf{Q}^{-1}\mathbf{J}f(t), \tag{3.18}$$

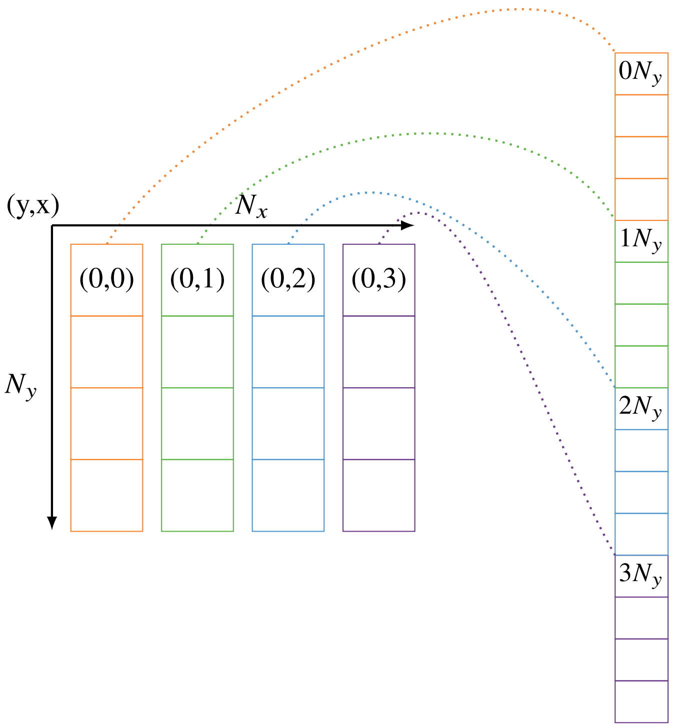


Figure 3.3: Arrangement of the finite difference plate as a linear vector.

where **C** is a (possibly mode-dependent) diagonal damping matrix. The system is truncated to the first N_{modes} in the frequency band of interest. The modal system (3.18) is, hence, entirely *parallel*, since the modal frequency matrix $\mathbf{\Omega}$, like **C**, is fully diagonal.

In practice, setting up the biharmonic matrix **B** allows one to:

1. Compute resonant frequencies and modal shapes via an eigenvalue problem defined for **B**.
2. Simulate the plate's transient response via (3.18) under dynamic loading $f(t)$, using the exact update formulas for the numerical harmonic oscillator [38].
3. For a measured experimental plate, estimate its Young's modulus E (and, in the orthotropic generalisation, Young's moduli E_x, E_y and the shear modulus G_{xy}) via an optimisation problem by inputting a few measured eigenfrequencies and corresponding mode shapes, as described in [56, 57].

The following section describes implementation details, with a specific focus on computational aspects and cross-language deployment.

$$\mathbf{B} = \begin{pmatrix} \ddots & & & & & \\ & \mathbf{B}_0 & \mathbf{B}_1 & \mathbf{B}_2 & & \\ & \mathbf{B}_1 & \mathbf{B}_0 & \mathbf{B}_1 & \mathbf{B}_2 & \\ & \mathbf{B}_2 & \mathbf{B}_1 & \mathbf{B}_0 & \mathbf{B}_1 & \\ & & \mathbf{B}_2 & \mathbf{B}_1 & \mathbf{B}_0 & \ddots \\ & & & & \ddots & \ddots \end{pmatrix}$$

with:

$$\mathbf{B}_0 = \begin{pmatrix} \ddots & \ddots & & & & \\ \ddots & 20 & -8 & 1 & & \\ & -8 & 20 & -8 & 1 & \\ & 1 & -8 & 20 & -8 & \ddots \\ & & 1 & -8 & 20 & \ddots \\ & & & \ddots & \ddots & \ddots \end{pmatrix}, \quad \mathbf{B}_1 = \begin{pmatrix} \ddots & \ddots & & & \\ \ddots & -8 & 2 & & \\ & 2 & -8 & 2 & \\ & & 2 & -8 & \ddots \\ & & & \ddots & \ddots \end{pmatrix}, \quad \mathbf{B}_2 = \begin{pmatrix} \ddots & & & & \\ \ddots & 1 & & & \\ & & & 1 & \ddots \\ & & & \ddots & \ddots \end{pmatrix}$$

Figure 3.4: Block–Toeplitz form of the discrete 2-D biharmonic operator. The blocks $\mathbf{B}_0, \mathbf{B}_1, \mathbf{B}_2$ encode the centre, first off-line, and second off-line couplings of the stencil. Only the central blocks are displayed here. The blocks involving near-boundary points have specialised forms involving following to the elastically restrained boundary conditions (3.12).

3.2 Development

The project is language-agnostic by construction. A minimal, shared specification of inputs/outputs (plate geometry, material set, boundary constants, grid, solver options) governs equivalent libraries in MATLAB, Python, and C++. Back ends differ only where platform conventions demand it (e.g., sparse formats and eigensolver interfaces); numerical results and reference examples are kept congruent by tests and cross-checks.

Distribution follows an "open first" approach: version-controlled source, machine- and human-readable metadata, explicit licences, and archival releases with persistent identifiers. Example notebooks and scripts ship alongside the libraries to promote repeatable workflows (from data import to inversion and reporting). The browser-facing interface (Section 3.3.1) is a thin layer over the same core routines.

Performance-sensitive stages are localised. Operator assembly is implemented explicitly (diagonals or structured blocks as appropriate to each back end), and eigenproblems are solved in shift–invert mode with symmetrical routines where applicable. These choices keep the numerics transparent while supporting large grids and routine parameter sweeps.

3.2.1 Design

The source code was structured using the model-view-controller (MVC) paradigm [142], splitting the software into three major components: data (Model), interface (View), and core logic (Controller).

```
mapie-matlab/
├── CONTRIBUTING
├── DOCS.md
├── LICENSE
├── ModalTimeInt.m
├── README.md
├── bhcoefs.m
├── bhmat.m
├── biharmdiag.m
├── docs/
├── fidimat.m
├── magpie.m
├── private/
│   ├── D00_coeffs.m
│   ├── D01_coeffs.m
│   ├── D02_coeffs.m
│   ├── D10_coeffs.m
│   ├── D11_coeffs.m
│   ├── D12_coeffs.m
│   ├── D20_coeffs.m
│   ├── D21_coeffs.m
│   └── D22_coeffs.m
├── trapzIntcalc.m
└── youngcalc.m
```

(a)

```
magpie-python/
├── dist/
├── dist.md
├── docs/
├── LICENSE
├── magpie
│   ├── Dxx_coeffs.py
│   ├── __init__.py
│   ├── bhmat.py
│   ├── data
│   │   └── material_properties.csv
│   ├── magpie.py
│   ├── modal_time_integration.py
│   └── youngcalc.py
├── nemus_magpie.egg-info/
├── nemus_magpie_mhamilt.egg-info/
├── README.md
├── requirements.txt
└── setup.py
```

(b)

Figure 3.5: Directory structure of *Nemus-Project/magpie-matlab: 0.0.2* [58] (a) and *Nemus-Project/magpie-python: 0.0.5* [116] (b).

Model Plate parameters (geometry, thickness, ρ, E or $E_{x,y}/G_{xy}$, ν), boundary stiffnesses, grid definition, and optional measurement data (frequencies, mode indicators).

Controller Numerical kernels: sparse operator assembly, eigenanalysis, modal integrators, and linear inversion utilities. These are packaged as a stable library API replicated across languages.

View Lightweight interfaces (Jupyter widgets and plotting helpers) for inspection, Chladni rendering, and report-ready figures. The UI is kept repository-separate and imports the library as a dependency. This layout has practical consequences:

- Interfaces are replaceable. The same kernels drive notebooks, command-line tools, or future web front ends without code duplication.
- Only affected quantities are recomputed when parameters change (e.g., grid refinement or boundary constants), enabling fast exploratory sweeps with coarse grids and high-fidelity reruns at higher resolution.
- Platform specifics are isolated. For example, CSC/DIA sparse storage and solver hooks (ARPACK/SciPy, MATLAB `eigs`, or Spectra / Eigen) live behind a consistent API, so examples and tests remain identical across languages.

The result is a compact core that is easy to audit and extend (additional boundary models, orthotropic variants, damping laws), and a view layer that can evolve independently to suit conservation and teaching use cases.

3.2.2 MATLAB

The first implementation of MAGPIE originated from a single 600-line MATLAB script used internally within the NEMUS project. This script produced eigenmodes, impulse responses, and stiffness estimates for rectangular Kirchhoff–Love plates under elastic boundary conditions. To make the tool reusable and extensible, the script was refactored into a modular library under version control on GitHub [58]. The refactor replaced monolithic procedural code with named functions, separated concerns, and removed repeated logic.

Adopting the MVC structure described in Section 3.2.1, the MATLAB code was split into three functional layers. The *model* is defined by plate geometry, material data, Poisson ratio, grid resolution, and the eight boundary stiffness constants. The *controller* exposes a small API: the main `magpie` function validates six required arguments (geometry, ρ, E, ν, grid, and boundary constants), and delegates to internal routines for eigenanalysis, modal synthesis (`ModalTimeInt`), and elastic constant inversion (`youngcalc`). The *view* layer is minimal in MATLAB and limited to plotting eigenshapes and Chladni fields.

Figure 3.5a show the directory structure for the MATLAB version preset in *Nemus-Project/magpie-matlab: 0.0.2* [58]. Central to all functionality is the construction of the biharmonic matrix by

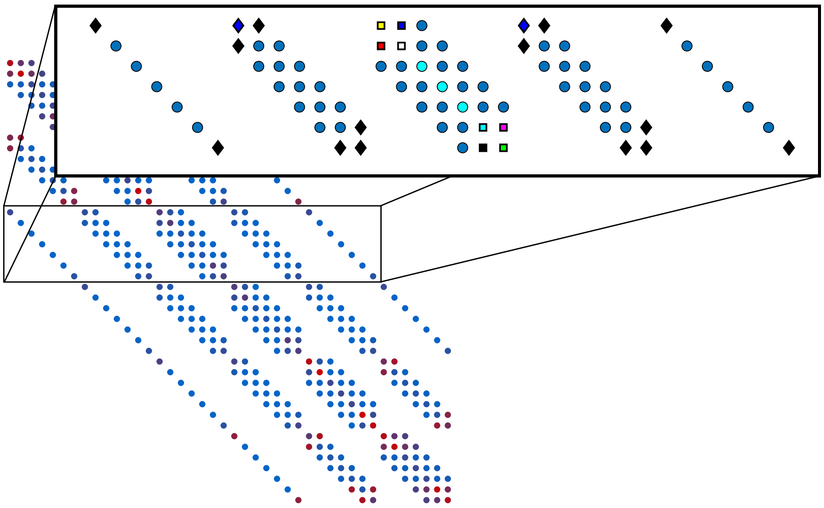


Figure 3.6: Cross-section of the biharmonic illustrating the coefficient content for a single grid line.

the function `bhmat`. In the simplest interior case the discrete operator corresponds to the 13-point stencil in Figure 3.2a and involves only four distinct coefficients. Under generalised elastic boundary conditions, however, up to 229 coefficients may arise; symmetry and repetition break down near edges and corners (Figure 3.2a). This rules out assembling the matrix by naïvely repeating a uniform stencil. Instead, `bhmat` computes the coefficients explicitly and places them into a sparse matrix.

The grid function $u_{l,m}$ on an $(N_x + 1) \times (N_y + 1)$ grid is vectorised as shown in Figure 3.3, giving a square matrix of dimension $N = (N_x + 1)(N_y + 1)$. For performance, all assembling is carried out in sparse format. MATLAB stores sparse matrices in compressed–sparse–column format (CSC), with values, row indices, and column pointers packed contiguously [94]. This makes repeated block concatenation expensive, as it forces reallocation and re-indexing of memory.

The original code used a block-structured approach (Figure 3.4), which was easy to read but slow to assemble at increasing grid sizes. The refactor isolates coefficient generation from matrix assembly within `bhmat`, ensuring that the expensive computations are not repeated unnecessarily and that any optimisation applies across all downstream calls (e.g. eigenvalue problems or modal time-stepping). This also makes the operator usable as a stand-alone object in other finite-difference schemes.

