Challenges in Basso Continuo Performance-to-Score Alignment

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Abstract. Basso continuo is a Baroque practice of creating harmonic improvisations above a given bass line. In addition to its historical heritage, it is also a living improvisation genre performed by most keyboard players in historically informed performance. However, present-day basso continuo performance has remained understudied empirically, mostly due to lack of data. One key enabler for such research is an automatic system that aligns basso continuo performances to the written bass line in the score. The task of basso continuo alignment, however, presents challenges that are distinct from those of standard performance-to-score alignment tasks, due to the underspecified notation of basso continuo. We analyze the specifics of basso continuo performance-to-score alignment through a dataset of basso continuo performances that we had previously introduced, based on manually annotated performance-to-score alignments of a subset of the pieces. From our analysis, we provide a compilation of challenges specific to basso continuo performance which need to be addressed during the alignment process.

Keywords: Basso Continuo · Historically Informed Performance · Performance-to-Score Alignment · Improvisation.

1 Introduction

Basso continuo is the musical accompaniment typical for the Baroque period. A continuo performance involves a keyboard instrument[3] player performing a notated bass line from the score and improvising upper voices above it, based on the bass line and the performer's knowledge of appropriate harmonic and stylistic patterns. Numerical figures and accidentals that imply expected harmonies are occasionally written above the given bass note [28]. This improvisation, called *continuo realization*, generally consists of three voices above the bass line, but

[3] Continuo for lutes and melodic instruments such as cellos is beyond our scope for now.

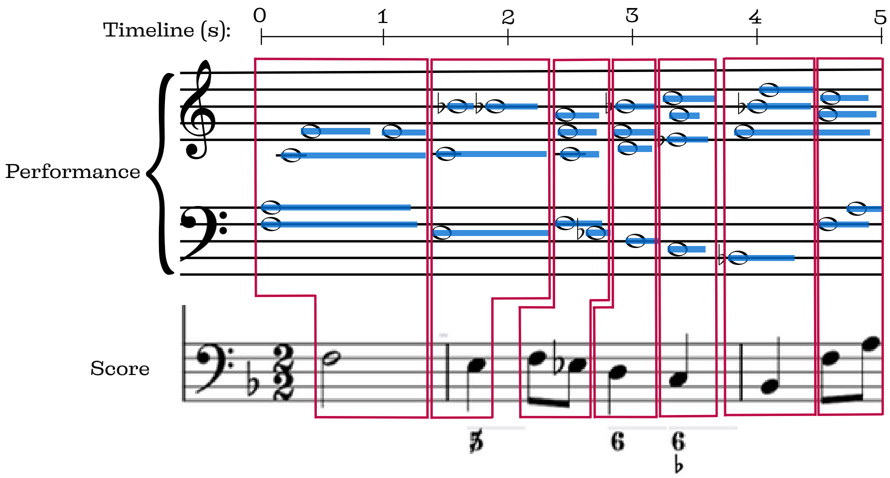

Fig. 1. Illustrating the relationship between a continuo realization (top) and the notated bass line in the score (bottom). Each score note corresponds to the realization notes within its segment (bordered in red). Blue lines indicate duration of realization notes (as in a piano roll).

the artist is free to choose the textures of the realization as long as they adhere to harmonic constraints implied by the bass line, as shown in Figure 1.

Historical performance practices of *basso continuo* have been studied extensively by musicologists and performers themselves [2, 17, 8]. However, continuo is still a living practice today[8], and is a required skill of almost every harpsichordist or organist of the successful Historically Informed Performance (HIP) movement of the 20th and 21st centuries [2]. Despite its importance for the early music community, *basso continuo* practice of today has been largely overlooked by empirical research, mostly due to lack of suitable materials that could be empirically analyzed.

Drawing on a tradition of researching performance, digital musicology and music information retrieval are uniquely positioned to provide appropriate methods to study how performers realize basso continuo today and how it relates to what we know of historical practice. The previously introduced Aligned Continuo Realization Dataset (ACoRD) [29] comprises 175 pilot MIDI recordings of continuo realizations, totaling 6 hours. The goal of the dataset is not to present perfect basso continuo realizations, but to observe what real-world problems may affect the overall quality of the realization (including performance mistakes). The dataset, thus, attempts at capturing as large variety of deviations from a theoretical ideal basso continuo performance as possible. The fact that 72 % of the performance notes in the dataset are not present in the score, but improvised by the performer, requires extending the currently existing performance-to-score alignment paradigm. The paper [29] explores the ability of the state-of-the-art performance-to-score alignment methods to handle basso continuo data and proposes an architecture capable of dealing with the alignment of the whole basso continuo performance. The dataset also contains manual performance-to-score alignment annotations for a subset of the performances. However, this annotation process uncovered a number of phenomena that show how alignment in this setting is more than just a version of the symbolic music alignment task with a lot of insertions on the performance side.