Two assembly strategies were trialled. A block-based strategy constructs sub-matrices and concatenates them, mirroring the stencil structure. While this keeps the code compact, performance degrades once the blocks are copied into CSC format. The alternative is to write coefficients directly into diagonals or into preallocated triplet-style structures before conversion to CSC. Loop-based application of the stencil was rejected because it does not produce a matrix object, which is required for the ARPACK-based eigensolver [145] used by MATLAB's `eigs`. By

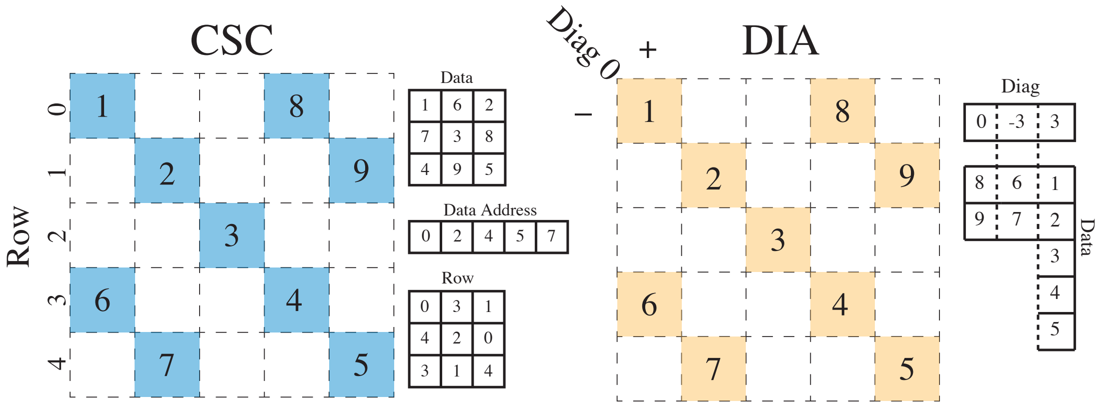


Figure 3.7: Compressed Sparse Column and Diagonal format sparse matrix storage structure. CSC format stores the data, a column pointer and a data address pointer, while the DIA format stores arrays of data and the corresponding diagonal index from which length can be calculated. For a banded matrix, less data is needed however any zero values in the diagonal band must be stored explicitly. Adapted from Eding [62].

consolidating everything in `bhmat`, later ports (e.g. Python, C++) could replicate the algorithm while shifting only the sparse back end.

In summary, the MATLAB refactor established the structure of MAGPIE: a small controller API, explicit operator assembly, and an isolated data model. This provided a reference implementation against which subsequent translations and optimisations could be tested.

3.2.3 Python

Python was the natural second target for MAGPIE. Unlike MATLAB, the language, ecosystem, and packaging infrastructure are fully open source, and its use in scientific computing continues to grow [103]. Porting the toolkit to Python aligned with the project's emphasis on transparency, accessibility, and reuse. The implementation is distributed via the Python Package Index (PyPI)[2] with the code hosted on GitHub and archived through Zenodo [116]. Structure of the Python package (Figure 3.5b) adhered as closely as possible to that of the MATLAB variant (Figure 3.5a).

A key change in the Python version concerns the construction of the discrete biharmonic operator. Rather than assembling sparse sub-blocks and concatenating them, the operator was reformulated explicitly by its 13 diagonals. Each diagonal is further split into non-repeating sectors, typically containing three to five unique coefficients each. This restructuring reflects the fact that elastic boundary conditions introduce up to eight distinct stiffness parameters, which disrupt the repeatable stencil pattern present in the interior. Figure 3.6 shows how the number of unique coefficients increases near edges and corners, undermining diagonal-level repetition across the whole matrix.

Because SciPy allows developers to specify sparse matrices in multiple formats, the

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[2] `https://pypi.org/project/nemus-magpie`

diagonal (DIA) representation (Figure 3.7) was adopted as the target. In contrast to the compressed-sparse-column (CSC) format used internally by MATLAB, the DIA format stores diagonals directly. Zero-padding of shorter diagonals is required but incurs minimal overhead due to the low proportion of non-zero bands.

SciPy also exposes intermediate construction formats such as coordinate and list-of-lists [62]. While this adds flexibility, it requires more explicit handling by the user than MATLAB, where sparse matrices are constructed using CSC exclusively [94]. Before a diagonal-based version was completed, an initial Python port reproduced the original block-based assembly. SciPy's `bmat` function [219] made this practical: blocks of size $N \times N$ could be arranged in lists-of-lists, with empty blocks represented by `None`. Python's list replication and unpacking operators allow the structure to be encoded compactly, avoiding extensive index manipulation.

```python
     [
     [B11,   B12,   B13,                       *Z * M3],
     [B21,   B22,   B23,   B24,                *Z * M4],
     [B31,   B32,   B33,   B34,   B35,         *Z * M5],
*[[*Z * r,   B31,   B32,   B33,   B34,   B35,  *Z * (M5 + r)] for r in range(1, M4)],
  [*Z * M4,              BM1M3, BM1M2, BM1M1, BM1M0],
  [*Z * M3,                     BM0M2, BM0M1, BM0M0],
     ]
```

Figure 3.8: Python syntax for the biharmonic structured from a list-of-lists of sub-blocks. The `Ma` multiplier variables are defined as $N_y - a$ and `Z` is a `[None]` list. The Python formulation permits a relatively direct translation of the block-Toeplitz form shown in Figure 3.4

Despite the elegance of the block construction in Python (Figure 3.8), benchmarking revealed similar limitations to those in MATLAB. Figure 3.9a compares the performance of three cases: block assembly in MATLAB, block assembly in Python, and diagonal assembly in MATLAB. Each operator size was generated ten times and the shortest runtime was recorded. At larger grid sizes ($\sim 3 \times 10^5$ unknowns), MATLAB's diagonal method was roughly forty times faster than its own block formulation (0.2 s vs. 8 s). Python's block performance tracked MATLAB's block performance: slower and less scalable than the diagonal approach.

It was projected that a diagonal composition in Python would likely outperform the block composition method once implemented. Comparison of between results from MATLAB and SciPy eigensolvers revealed a percentage error in the order of 10^{-9} (Figure 3.9b) and the highest error between solvers is concentrated within the first few modes. This error is not unexpected and likely arises from a mixture of floating-point error and differences in the BLAS and LAPACK versions and the LU Decomposition[3] methods used by MATLAB and SciPy respectively.

Eigensolver Process

Both MATLAB and Python provide eigensolver functionality through an interface with the ARPACK library [217]. For the standard eigen problem $A\vec{x} = \lambda\vec{x}$ the ARPACK solver routines

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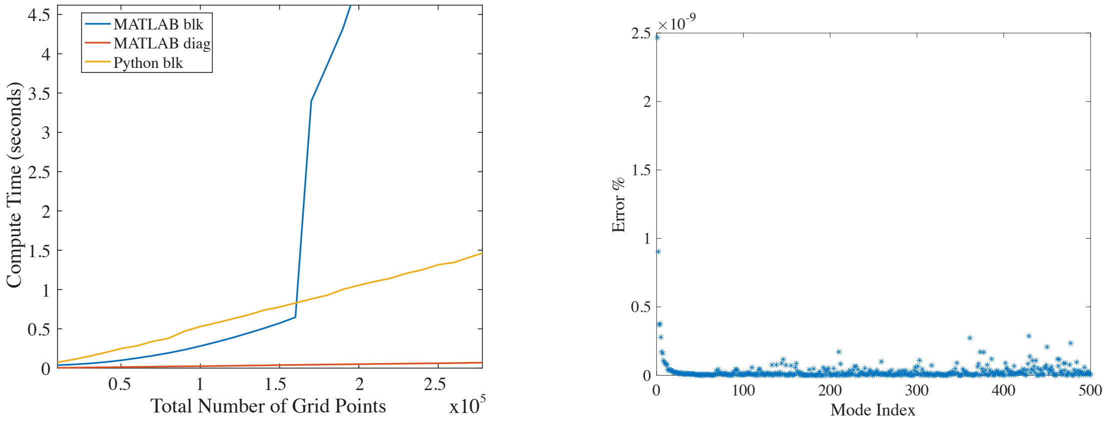
[3] UMPACK for MATLAB [48] and SuperLU for SciPy [218]



(a) (b)

Figure 3.9: (a) Computational performance of the biharmonic assembled in a block format in Matlab and Python and a diagonal format in Matlab. Each size of biharmonic was computed 10 times and the shortest time was recorded. (b) Percentage error between Matlab and SciPy for the first 500 eigenvalues.

find eigenvalues iteratively, ranked by magnitude, with the largest magnitude eigenvalues requiring the least computation [145]. The biharmonic is multi-diagonal, sparse, real, and can be symmetric positive definite [115]. The eigenvalues of the biharmonic are the modes of the system and, for musical acoustics, the lower and fundamental modes are those of greatest interest. For small magnitude eigenvalues, the eigensolvers will either converge slowly or fail entirely, leading to much longer compute times [217].

In order to find these smaller magnitude eigenvalues, the solver must be operated in a shift-invert mode. This consists of transforming the eigenvalue problem from $Ax = \lambda x$ to $(A - \sigma I)^{-1}x = \frac{1}{\lambda - \sigma}x$ with shift value σ. For $\sigma = 0$, $A^{-1}x = \frac{1}{\lambda}x$, large λ therefore becomes small to the solver and smaller magnitude eigenvalues will be found first. When the biharmonic is large, inverting it can be a computationally expensive operation. The biharmonic can be inverted algebraically as part of LU decomposition.

For a shift-invert solve, the matrix is never explicitly inverted. Instead the backwards substitution of LU decomposition inverts the matrix algebraically. LU decomposition is defined as $A = LU$, where L is the lower triangular matrix with ones on the diagonal, and U is the upper triangular matrix. Applied to the eigen problem, one obtains

$$x = U^{-1}L^{-1}\lambda x, \quad \frac{1}{\lambda}x = U^{-1}L^{-1}x, \quad \frac{1}{\lambda}x = A^{-1}x.$$

For a shift-invert using $\sigma = 0$ with LU decomposition, A and λ will be re-inverted. Both Matlab and SciPy interfaces with ARPACK can be passed a σ value of 0 to find the smallest magnitude eigenvalues. ARPACK requires that the option to find largest magnitude is kept, but when a σ value is provided the values will be implicitly passed through a second shift-invert process.

```
for k = 1 to n
    pivot_row = index of max(abs(A[k:n, k])) + k - 1
    if pivot_row != k
        swap row k of A and pivot_row of A
        swap row k of A and pivot_row of P
        if k > 1:
            swap row k of L and pivot_row of L (columns 1..k-1)

    for i = k+1 to n
        L[i,k] = A[i,k] / A[k,k]
        for j = k to n
            A[i,j] = A[i,j] - L[i,k] * A[k,j]

    for j = k to n
        U[k,j] = A[k,j]
```

Figure 3.10: Pseudocode for the LU Decomposition algorithm.

Parameter	**Value**	**Description**
L_x	1.10 m	Length in the x-direction
L_y	0.80 m	Length in the y-direction
L_z	0.005 m	Thickness
E	9×10^9 Pa	Young's modulus
ρ	8765 kg/m^3	Density
ν	0.3	Poisson's ratio
h	$10^{-2}\sqrt{L_x L_y}$ m	Spacing between grid points
R	10^{15} N·m^{-1}	Rotational elastic restraint (All boundaries)
K	10^{15} N·m^{-2}	Flexural elastic restraint (All boundaries)

Table 3.1: MAGPIE parameters used throughout benchmarking tests in this chapter.

SciPy and MATLAB both interface with ARPACK and the results between solvers appear similar. Figure 3.9b shows the percentage error for the first 500 eigenvalues calculated by the ARPACK interfaces in SciPy and MATLAB. Table 3.1 shows the parameters used in Python and MATLAB.

Although the percentage error is relatively small, the eigenvalue compute time is noticeably longer in Python compared to MATLAB, which is compounded further by the compute time biharmonic using SciPy (Figure 3.9a). A further implementation was required to determine whether the compute time could be improved upon, and to achieve this, we looked toward a compiled language.

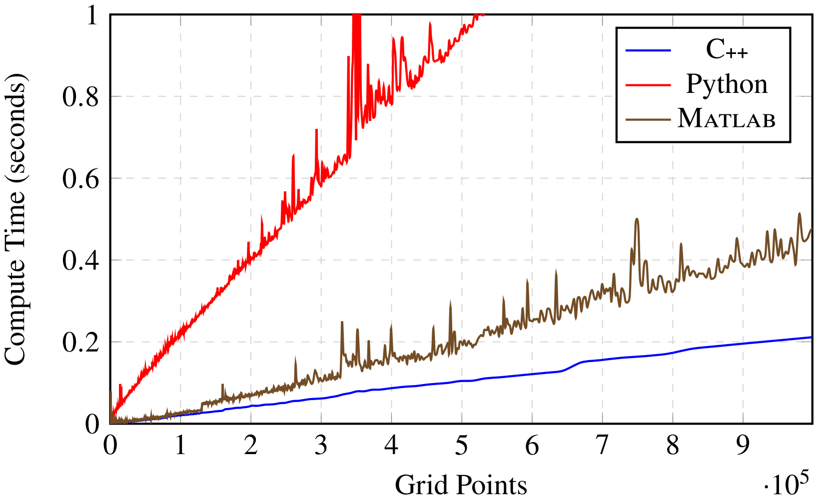


Figure 3.11: Construction time for the diagonalised biharmonic in MATLAB, Python and C++.

3.2.4 C++

Like Python, C++ is entirely open source and therefore compatible with the FAIR principles underpinning the project's methodology. Its status as a compiled, strongly typed language introduces additional development overhead, but it also enables direct control over memory, performance, and solver back ends.

The primary bottleneck in all versions of MAGPIE is the eigensolver stage. Both MATLAB and SciPy rely on ARPACK [145] as the back end. In MATLAB, the user has no visibility into the analysis or pre-processing applied to the matrix. Additionally, MATLAB employs its own internal sparse representation [94], which further obscures the process. The `eigs` function cannot be code-generated and requires the MATLAB runtime environment, limiting portability and access to anyone without a licence.

ARPACK itself is open source[4] and depends on BLAS[5] and LAPACK[6] . While callable from C++, it is written in Fortran, which requires a working Fortran toolchain during compilation. This introduces cross-platform complications that are undesirable for lightweight deployment.

To avoid reliance on Fortran binaries, the C++ implementation of MAGPIE uses the Spectra library [260]. Spectra is a header-only C++ reimplementation of ARPACK that compiles natively without external linking. It builds on the Eigen library [213], which provides sparse matrix types, iterative solvers, and BLAS / LAPACK interoperability when needed. Although, there is no required dependency from Eigen on BLAS / LAPACK which makes its combination with Spectra much more portable.[7]

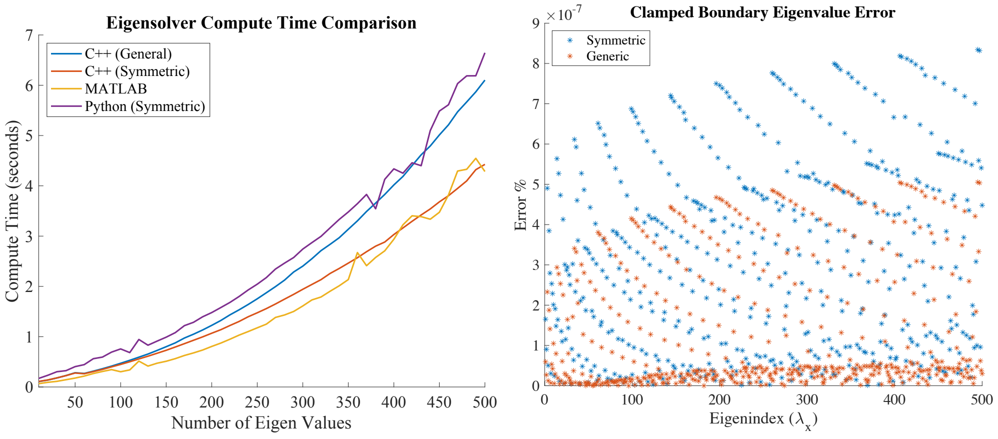
---

[4] The actively maintained fork `arpack-ng` is available via GitHub: `https://github.com/opencollab/arpack-ng`

[5] `http://www.netlib.org/blas/`

[6] `http://www.netlib.org/lapack/`

[7] And for this reason development was pursued with Spectra and Eigen as opposed to the SLEPc library (`https://github.com/slepc/slepc`, which does have BLAS / LAPACK dependency. The benefits of more portable C /



(a) (b)

Figure 3.12: (a) Comparison of eigensolver compute time in Matlab, Python and C++ (generic and symmetric Spectra solvers). (b) C++ times shown are with `-O3` compiler optimisation.

Both libraries are heavily templated, which makes the learning curve steeper but provides type safety and performance advantages. The C++ development followed the same structure and methodology as the Matlab and Python implementations [112].

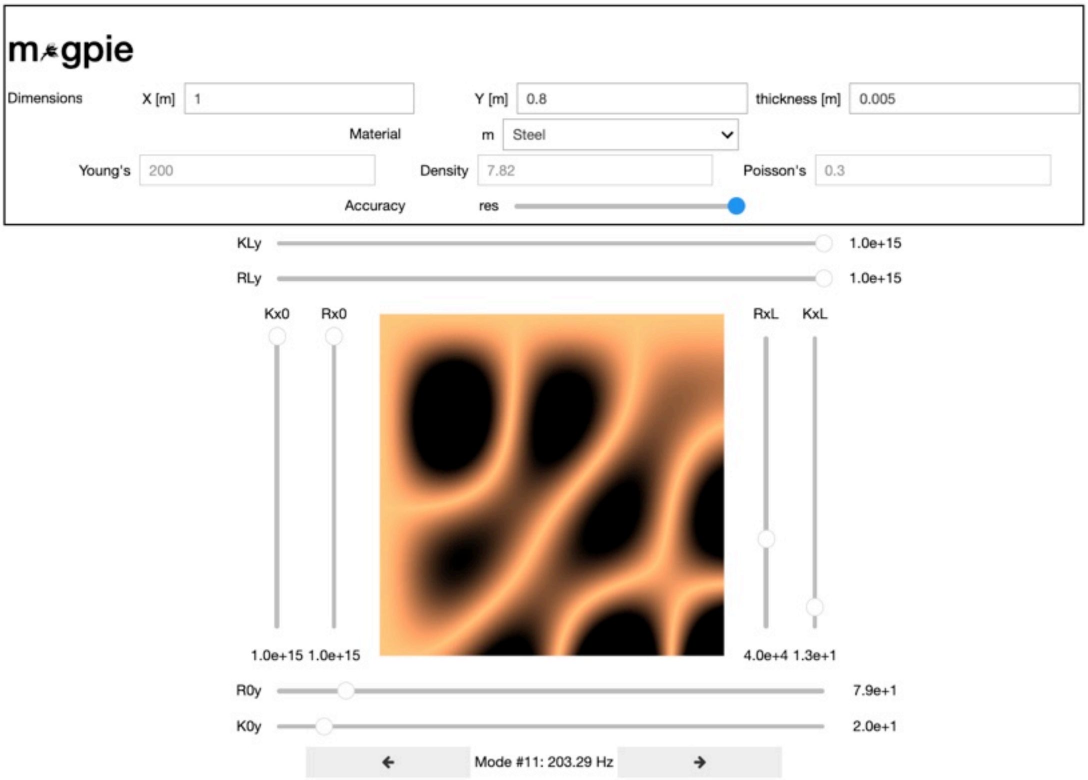
Although the C++ version remains under active development, early benchmarks indicate strong performance and numerical agreement with Matlab. Figure 3.11 compares construction times for the diagonal biharmonic operator across Python, Matlab, and C++. The C++ implementation is comparable to Matlab and is likely to improve further with targeted optimisation. Eigen stores sparse matrices in CSC format, as Matlab does, but it exposes explicit control over memory during assembly. Using triplet insertion,[8] followed by a finalisation step, avoids repeated memory reallocation.

Figure 3.12a shows the eigensolver performance using the parameters listed in Table 3.1. As in SciPy, Spectra allows the choice between generic and symmetric solvers. Unlike SciPy, the difference in performance between the two modes is substantial, with the symmetric solver matching or surpassing Matlab in some cases. Figure 3.12b shows the percentage error between Spectra (both solver types) and Matlab's `eigs`. Errors are a few orders of magnitude higher than those observed in Python (Figure 3.12b), resulting in a trade-off between performance and accuracy when using Spectra.

Relaxing the tolerance slightly (to approximately 10^{-6}) offers a further performance gain for large matrices, with only a negligible impact on accuracy. Taken together, Figures 3.11 and 3.12a indicate that C++ provides both high performance and high fidelity, and supports the conclusion that the elevated Spectra error arises from the implementation of the eigensolver. Since SciPy and Matlab share a common element in ARPACK, errors are much lower.

C++ code are discussed further in Section 4.2.2.

[8] In the format `(value, row, column)`



magpie

Dimensions X [m] 1 Y [m] 0.8 thickness [m] 0.005

Material m Steel

Young's 200 Density 7.82 Poisson's 0.3

Accuracy res

KLy 1.0e+15

RLy 1.0e+15

Kx0 1.0e+15

Rx0 1.0e+15

RxL 4.0e+4

KxL 1.3e+1

R0y 7.9e+1

K0y 2.0e+1

Mode #11: 203.29 Hz

Figure 3.13: Beta version user interface for MAGPIE in Jupyter Notebooks.

3.3 Applications

In this section, two practical applications of the MAGPIE framework are illustrated. The first explores the graphical user interface (GUI), allowing non-expert users to run the MAGPIE framework in a user-friendly environment. The second illustrates the inverse estimation of the elastic constants in wood and metal specimens.

3.3.1 Interfacing with MAGPIE

This section covers the creation of a graphical user interface to MAGPIE, forming a case study on how interfaces with the library can be built. The interface was designed around a scenario where a user wishes to explore the transition from a simply-supported condition case to a clamped case. This is done by gradually increasing rotational spring stiffness across one edge of a plate and observing the effects on modal patterns and frequency response. The user first defines the plate material parameters, which are Young's modulus, density, Poisson's ratio, and dimensions. These parameters compute the discrete biharmonic operator in a sparse matrix format. The biharmonic operator is then used as input for an eigensolver, which returns the eigenvalues and eigenvectors.

The intention was to design an interface to the MATLAB version of MAGPIE, given the performance, accuracy and ease of use of the development environment. The interface was to

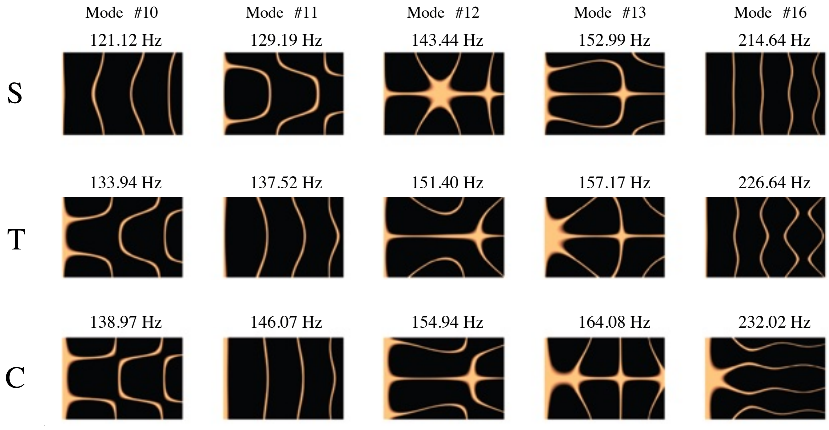


Figure 3.14: Simulated Chladni patterns of modes 10, 11, 12, 13, and 16, for a plate with free boundary conditions along all edges except the leftmost one. The last condition moves from simply-supported (**S**) to a fully clamped cantilever case (**C**), with an intermediary step corresponding to a high rotation stiffness (**T**). The choice of specific modes is the result of an exploration using the Jupyter Notebook graphical interface depicted in Figure 3.13.

be designed using Matlab's GUIDE tool, but it was deprecated in 2021a and finally removed in 2025a [155]. Instead, the Jupyter notebooks system was chosen for portability, given its web browser interface, as well as existing UI element support (Figure 3.13).

The user wishes to compare with Chladni patterns recorded during the course of experiments on a real plate. As such, the user chooses the 'Chladni' format option for plotting mode shapes. The 'Chladni' option renders a top-down 2D visualisation of mode patterns where points at or near zero are highlighted, effectively reproducing the *nodal lines*. This allows the user to render Figure 3.14, which shows the effect of the transition on the rotational stiffness. From these plots obtained by magpie, the user can illustrate how the mode shapes develop between simply supported and clamped cases. As expected, an increase in rotational stiffness increases modal frequency.

Secondly, the eigenvalues returned from the eigensolver are used to calculate modal frequencies. The user can then use the modal time integration functionality of magpie with these modal frequencies to produce a simulated impulse response of the plate. The impulse response of the simulation is then used to create a series of FRF plots that contrast the transition between boundary conditions, as shown in 3.15.

3.3.2 Material Property Estimation with magpie

One of magpie's functionalities is the estimation of a specimen's elastic constant from vibroacoustic measurements. The method is described in detail in [57], and can be applied equally in the isotropic and orthotropic cases. In the first case, the output of the inverse method is Young's modulus E. In the second, the method returns the two Young's moduli in the mutually orthogonal isotropy axes E_x, E_y, and the shear modulus G_{xy}. The method relies on a few key observations, as found in [57], and summarised here:

- Plates with identical aspect ratio L_x/L_y, boundary conditions, and elastic constant ratios E_x/G_{xy}, E_y/G_{xy} produce the same set of non-dimensional eigenshapes and frequencies when non-dimensionalisation is carried out as explained in [57].
- The squared non-dimensional modal frequencies depend linearly on the elastic constants E_x, E_y, G_{xy}. Thus, a linear-in-parameters optimisation problem is formulated and solved via matrix inversion.
- To perform inverse estimation, the method requires at least three modal shapes and associated frequencies in the orthotropic case, yielding E_x, E_y, G_{xy}, and at least one modal shape and related frequency in the isotropic case, yielding E. Using larger sets of modes allows multiple estimations of the elastic constants, thus yielding their mean values along with deviations.

A metal plate

A case study taking the experimental measurements from Duran et al. [60] to calculate Young's modulus using Magpie is illustrated. The experimental plate is represented in Figure 3.16, along with the plate's physical dimensions and density.

The copper plate, with an unknown Young's modulus, was clamped on one side and struck with a hammer. The eigenfrequencies were measured by transforming the signal recorded with an accelerometer into the frequency domain. Modal shapes were identified using the method by Chladni [36]. Running the inverse method using the first two identified modes, Young's modulus was estimated as $E \approx 102$ GPa, a standard value for copper.

Table 3.2 shows the modal shapes and frequencies recorded during that experiment alongside those generated by MAGPIE and COMSOL using the estimated Young's modulus. It can be appreciated that the extrapolated modal shapes and frequencies beyond the second are within marginal error bounds compared to the experimental ones, confirming successful estimation.

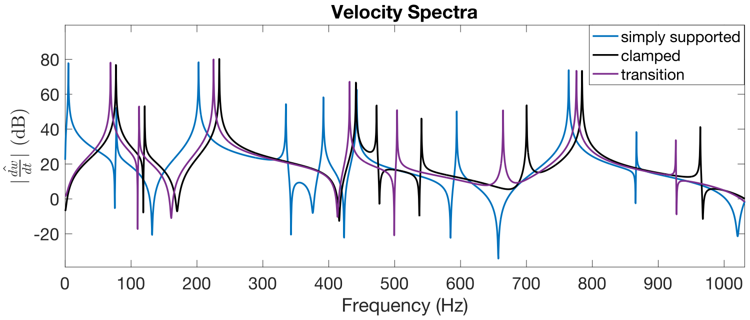


Figure 3.15: FRF of impulse response from simulations of the same plate under different boundary conditions.