The contribution of this paper is the identification and systematic analysis of these phenomena that make aligning performed continuo realizations to reference scores problematic, but which nevertheless have to be addressed for empirical continuo research to proceed. In our manual annotation process, we observed recurring situations in which the correct alignment is ambiguous or not clearly defined. We provide detailed descriptions and frequency estimates of these alignment challenges, based on our annotations. On the basis of this analysis, we conclude by proposing the term "weakly notated music" for continuo and other structurally similar traditions, as a step towards addressing the challenges these musical traditions pose systematically. Supplementary materials can be found online [4].

2 Related Work

Computational research on basso continuo has largely centered on generating realizations from musical scores, primarily through algorithmic methods [16, 15], decision trees [26], and machine learning techniques [6]. This line of research is closely related to the broader domain of AI-driven music generation, where approaches based on convolutional neural networks [5] and transformers [25] have achieved state-of-the-art results. However, existing systems do not address the specific challenges and intricacies of modeling human-performed basso continuo improvisations by aligning them to the continuo score.

While the harmonic language of basso continuo is clearly defined within the Western classical tradition [2], existing datasets—such as the Bach chorales [3] or GiantMIDI [7]—represent aspects of Baroque music and, by extension, certain ideals of continuo realization. However, these datasets fall far short of representing the full diversity and inherent variability found in live continuo practice.

Performance-to-score alignment involves synchronizing a musical performance with its corresponding score [9, 20]. In the symbolic domain, it refers to matching notes in a symbolic performance (e.g., MIDI) to those in a symbolic score (e.g., MusicXML or MEI). Probabilistic approaches to alignment, such as hidden Markov models (HMMs), treat score positions as latent variables and model performance notes as observations [12, 23, 1]. Dynamic programming techniques, particularly dynamic time warping (DTW), align sequences by minimizing cumulative cost and, though originally used for audio alignment [9, 27, 10], have been effectively adapted for symbolic alignment [20, 19]. Symbolic algorithms tend to have high accuracy typically when the performance aligns closely with

[4] https://basso-continuo-alignment-challenges.github.io/supplementarymaterial.github.io/

a fully notated score, as is common in Western classical piano music [20, 12]. Alignment of performances that are not fully notated has not been addressed much. The PiJAMA dataset of jazz piano [4] represents a music tradition that is improvised and not fully notated, but it does not contain alignment to any scores.

3 Challenges in Continuo Alignment

The paper on basso continuo alignment [29] proposes a two-step basso continuo realization alignment pipeline. Every basso continuo realization consists of bass notes that are captured in the score, and realization notes that are improvised by the performer. In the first step (called bass alignment), the performance bass notes are aligned with the score, whereas all the other performance notes are then aligned in the second step, called realization alignment (Figure 1). In order to evaluate this two-step architecture, manually annotated ground-truth data reflecting both steps (bass alignment annotation on 35 performances, and realization alignment annotation on 15 performances in the dataset) were created, and are provided in the ACoRD dataset. Four state-of-the-art symbolic performance-to-score alignment methods were used for the first step: *DualDTWNoteMatcher* [19], *TheGlueNoteMatcher* [21], *Pitch-IOI HMM* [18] and *Merged-output HMM* [13]. Two performance preprocessing methods were also introduced, their task being to trim down the performance notes to those that are likely to be the bass notes; thus helping the alignment algorithms thereafter. The first step therefore becomes a case of "regular performance-to-score alignment with many insertions" and is handled to a high degree of success by existing symbolic performance-to-score alignment algorithms (F1-score up to 97.9 % [29]). The second step is then reduced to many small-scale alignments of segments of performance notes delimited by the aligned bass notes. This is done using a position-based algorithm, in which every performance note that was not yet aligned (i.e. the realization notes) is grouped with a performance bass note that has already been aligned to a score note in the first step. This grouping is done based on the temporal co-occurrence of the realization note and the performance bass note. This realization note is then aligned with the score note to which the bass note was aligned in the first step. This algorithm's baseline performance shows an F-score of 94.4 %, indicating that a sizeable number of realization notes were misaligned [29]. These results prompted a closer look at the misaligned notes. The analysis of these misalignments with respect to the manual alignment annotations unearthed a variety of challenging situations in identifying the appropriate continuo performance-to-score alignment in both of these steps. Statistics of all such ambiguous situations are provided in Table 1, and we discuss these challenges in this section.

3.1 Performance Bass Notes Alignment

We first perform one-to-one alignment of the notated bass line to the performance. This follows from the premise that the notes in the continuo score should

Table 1. Estimated absolute counts of performance notes involved in different types of ambiguous situations and their frequency of occurrence (as percentages) relative to the total number of score notes in the case of performance bass note alignment (526 notes) and performance notes in the case of performance realization note alignment (1836 notes) in five representative examples from the dataset.