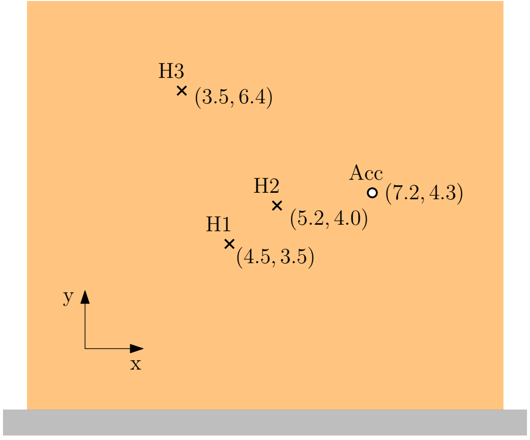


Plate parameters

L_x (cm)	L_y (cm)	L_z (mm)	ρ (kg · m^{-3})
10	8	0.81	8765

Figure 3.16: Pictorial representation of the cantilever copper plate investigated in Duran et al. [60]. The impact hammer (Hx) and accelerometer measurement positions are also represented. Measurement locations are reported as (x, y) coordinates on the plate surface, in cm.

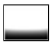
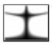
Mode		**Experiment**	MAGPIE	**COMSOL**
1		73	72	72
2		148	150	149
3		376	382	381
4		431	460	459
5		559	578	576
6		910	890	888

Table 3.2: Eigenfrequencies in Hz for experiment data in Duran et al. [60] against numerical simulations in MAGPIE and COMSOL, using the estimated Young's modulus again from MAGPIE. The first two eigenmodes were used as input modes for the inverse estimation problem.

A wooden plate

As a more involved example, a spruce specimen is considered here. Spruce is a common wood type in musical instrument making, with orthotropic behaviour. The experimental setup is shown in Figure 3.17, along with the experimentally measured modal shapes.

The elastic constants E_x, E_y, and G_{xy} for a rectangular sample can be obtained using the `InverseModelling` script within the Matlab implementation of MAGPIE. The script is initialised by setting the plate's parameters:

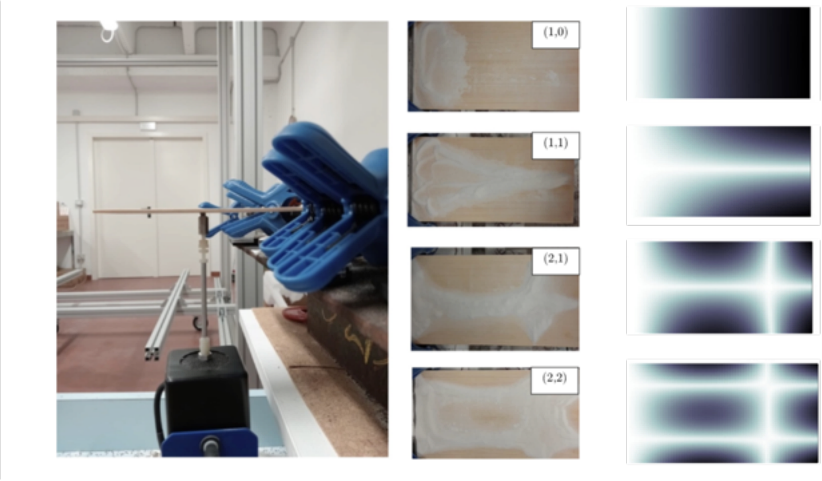


Figure 3.17: Reference experimental and numerical eigenshapes for the wooden plate. The plate is clamped along one edge and free along the others. Chladni patterns are generated with an electromechanical shaker exciting the board. The listed experimental frequencies are derived from accelerometric spectra. Reproduced from [57].

```
%% Plate parameters
rho = 473.9;
Lx  = 0.223;
Ly  = 0.114;
Lz  = 0.003;

%% elastic constants around the edges
KRmat = [0e10, 0e10;  % Kx0 Rx0
         1e10, 1e10;  % K0y R0y
         0e10, 0e10;  % KxL RxL
         0e10, 0e10]; % KLy RLy

%% measured experimental frequencies (Hz)
ExpFreqs = [52 98 311 337 398 637];
```

Because the elastic constants are initially unknown, reasonable starting values must be provided:

```
%% guessed values
Ex0  = 10.7e9;
Ey0  = 716e6;
Gxy0 = 500e6;
```

These guesses serve only to generate numerical eigenmodes that resemble the measured ones and appear in the same order, as illustrated in Fig. 3.17. The script evaluates modal shapes

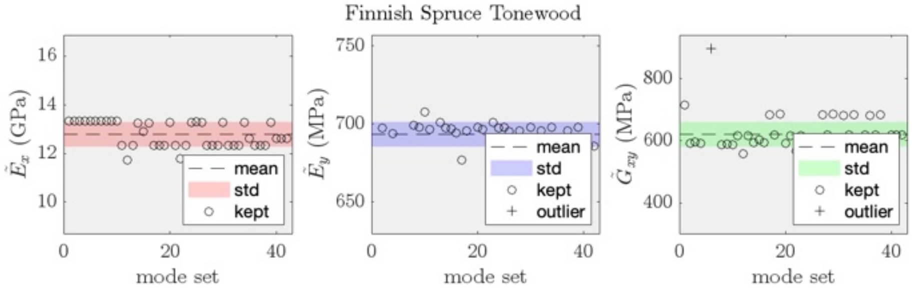


Figure 3.18: Least-squares results for the Finnish spruce plate shown in Fig. 3.17, reproduced from [57].

		$E^{(x)}$ (GPa)	$E^{(y)}$ (MPa)	$G^{(xy)}$ (MPa)
Finnish spruce	mean	12.8	693	621
	rel. std	4.0%	1.1%	6.4%

Table 3.3: Mean values and relative standard deviations of the elastic constants for the experimental plate. These values are consistent with previously reported data for spruce.

and frequencies for different choices of the elastic constants using `freq_domain_sim` and compares the resulting eigenshapes with the reference set produced by the guessed parameters. An example of these shapes, displayed via Chladni patterns, is shown in Fig. 3.17.

Finally, a least-squares procedure is used to extract the elastic constants, returning both mean values and standard deviations. Results for the experimental plate in Figure 3.17 are reported in Figure 3.18 and summarised in Table 3.3.

3.4 Conclusions

This chapter introduced MAGPIE, a free/libre, citable toolkit that makes standard thin-plate models and inverse workflows accessible to conservators, luthiers , and students. In contrast to the previous chapter's emphasis on public interaction with digital reconstructions, the present work focused on *analysis*: modelling rectangular plates with elastic edge restraints, estimating elastic constants from vibration data, and packaging the whole workflow so it is reproducible, inspectable, and usable in a browser.

Key outcomes

1. **Modelling and numerics.** We derived and discretised the Kirchhoff–Love plate with energy-consistent, elastically restrained boundaries. A sparse finite-difference biharmonic operator was implemented with explicit near-boundary specialisations, enabling stable eigenanalysis and time-domain synthesis from the same core.

2. **Cross-language implementation.** The model and APIs were reproduced in MATLAB, Python, and C++. Diagonal (banded) assembly was shown to be markedly more scalable than block concatenation. On the eigensolver side, a symmetric shift–invert configuration (Spectra/Eigen in C++) matched or exceeded MATLAB's `eigs`, but at a cost of elevated error compared to SciPy.

3. **FAIR and citation.** Code, examples, and datasets were aligned with FAIR and FORCE11 principles: versioned releases with persistent identifiers, minimal dependencies, and stable, documented interfaces. This supports long-term reuse in conservation workflows.

4. **Applications and validation.** Two case studies demonstrated end-to-end use. For a cantilever copper plate, inverse estimation recovered a plausible Young's modulus and reproduced higher modes within small error. For an orthotropic spruce plate, the linear least-squares inversion produced E_x, E_y, and G_{xy} consistent with literature ranges, using a handful of modes and Chladni patterns. The same kernels power an instructional Jupyter UI for visualising eigenshapes, nodal (Chladni) patterns, and FRFs.

Limitations Current scope is restricted to rectangular plates, linear KL theory, and simple damping; mode-matching still requires curation; and performance depends on solver configuration (shift–invert, symmetry exploitation) and matrix assembly strategy.

Outlook Near-term work will (i) expose the orthotropic KL model as a first-class path (including lumped masses to emulate bracing), (ii) add automated mode tracking and uncertainty quantification for inverse estimates, and (iii) package releases as a MATLAB toolbox, Python wheels, and a header-only C++ library. Medium-term, we will extend to the Föppl–von Kármán regime and broaden boundary/geometry support, while exploring parallel assembly and solver pipelines for large grids. These steps keep MAGPIE aligned with conservation practice—non-intrusive, repeatable, and auditable—while strengthening its role as a teaching aid and a reliable workbench for instrument makers.

Chapter 4

Future Directions

The two systems presented in the preceding chapters already function as viable tools in their current forms, yet neither represents an endpoint. The thesis as a whole should be read less as a finished artefact and more as a platform from which further iterations can evolve. Each prototype—whether the haptic keyboard interface or the MAGPIE software—reveals new questions that extend beyond the practical scope of this work but remain central to its aims.

Some of these developments are already underway or have been tested in parallel with writing. In contrast, others remain prospective because of constraints in time, resources, or the need to preserve core methodological principles such as openness and reproducibility. This chapter, therefore, outlines a forward trajectory rather than a wish list: identifying where refinement is technically feasible, where further exploration is warranted, and where expansion may introduce trade-offs that require careful ethical or methodological justification.

The discussion is organised by project. Section 4.1 focuses on the keyboard interface, detailing improvements to fabrication, sensing, and visitor interaction while maintaining its role within a conservation framework. Section 4.2 then turns to MAGPIE, considering its continuing development as an open source research environment and the broader community practices that will shape its evolution. Together, these sections frame Chapter 4 as a roadmap for sustainable growth—technical, conceptual, and collaborative—beyond the immediate boundaries of this thesis.

4.1 Interface

Future work on the keyboard interface builds directly on the constraints, improvisations, and design compromises described in Chapter 2. Rather than approaching these retrospectively as isolated shortcomings, the developments in this chapter are framed as continuations of specific pressures: how to make the system maintainable at scale, how to reduce calibration friction, how to improve robustness without abandoning openness, and how to support richer embodied experience in exhibition contexts. Table 4.1 summarises the key limitations encountered and the strategies that now shape the direction forward.

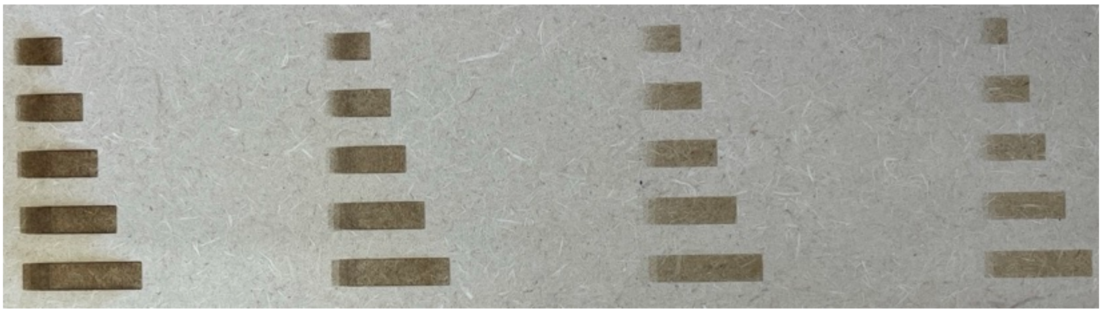


Figure 4.1: Test gradients of various heights using a laser cutter on MDF with decreasing laser power from left to right. The range of the gradient was too compressed to be differentiated by the optical sensor. On high power settings, scorching tends to bleed around the raster, thus affecting the surrounding material and area of the gradient.

The remainder of Section 4.1 develops these strategies as a series of responses that extend, refine, or redirect earlier design decisions. The following subsections trace this progression through fabrication and sensing (§4.1.1), electronics and layout (§4.1.2), temporal performance (§4.1.3), exhibition integration, and research/application trajectories.

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4.1.1 Integrated Jack Fabrication

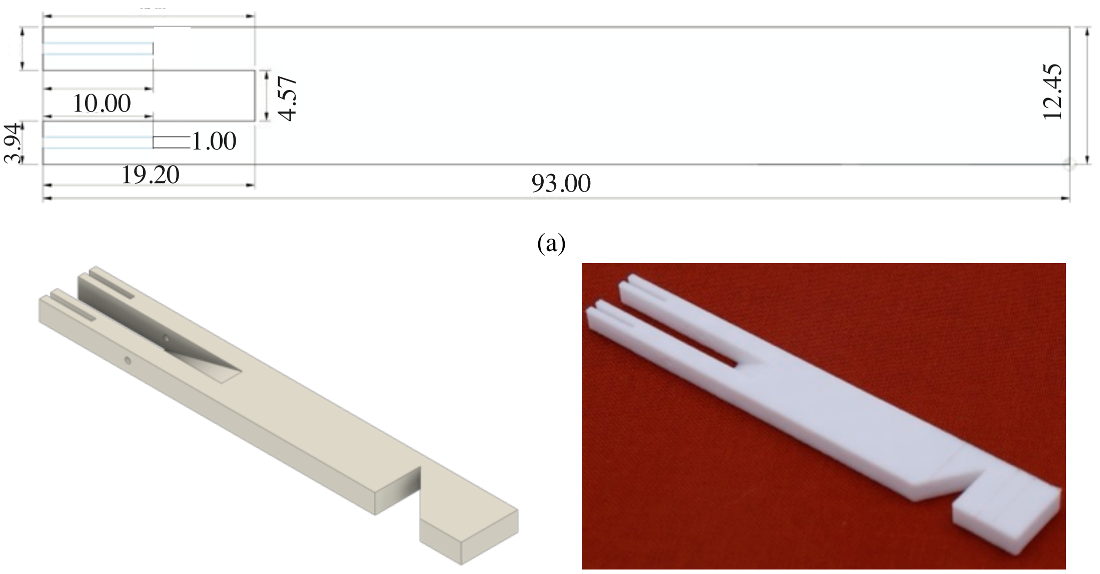
Reflective gradient stickers were originally adopted as a fast, inexpensive, and reproducible way to enable optical sensing across multiple jacks. That choice made prototyping feasible, but it also introduced a maintenance loop that has grown rather than diminished with refinement. Dimensional variability in the jack bodies (typically 4.35 mm across the short edge), humidity-driven expansion and contraction, and the finite lifespan of adhesive layers [7] all contribute to drift and repeated recalibration. What initially functioned as a practical shortcut has therefore become a persistent source of labour. The question is no longer how to improve the sticker, but how to remove it from the sensing chain altogether.

A more sustainable approach treats the reflective surface not as an applied layer but as a property of the jack itself. This shifts attention from the process of correction to the process of fabrication: if the relevant geometry and reflectance are built into the component, there is less to realign, replace, or reattach. At the same time, any change in fabrication method must remain compatible with the open, small-scale production ethos that underpins the interface as a conservation tool. Techniques must therefore rely on accessible materials, common CAM workflows, and file formats that can circulate outside specialist workshops.

One early path was to adapt the existing wooden jacks through laser etching. This had the appeal of retaining the original material while introducing a textured surface that could modulate

Area	**Limitation**	**Strategy**
Fabrication	Gradient stickers require manual application and periodic rework; humidity changes affect the jack fit, adhesive lifespan, and the need for recalibration when reapplying.	Make sensing surface *integral* to the jack via CAD/CAM: (a) geometric ‘shutter’ feature in jack body (CNC/3D print), (b) revisit laser-etched reflectance once electronics improve sensitivity. Retain stickers as a low-risk baseline until jigs/workflow stabilise.
Mechanical Integration	Vertical sensor boards are fragile in tight spaces, difficult to install, and prone to misalignment; limited clearance in multi-register actions.	Split into *sensor module* (fixed pitch, pluggable) + *signal board* (horizontal, robust routing). For multi-register: use per-key mini-modules where needed or interpolate inner-register thresholds from outer sensors to reduce install burden.
Visibility during Calibration	LED indicators may be hidden with horizontal mounting; calibration visibility suffers under exhibit lighting.	Fit small opaque diffusers over on-board LEDs to improve angular visibility during calibration; keep indicators minimal in exhibition mode.
Sensing Electronics	Voltage-divider readout limited by phototransistor parasitic capacitance (low-pass effect); speed/noise trade-offs.	Adopt a transimpedance amplifier (TIA) with feedback capacitor and biasing; place TIAs on the signal/controller board near power rails; trim values where necessary while keeping BOM accessible. Consider QRD1114 as a faster sensor with a retuned TIA.
Firmware	Low jitter is hard with a free-running main loop; portability constraints limit use of high-precision timers.	Use hardware timers on nRF52 (`NRF_TIMERx`) or `mbed::Ticker` to schedule sensing/MIDI; keep ISRs minimal. Alternatively evaluate ESP32-S3 (ESP-IDF) for timed tasks, documenting trade-offs vs. portability. Prioritise predictable jitter over absolute minimum latency.
Exhibition Acoustics	Perceptual disconnect between headphone playback and room acoustics.	Add convolution with venue impulse response at listening position; optionally add lightweight IMU head-tracked binaural for stabilised cues.
Exhibition Haptics	Headphones reduce embodied cues; limited tactile immersion at the keyboard/bench.	Introduce subtle keybed/bench vibration using low-passed signal with conservative levels (per noise policies), following tactile-perception best practice.
Visitor Engagement	Some visitors misread the interface as untouchable due to museum norms; signage alone can be ambiguous.	Repurpose existing RGB LEDs for a slow, warm ‘breathing’ idle glow to signal interactivity (disabled during performance), visually differentiating the interface from historical instruments.

Table 4.1: Haptic keyboard limitations and going-forward strategies



(a)

(b)

(c)

Figure 4.2: (a) CAD drawing of the jack body used for CNC routing and 3D printing. Values in millimetres. (b) CAD jack body with a sloped recess to create a ‘shutter’ for the optical sensor. (c) 3D printed variation of the jack body with inverted slope. The height of the slope is longer than the jacks travel to provide some leeway for misalignment and variation in the sensor heights across the entire keyboard.

reflected light. However, tests such as those shown in Figure 4.1 exposed the limitations of that approach. Low-power passes produce insufficient contrast for the optical sensor, while higher-power settings burn and bleed into the surrounding area, flattening any gradient. Although the method is not ruled out entirely—improvements in sensor-side sensitivity (see Section 4.1.3) could make it viable—the reliability and repeatability required at scale cannot be guaranteed with current hardware.

A more decisive shift came from reframing the problem as one of fabrication rather than surface treatment. Instead of modifying a finished jack to make it senseable, the geometry of sensing can be designed into the part from the outset. Figures 4.2a–4.2c show the progression of experiments that take this approach. In each case, the jack body incorporates a sloped or recessed “shutter” feature that passes through the sensor’s field of view. Reflectance then becomes a function of motion through space rather than the condition of an applied layer.

Two fabrication routes were tested in parallel: CNC cutting in hardwood and additive manufacturing in PLA. CNC work promises material familiarity and structural rigidity, but introduces its own friction points. As shown in Figure 4.3, tear-out occurs along the narrow slots needed for tongues and quills, and post-planing is required to achieve consistent thickness across a set. More significantly, the equipment and skill requirements place it at odds with the accessibility and reproducibility that underpin the interface as a conservation-led system.

PLA-based printing, by contrast, tolerates complex geometry, supports colour and dimensional iteration, and scales quickly. It does not remove labour entirely: tongues and quills

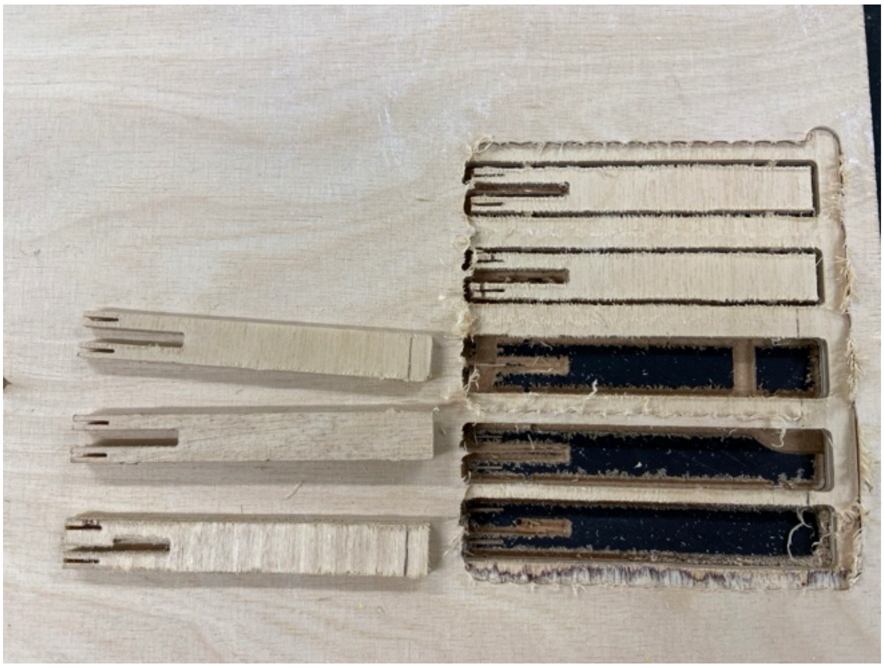


Figure 4.3: Jacks created plywood and a CNC router. Though the jacks could be milled to a precise thickness, the cutting process was prone to tear outs in the material. As such, the CNC approach was subsequently abandoned in favour of experiments in laser cutting.

still require fitting, and small dimensional variances shift attention from sticker placement to jack-height alignment. Yet this is labour that serves a single fabrication stage rather than a recurring cycle of reapplication and recalibration. The material choice also reflects the function of these jacks within the broader conservation framework. They are not introduced into historic instruments, nor intended to replicate their material authenticity. Their purpose is to externalise and preserve action behaviour in a form that can be installed, tested, and iterated without risk to the original mechanism.

Figure 4.2c shows one such prototype (see also Section 2.6). Constraints around quilling remain—whether in PLA, Delrin, or other substitutes [17, 59, 239]—but these affect assembly technique rather than the sensing strategy itself. As the electronics evolve (Section 4.1.3) and a stable workflow for jack fabrication emerges, the need for stickers should recede further, with the printed shutter serving as the primary surface for modulation.

4.1.2 Modular Sensor Architecture

As the sensing system matured, the physical arrangement of the electronics emerged as a constraint in its own right. The original vertical sensor boards were designed to minimise footprint and sit close to the jack body, but their orientation made them mechanically fragile and difficult to install in the confined geometries of harpsichord actions. Narrow clearances between registers leave little room for board-edge components, and misalignment at installation has repeatedly resulted in damage or the need for ad hoc spacing interventions. These issues

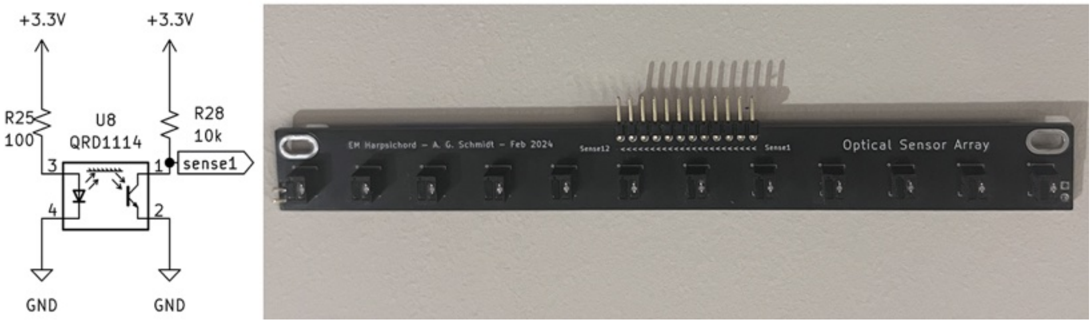


Figure 4.4: Example sensor module, Figure 1.3 of Schmidt et al. [214].

do not reflect a flaw in the sensing principle, but in how the circuitry is embedded within the mechanism.

A more robust approach separates the assembly into two distinct elements: a *sensor module* that maintains fixed pitch and optical alignment, and a *signal board* that handles routing, power conditioning, and analogue front ends. This modular structure localises mechanical risk to the sensor element while allowing the rest of the electronics to be placed where space and airflow are more permissive. Figure 4.4 illustrates one such module from Schmidt et al. [214], where the sensing surface and connector remain compact and serviceable.

Spatial constraints become especially acute in multi-register instruments. Figure 4.5 shows how stacked or closely spaced registers leave insufficient clearance for a long vertical board, regardless of pitch. In these cases, smaller per-key mini-modules provide an alternative that respects the geometry of the mechanism while retaining the same sensing principle. Where even that proves impractical, a hybrid strategy can be applied: two outer sensor rows capture motion directly, and values for the inner registers are interpolated during calibration. This trades installation complexity for computational load, but in a way that isolates mechanical risks rather than multiplying them.

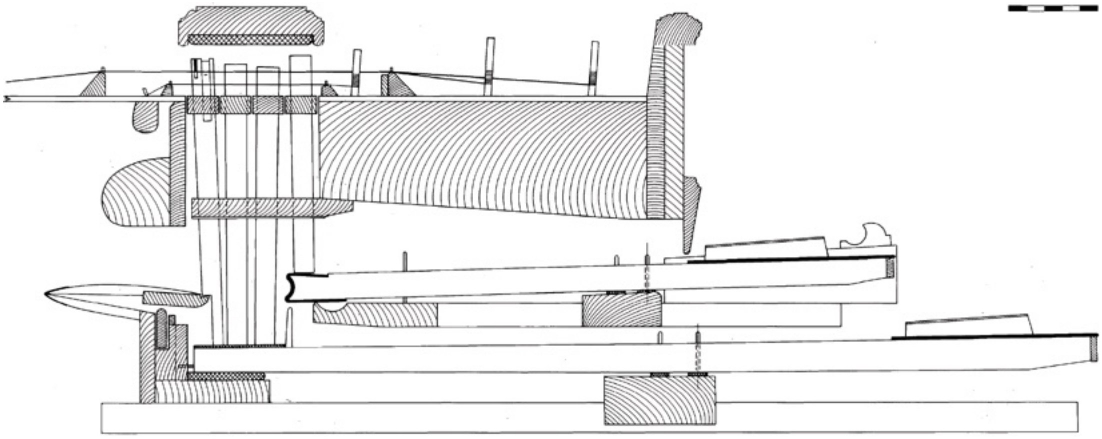


Figure 4.5: Cross section of a multi-register harpsichord mechanism from Koster et al. [141, p. 53]. Image is of a two-manual instrument, with the lower manual in control of three registers.

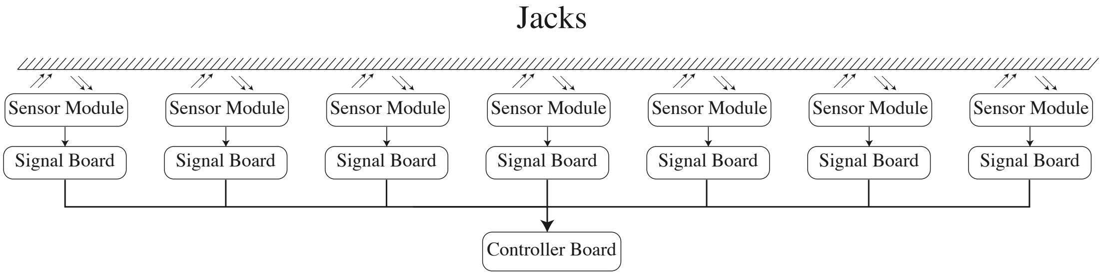


Figure 4.6: Block diagram of the suggested updated system incorporating a ‘sensor module’ and a ‘signal board.’

Figure 4.6 summarises the updated topology. The signal board resides horizontally under the wrestplank, away from key travel and optical apertures. This not only improves mechanical resilience but also opens space for analogue refinement and power management, both of which have been limited by previous board geometries. Because LEDs mounted in this position are less visible during calibration, a small opaque diffuser can be added to preserve visual feedback without affecting exhibition conditions (see Figure 4.7).

4.1.3 Latency and Jitter

Responsiveness in the keyboard interface is already adequate for both performance and exhibition use, yet further refinement depends less on absolute speed than on timing consistency. In this context, *latency* denotes the delay from pluck to MIDI transmission, while *jitter* refers to its variability. Measurements of around 2 ms latency and 1 ms jitter (Section 4.1.3) demonstrate that the system performs well in average conditions, but musical perception and haptic coupling benefit most from predictable timing behaviour rather than marginal speed improvements. Two factors dominate this predictability: the speed of the analogue front end and the determinism of the firmware scheduler. The development pathway therefore proceeds in three stages: first, improve the precision of sensor signal measurement (Section 4.1.3); then constrain the timing sources and interrupt routines in firmware; finally, evaluate microcontroller platforms that can support these constraints while remaining open and reproducible.

Sensor Signal Measurement

The current voltage-divider circuit (Figure 4.8a) is intentionally simple, inexpensive, and resilient to component changes, aligning with the thesis’ open-methodology principle. However, the phototransistor’s parasitic capacitance imposes a low-pass effect [64, 124, p. 283], slightly smoothing rapid transitions and introducing small, variable delays. When precision of onset is crucial—such as when synchronising gesture with sound playback—this behaviour becomes a measurable limit rather than a theoretical one.

A transimpedance amplifier (TIA) addresses this limitation by converting sensor current directly into voltage, bypassing the slow pull-up resistor and improving bandwidth (Figure 4.8b).

Figure 4.7: Demonstration of light diffusion applied to the RGB LEDs. If mounted horizontally and flush to the wrestplank, the source of the light would be difficult to locate, reducing its value as a calibration indicator. Right: example of a bare LED and an LED with a diffuser attached. Left: CAD model of the light diffuser.

Stability is maintained through a feedback capacitor (Figure 4.8c) [123, p. 233], while biasing the collector–emitter junction further increases sensitivity and speed [64, 188]. To prevent the output from approaching supply rails, a differential configuration biases the inverting input (Figure 4.8e), following McPherson [161], with resistor ratios tuned for optimal common-mode rejection [123, p. 227]. The resulting circuit family, summarised in Figure 4.8, trades a small increase in complexity for a substantial gain in temporal precision.

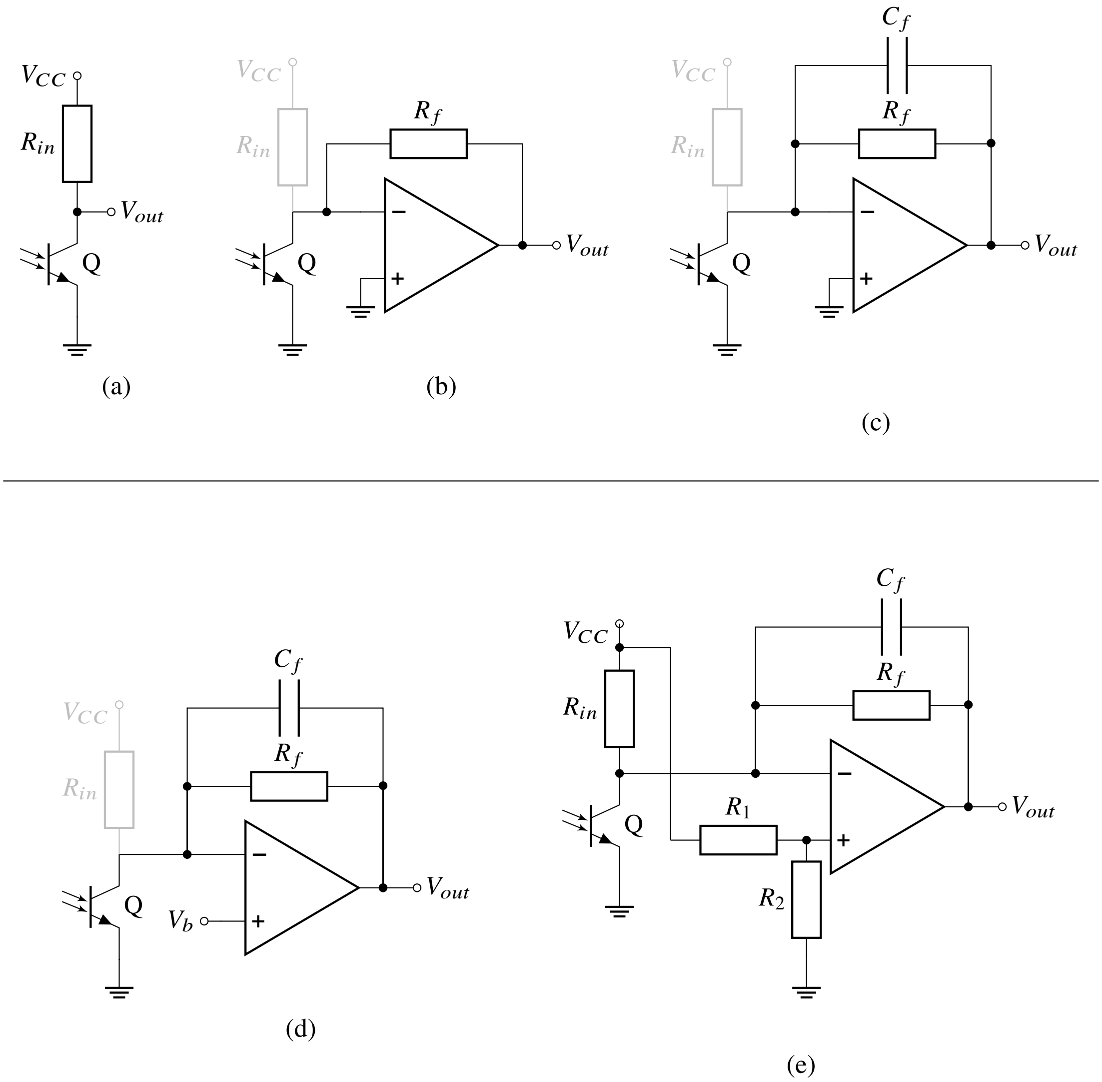
Implementing the TIA stage nudges the design toward surface-mount components and denser layouts. This transition reduces prototyping convenience but remains compatible with low-cost PCB services. To maintain accessibility, TIAs should reside on the shared controller or signal board—close to power rails—rather than on each key module. Variations in resistor tolerance and sensor response may be managed through best-average networks [161] or limited trimming. Where speed is less critical, the simpler voltage-divider circuit remains a valid and maintainable fallback.

Optical Sensor

Performance can be improved further through sensor substitution. The QRD1114, compared with the QRE1113, offers higher on-state current and faster rise times (Table 4.2), although it introduces greater asymmetry and cross-talk. When paired with a tuned TIA (Figure 4.8e), these parameters yield more consistent transitions and may restore the viability of laser-etched patterns discussed in Section 4.1.1. As always, any such substitution must balance enhanced speed with reproducibility and sourcing longevity.

Microcontroller

With the analogue stage stabilised, attention shifts to the temporal precision of firmware. The current implementation [109] prioritises portability across Arduino-supported boards, ensuring long-term reproducibility but limiting access to high-resolution hardware timers. Deterministic scheduling can be introduced by employing a dedicated timer on the Nano 33 BLE (nRF52), using either `NRF_TIMERx` [220, 221] or `mbed::Ticker` for periodic sensing and MIDI dispatch, provided interrupt routines remain minimal [138]. This approach may increase baseline latency slightly but significantly reduces variance, which has greater perceptual



(a) (b) (c)

(d) (e)

Figure 4.8: Circuit evolution for phototransistor (Q) voltage measurement from a simple voltage divider to a biased transimpedance amplifier following McPherson [161]. The pull-up resistor R_{in} has been greyed to indicate its optional removal and to clarify the circuit extension around the phototransistor collector.

(a) Phototransistor with pull-up resistor.
(b) Basic transimpedance amplifier using a phototransistor [123, Fig. 4.22].
(c) Feedback capacitor C_f reduces high-frequency noise and ringing [124, p. 283].
(d) TIA with voltage bias V_b [188], moving the input voltage away from supply rails and avoiding saturation.
(e) Differential TIA from McPherson [161, Fig. 3] that necessitates a balance of resistor ratio for optimal common-mode rejection as per Horowitz et al. [123, p. 227].

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Symbol	Parameter	QRD1114	QRE1113	Unit
$I_{C(ON)}$	On-State Collector Current	1 (min)	0.3 (min)	mA
$V_{CE(SAT)}$	Collector–Emitter Saturation Voltage	0.4 (max)	0.3 (max)	V
I_{CX}	Cross Talk	10 (max)	1 (max)	μA
t_r	Rise Time	10 (typ)	20 (typ)	μs
t_f	Fall Time	50 (typ)	20 (typ)	μs

Table 4.2: Electrical characteristics of the QRD1114 [222] and the QRE1113 [223]. Typical performance denoted with “(typ)”.

impact [129]. An alternative is to migrate to an ESP32-S3 (e.g., Nano ESP32) using ESP-IDF for audio-synchronous tasks. Such a move enhances timing flexibility but introduces new dependencies and the need to port drivers (e.g., I^2C FRAM). Any platform-specific adaptation must therefore be fully documented and archived to preserve the project’s reproducibility and open-access integrity.

4.1.4 Exhibition Enhancements

Exhibition deployment should couple the interface more closely to its acoustic and tactile context, within constraints of headphone use and gallery sound policy. The following enhancements align with perceptual evidence while keeping the chain open and reproducible.

Convolution

A lightweight convolution stage matches the rendered instrument to the venue’s impulse response at the listening point, reducing the disconnect between headphones and space. Open-back headphones preserve some room cues; optional IMU head-tracking via an Arduino Nano 33 BLE [80][1] adds stabilised binauralisation when appropriate.

Vibration

Low-frequency, low-level tactile feedback increases immersion and reported audio quality in seated contexts [169, 170]. For headphone-based exhibits, vibration signals should follow the noise-reduction practices in Merchel et al. [169] (lower cut-offs, octave shifting where needed), acknowledging the different acuity of touch [234]. For keyboard use, subtle keybed or bench actuation provides whole-body cues without compromising museum noise policies.Research over several decades has shown that musicians can extract information about an instrument through haptic feedback. Early studies demonstrated that expert pianists could identify instruments

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[1] an example of which can be found at `https://github.com/ysoldak/HeadTracker`

purely by playing, where they otherwise could not by listening [89, 90].[2] Subsequent work has revealed that vibrotactile feedback in particular shapes perceptions of both loudness [77] and instrument quality [75]. Although the harpsichord lacks the piano's dynamic control, Young et al. [261] found that performers preferred interfaces combining vibrotactile and kinaesthetic feedback on a custom interface, reporting a higher score for both playability and "learnability." It is clear that vibrotactile feedback conveys information that is accessible to the player and represents a natural avenue for extending the augmented interface.

Encouraging Engagement

Visitor behaviour in the oratory suggests that some passers-by do not recognise the interface as 'meant to be touched,' a learned museum norm [39, 125]. Signage helps but may be insufficient or ambiguous [2]. A gentle visual affordance can disambiguate: repurpose the existing RGB LEDs (Figures 2.16 and 2.25) for a slow, warm 'breathing' pattern during idle. This differentiates the interface from adjacent historical instruments without compromising the aesthetic integration; the calibration indicators then serve a secondary role as an engagement cue.

4.1.5 Application

Beyond conservation and exhibition, the interface serves as a research probe and a platform for new performance practices.

As Research Probe

The system enables controlled studies on the role of kinaesthetic and vibrotactile feedback, and on the influence of visual aesthetics, analogous to studies using Yamaha AvantGrand and Disklavier pianos [77, 211]. Because registers can be disengaged mechanically (Figure 4.9) while still emitting MIDI, experiments can independently vary pluck occurrence and timing (e.g., staggering effects), with Mark 2 intended for this role. The modular PCB approach in Section 4.1.2 supports deployment on differing jack pitches and on multi-register instruments, enabling comparison across the augmented interface, an acoustic instrument, and traditional MIDI systems [157]. Such work tests whether faithfully reproducing the mechanical action and kinaesthetic forces suffices for 'tactile realism' before pursuing more elaborate electromechanical emulation [95, 150, 157, 242].

Old Interfaces, New Expression

While the conservation use case motivates the design, the same sensing opens expressive controls unavailable to historical instruments. With continuous displacement streams before

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[2] As well as being blindfolded the "kinaesthetic test" had experts wear headphones playing white noise to block sound from the piano [91].

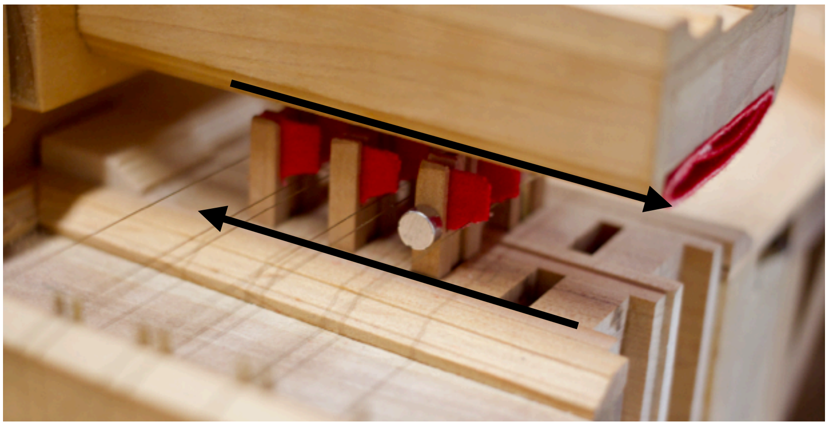

Figure 4.9: Detail of the registers on the three-key rig. Arrows indicate the direction that each register can be moved in order to engage or disengage the jacks.

and after pluck, the firmware can map post-onset gestures to synthesis parameters, analogous to MIDI aftertouch [130, 253] but tailored to the harpsichord action. Additional pressure sensing at the keybed or jack rail [117] augments this space. In this way, the interface both preserves kinaesthetic information inherent in historical performance and enables contemporary expressions rooted in that tactile grammar, addressing long-standing debates about post-onset control in keyboard instruments [152, 257].

4.2 MAGPIE

The preceding section has treated interaction through a physical interface; this section turns to its computational counterpart. Whereas the keyboard interface reconstructs material and tactile behaviour, MAGPIE models the soundboard acoustics through simulation. Together they form complementary approaches to the same conservation and research agenda: to make the behaviour of musical artefacts intelligible, reproducible, and openly available. The following discussion, therefore, situates MAGPIE within that shared framework while outlining how its functionality and interface could evolve into a more flexible research platform.

At present, MAGPIE is already a capable tool for analysing modal behaviour and material properties, supporting a range of educational and research use cases. Yet the software remains a starting point rather than a finished environment. Further development is needed to strengthen both its computational engine and its usability, particularly if it is to serve as an open source alternative to proprietary acoustics packages. In practical terms, improvement paths fall into two categories: *functionality*, which addresses the scope and efficiency of simulation, and *portability*, which addresses how the software can be deployed and maintained across different systems.

The current Python implementation, designed for clarity and accessibility, demonstrates the underlying algorithms but relies on the Jupyter notebook interface, which poses portability and

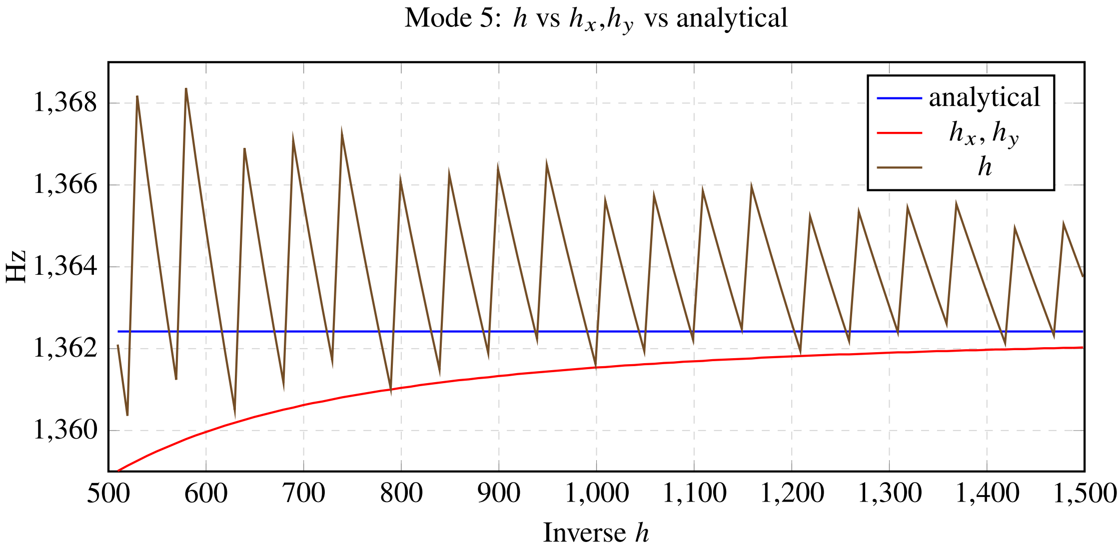

Figure 4.10: Comparison between analytic and modelled fifth mode of a plate for isotropic cases using shared and independent grid spacing in the x and y dimensions. Shared spacing shows saw-tooth convergence, while independent spacing converges smoothly.

maintenance challenges. Translating the computational core into a compiled language such as C / C++ or Rust would provide greater control over optimisation, allow for direct native compilation, and open possibilities for integration into broader toolchains. In both cases, the aim is not to depart from the open ethos established in earlier chapters but to extend it into more efficient, sustainable code.

The primary technical constraint remains the eigensolver stage that underpins modal analysis. In MATLAB, this is handled via the `eigs` function; in Python, through the SciPy sparse linear algebra library (`scipy.sparse.linalg.eigs`). Both are interfaces to the ARPACK library [145]. MATLAB's sparse infrastructure [94] further obscures the solver process and is not supported by the software's code generation tools, meaning external integration still requires the MATLAB runtime. This limits reproducibility to those with licensed access.

Within C++, open source solutions such as the Eigen[3] and Spectra[4] libraries offer viable paths forward. The latter reimplements ARPACK solvers natively in C++, enabling full compilation without proprietary dependencies. Such developments would move MAGPIE closer to the same ideals that underpin the hardware work of earlier chapters: transparent methods, accessible tooling, and a community-maintained code base that supports both research and pedagogy.

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[3] `https://gitlab.com/libeigen/eigen`

[4] `https://spectralib.org`

4.2.1 Functionality

Development in this area concerns the core numerical and modelling functions that underpin the MAGPIE framework. As an open source project, MAGPIE remains intentionally fluid, and its functionality evolves with each release. At the time of writing, the most recent version of *Nemus-Project/magpie-matlab: 0.0.2* includes the capabilities discussed in Chapter 3. Continuing work focuses on refining those routines, extending their applicability to orthotropic materials, and improving efficiency in the underlying numerical methods.

Orthotropic Case

Earlier implementations of MAGPIE used a shared grid spacing (h) for both x and y directions. This constraint simplified the discrete biharmonic operator but limited accuracy to plates whose aspect ratio produced integer grid ratios. In practice, the model performs best when the ratio of plate dimensions L_x/L_y matches the ratio of grid points N_x/N_y. The alternative–fixing h and truncating $\frac{L_x}{h}$ and $\frac{L_y}{h}$ independently–avoids this restriction but requires separate spacings h_x and h_y.

Figure 4.10 illustrates the error introduced by shared grid spacing. Because the effective plate dimensions are slightly altered, the simulation diverges as grid resolution increases unless the grid ratios are perfectly matched. This is manageable only for small N_x and N_y, since total grid size N_{xy} scales exponentially with N_xN_y. For instance, for a plate of $L_x = 100.1\,\text{cm}$ and $L_y = 81.1\,\text{cm}$, matching accuracy would require roughly $N_x = 1001$ and $N_y = 811$ grid points–about 4.2 GB of memory for the sparse biharmonic matrix and eigensolver. By contrast, independent grid spacing achieves equivalent accuracy at roughly 118 MB, a crucial difference when deploying on resource-limited systems such as embedded devices or web-based applications, where computational overhead directly affects feasibility.

Independent spacing has therefore been implemented as part of the new orthotropic plate model, as per the wooden plate case study presented in Section 3.3.2. These extensions have been merged into the MATLAB library of MAGPIE, following the orthotropic and lumped-mass formulation described in Ducceschi [56]. Although the source code is not yet in a distributable format, the underlying principles generalise easily from the isotropic to the orthotropic case, allowing MAGPIE to model distinct elastic moduli E_x and E_y and shear modulus G_{xy}–all required for representing wooden soundboards.

The latest development stage introduces a lumped-mass model, enabling simulation of structural features such as soundboard bracing (Figure 4.11). These braces stiffen specific regions of the plate and alter its modal distribution, providing a realistic representation of historic construction techniques. The same mechanism also accommodates localised attachments, such as accelerometers or exciters used in experimental setups [60]. In this way, MAGPIE bridges physical and virtual modelling: it can incorporate measurement artefacts directly into its simulations, making comparison between computational and empirical data more meaningful.

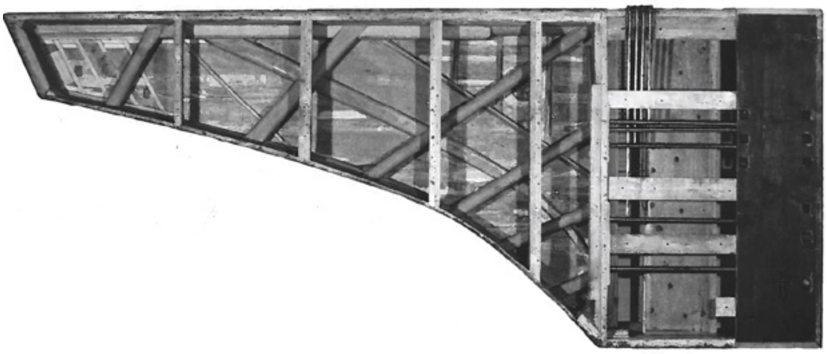

Figure 4.11: Soundboard bracing of a seventeenth-century Couchet harpsichord from Koster et al. [141, p. 49].

Although these functions can be accessed through the code interface, they would be more intuitively explored through a graphical interface that allows direct manipulation of parameters, visualisation of mode shapes, and integration with measurement data. Interface development, therefore, remains a key avenue for expanding the research and educational reach of MAGPIE.

4.2.2 Graphical User Interfaces

Graphical user interfaces (GUIs) provide an essential bridge between MAGPIE's computational framework and its users. They allow multiple parameters to be adjusted rapidly and intuitively, transforming what might otherwise be a command-line experiment into an exploratory, visual process. Beyond convenience, such interfaces embody a key design principle identified by Wang [252]: "design is constraints which give rise to interactions." When a parameter space is too large, exploration becomes abstract and disconnected; when it is shaped by meaningful constraints, new patterns and insights emerge.

In its current form, MAGPIE exposes a programmatic interface that is ideal for long automated runs and algorithmic parameter sweeps. Yet the same openness that enables large-scale computation can also hinder intuitive exploration. Small adjustments to a single variable may yield dramatic changes in modal frequencies or mode shapes, and such nonlinearities are best discovered through direct interaction. A graphical layer therefore serves both as a research tool and as a pedagogical one, helping users understand the sensitivity of acoustic behaviour to material or geometric parameters.

A GUI also enables modes of feedback that are difficult to achieve in code alone. For example, comparing computational results to experimental data can be made interactive: percentage error for each mode could be visualised directly, allowing researchers to refine material constants in real time (Figure 4.12). Similarly, flexible slider limits and editable ranges permit navigation between global and local scales of a parameter space. Coarse exploration identifies regions of interest; finer sub-ranges then allow detailed tuning (Figure 4.12). This multi-scale control transforms simulation from a static task into a responsive dialogue between

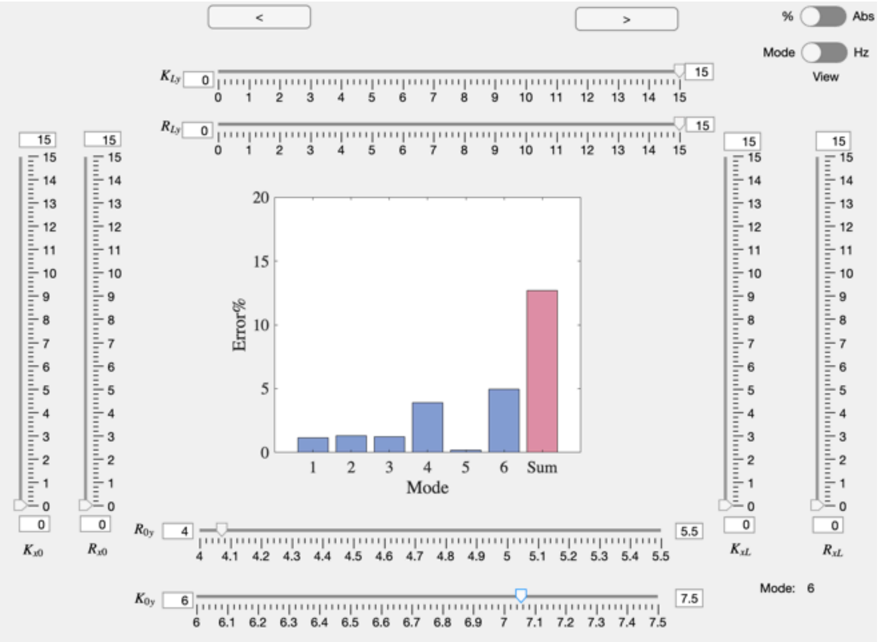

Figure 4.12: Prototype user interface for MAGPIE created using MATLAB's App Designer environment. The UI demonstrates a potential "Error View" for fine-tuning elastic constants to match experimental results. The R_{0y} and K_{0y} parameters illustrate editable slider sub-ranges for fine control. Both parameters operate on logarithmic scales from 0 to 10^{15}.

user and model.

As discussed in Section 3.3.1, an early interface for the Python version of MAGPIE [116] has been developed within the Jupyter Notebook environment [113]. While this approach demonstrates proof of concept, it is limited by the capabilities of `ipywidgets`, which restrict interactive elements and responsiveness. Similarly, MATLAB's App Designer[5] provides a straightforward environment for prototyping but remains constrained to built-in components and ultimately tied to a proprietary runtime.

These platform dependencies raise broader questions about accessibility and sustainability. The `eigs` function, central to MAGPIE's modal analysis, cannot be compiled through MATLAB's code generation system and still requires the MATLAB runtime for deployment. This limits reproducibility to users with licensed access, running counter to the open methodology outlined throughout this thesis. By contrast, translating the computational core into a compiled language such as C++ would enable standalone executables and unlock a wider range of interface frameworks, from lightweight Qt or JUCE front-ends to web-based visualisations.

A dedicated MAGPIE GUI could therefore support both expert and non-expert users: providing immediate visual feedback for research, while also functioning as an educational platform that communicates complex acoustic relationships through interaction. In doing so, it would extend the project's broader aim—to make the physical and computational behaviour

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[5] `https://uk.mathworks.com/products/matlab/app-designer.html`

of musical instruments transparent, reproducible, and accessible to the communities that study and preserve them.

C++ Interface

While the Python and MATLAB implementations of MAGPIE have been instrumental in validating algorithms, long-term accessibility depends on portability and efficient compilation. Graphical interfaces are typically platform-specific–Cocoa for macOS, Win32 for Windows, and GTK or Qt for Linux–each requiring distinct implementation layers. The JUCE framework provides a compelling cross-platform solution, offering unified native wrappers for audio libraries and OpenGL-based rendering. Its abstraction layer enables deployment across all major operating systems without sacrificing performance.

For applications where 3D rendering or real-time visualisation is central, the open source `bgfx` framework[6] offers an alternative. It supports multiple low-level graphics APIs, including Direct3D, Metal, and Vulkan, while maintaining a consistent interface. Choosing either JUCE or `bgfx` would depend on the intended balance between audio integration and visual complexity.

Beyond desktop deployment, translating MAGPIE into a compiled language such as C++ also establishes a foundation for other targets, including web delivery. A compiled core ensures numerical consistency across builds, tighter control over optimisation, and compatibility with open libraries such as Eigen and Spectra. In this way, MAGPIE can retain the transparency and reproducibility central to its open methodology, while extending its reach beyond proprietary environments.

Web Technology

Porting MAGPIE to a compiled language opens the possibility of distributing it directly through the web. Traditionally, scientific software has required installation and system-specific binaries, but developments in browser technology now make high-performance applications viable as client-side experiences. Chief among these is WebAssembly (WASM), an open standard that allows optimised binary code to execute within a browser-based virtual machine. Using the `emscripten` compiler[7] , C / C++ code can be compiled into WASM for near-native execution speeds [203]. When combined with Eigen and Spectra, this approach could enable the entire MAGPIE core to run directly in the browser, without reliance on external servers or proprietary runtimes.[8]

This model contrasts sharply with traditional client–server arrangements, in which simulations execute remotely via ARPACK or MATLAB runtimes. Such architectures impose both financial and technical overheads, introducing latency and limiting scalability. In contrast,

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[6] `https://github.com/bkaradzic/bgfx`

[7] `https://emscripten.org`

[8] A demonstration of Eigen compiled to WebAssembly is available at `https://observablehq.com/@rreusser/eigen`.

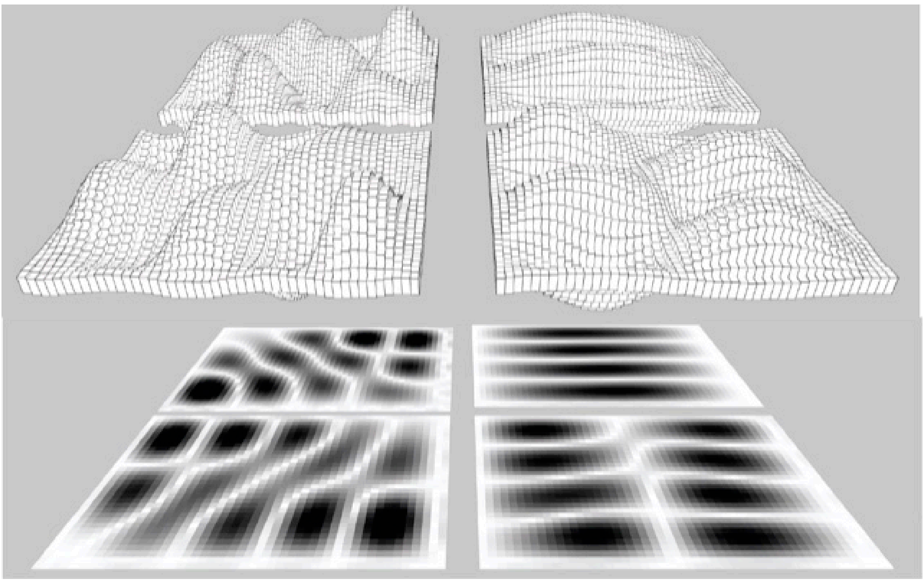

Figure 4.13: Prototype interface using WebGL via `p5.js` to render plate modes. Four eigenmodes and their projected “Chladni pattern” shadows are shown; the interface renders at approximately 11 fps using JavaScript arrays derived from MAGPIE’s C++ output.

WASM permits fully client-side computation, removing network dependency and aligning with MAGPIE’s principle of open accessibility.

That said, browser-based performance depends on local hardware and engine support. The MAGPIE prototype shown in Figure 4.13 demonstrates the feasibility of real-time interaction using WebGL. Here, eigenmodes generated by the C++ backend are visualised with the `p5.js` library[9] , yielding around 11 fps for approximately 12,000 grid points across four modes and their projected “Chladni pattern” shadows. Although this remains a proof of concept, implementing the shading and displacement directly in vertex and fragment shaders would likely raise performance to interactive frame rates.

The use of WASM allows both native and web clients to be compiled from a single shared codebase, preserving numerical fidelity while maximising accessibility. Nevertheless, browser support for WASM and related technologies such as WebGL and WebGPU [35] remains uneven across versions and devices.[10] This variability reinforces the importance of open sourcing and version control: by maintaining transparent repositories, multiple deployment targets can be supported in parallel without fragmenting the project.

Although MATLAB now provides limited functionality for generating JavaScript and WASM binaries [165], sparse-matrix operations and eigensolvers remain excluded from its code-generation tools.[11] Consequently, reproducing MAGPIE’s full capabilities in the browser is only feasible through native compilation and open source toolchains.

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[9] `https://p5js.org/reference/p5/WEBGL/`

[10] See `https://developer.mozilla.org/en-US/docs/WebAssembly#browser_compatibility`.

[11] Supported functions listed at `https://uk.mathworks.com/help/referencelist.html?type=function&capability=codegen&listtype=alpha`.

Looking forward, the addition of orthotropic models and lumped-mass systems described earlier [56] would further align the computational behaviour of MAGPIE with the physical characteristics of quarter-sawn wood used in string-instrument soundboards. Presenting this toolkit in an open, well-documented, and cross-platform form will encourage collaboration and extension as the system matures–ensuring that, like the haptic interface, MAGPIE remains a living resource rather than a static artefact.

4.3 Closing Remarks

This thesis has argued for the importance of an open methodology in digital research and demonstrated two use cases that reveal why such an approach matters. When applied to digital conservation, the principle is simple but far-reaching: the means by which we preserve must themselves be preservable. Two projects have embodied this argument in practice. The first, a haptic keyboard interface, explored how the instructional and experiential value of musical instruments might be conserved through interaction. The second, the MAGPIE analysis toolkit, addressed how the physical behaviour of those instruments can be modelled, shared, and developed through open code. Together they frame opposite ends of the conservation spectrum–the act of preserving and the act of engaging with what is preserved.

There is, as it were, an "as above, so below" symmetry to digital cultural heritage: both the artefacts and the digital tools that represent them require conservation. In musical instrument heritage, this symmetry takes on an additional dimension. Instruments are not only objects but teachers; their value lies in the gestures and feedback loops they enable. Simply creating a digital facsimile of such objects does not conserve the experience of playing or learning from them. What must also be preserved is the *exchange*–the embodied relationship between human and material, sound and motion.

The open methodology developed in this work has sought to model that same balance in its structure. Each component—mechanical, electronic, and digital—is modular and version-controlled, ensuring that it can evolve independently without compromising the whole. Software has been separated into data, processing, and interface layers, each documented in repositories that also serve as historical records of development. Version control is therefore not merely a technical convenience but an epistemic one: a trace of how ideas, as well as code, come into being.

Online Git services enable open source distribution, but their persistence is not guaranteed. Commercial hosting platforms provide decentralised access yet cannot be assumed to provide permanent archiving or resolvable identifiers [29]. The responsibility for preservation should rest with academic institutions, just as they already safeguard research literature. Services such as Zenodo, operated by CERN, offer an interim solution by issuing persistent DOIs for software releases and integrating directly with GitHub, making archiving almost frictionless. The DOI, analogous to an ISBN for digital artefacts, formalises citation and version specificity [227].

Even so, true sustainability demands that universities integrate their existing Git infrastructure with archival repositories—a simple but powerful step toward institutional stewardship of digital research outputs.

The examples of ARPACK [145] and Aurora (Section 1.2.3) illustrate how software longevity is rarely proportional to its adoption. ARPACK, released in 1990, remains active through open maintenance, while Aurora, only a few years younger, risks disappearance without deliberate intervention. Software sustainability should not depend on chance or popularity; it should be built into the research lifecycle as intentionally as peer review or data citation.

An open methodology is not without drawback and does impose a cost. It requires time, discipline, and a willingness to acquire technical skills beyond one's disciplinary training. It is apparent that more investment is needed in digital, data and software training within the arts and humanities research communities [238]. For many humanities researchers, version control, documentation, and archiving still represent additional labour rather than standard practice. Yet, as with any craft, fluency reduces effort over time, and shared infrastructures create communities of support. There are no shortcuts to doing research well, and the cost of openness is ultimately an investment in durability and trust.

The issue extends beyond research software to the digital conservation of cultural heritage itself. Digital preservation is not neutral. As scholars such as Rubio et al. [209], Schwarz et al. [215], and Parry [190] have warned, poorly considered digital methods can distort the very histories they aim to protect. Conservation, whether physical or digital, is always an act of interpretation. Following DeSilvey [50], we should resist the temptation to "pickle" the past—to preserve without reflection—and instead act with awareness of consequence. If a tool is meant to be disposable, then let that ephemerality be intentional; if it is meant to endure, then endurance must be designed into its fabric.

The sentiment of DeSilvey is echoed in the "benign neglect" of Barclay [17, p. 75–76], a promotion of a passive approach to conservation which is far preferable to a "failed restoration" [17, p. 244]. If we are to continue to interact with historical musical instruments—and those instruments are destined to reach a state where they are no longer playable—then the conservation and curatorial choices taken must be deliberate. Whatever the choice made, it should be informed by the wider context of musical acoustics as well as the feasibility of sustainable maintenance and restoration of historical musical instruments.

The two projects in this thesis exemplify those choices. Each balances immediacy and longevity, access and authenticity, openness and rigour. More broadly, they argue that digital conservation should not be a technical afterthought but a cultural responsibility. To conserve experience as well as artefact, we must also conserve the tools, languages, and methods through which that experience is studied. The future of digital heritage, like that of research itself, depends on our willingness to build systems that remember not only their subjects but their own making.

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