Ambiguity type	**Number of notes**	**% of occurrence**
Performance Bass Notes Alignment		
Pitch Substitutions	6 / 526	1.1%
Repetitions	21 / 526	4.0%
Ornaments	11 / 526	2.1%
Skips	29 / 526	5.5%
Performance Realization Notes Alignment		
Bass note to realization note	211 / 1836	11.5%
Sustained Realization Notes	571 / 1836	31.1%

as a rule be preserved in performance [2], implying that each score note should correspond to a bass note in the performance. Any additional notes played in the performance are interpreted as realizations of the underlying bass note. The following subsections discuss challenging cases encountered during the bass line alignment annotation process. Although these cases are seemingly infrequent (see Table 1) during the bass alignment step, the subsequent realization notes alignment step is built upon the correct alignment of the performance bass notes in this step, and therefore requires careful consideration.

Pitch Substitutions Pitch substitutions/errors are a challenge common in performance-to-score alignment with fully notated scores as well, but continuo alignment presents additional complexity: the correct alignment of realization notes in the second step of the alignment process depends on correct identification and alignment of performance bass notes in the first step. Figure 2a[5] illustrates a situation where it is unclear whether a note with a pitch error but correct timing (C#4, circled in green) in the performance should be aligned with its corresponding score note (C4, circled in blue), or if the score note should be marked as a deletion. Furthermore, the performer seemingly corrected the pitch error by playing the correct note on a subsequent beat (C4, circled in red), which was detected by the automatic alignment system.

Note Repetitions Situations involving repeated consecutive bass notes in the performance that correspond to a single score note are challenging for one-to-one alignment because determining the most appropriate match can be ambiguous. Such cases seem to occur approximately once in every 26 score notes.

Figure 2b shows a case where the same bass note F#3 was played twice in the performance, both times corresponding to one score note: F#3. Although the automatic alignment process aligns the score note (blue) with the second performance note (red), the first F#3 performance note (green) may have been

[5] Screenshots captured from the web alignment tool, Parangonada [20].

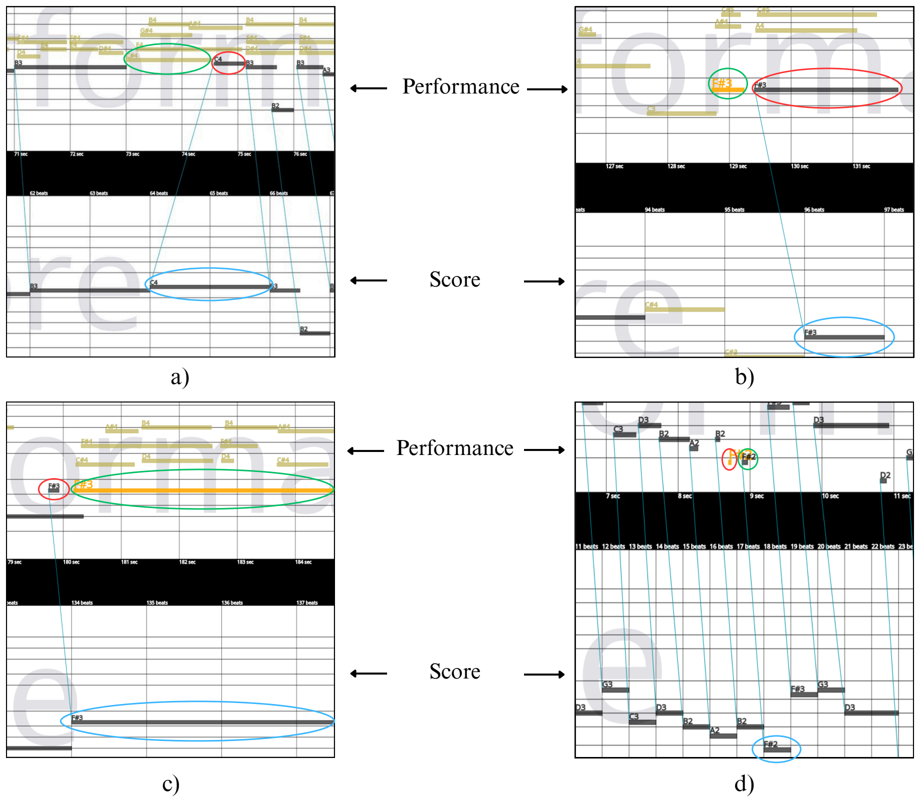

Fig. 2. The four case studies of challenges in performance bass note alignment as detailed in section 3.1. The thin blue lines represent the alignment computed by an existing automatic alignment system.The score notes that are difficult to align with the performance are circled in blue, while the potential corresponding notes in the performance are highlighted in red and green.

the correct choice, as it is the first occurrence of the bass note, even though the second occurrence of the bass note has a longer duration. On the other hand, Figure 2c shows a case where it would be more apt to ignore the first occurrence of the bass note F#3 (red) and align the second occurrence of the same note (green) with the score note (blue), owing to the long duration of the second occurrence of the performance note, as well as the fact that all the improvised realization notes above fall within the duration of the second performance bass note. Finally, Figure 2d shows a case where both occurrences of the bass note in the performance are extremely short. It seems appropriate here that the second occurrence of the performance bass note F#2 (green) is aligned to the score note (blue) instead of the first occurrence (red) for two reasons: it is slightly longer duration, and the second occurrence falls better in tempo, as indicated by the

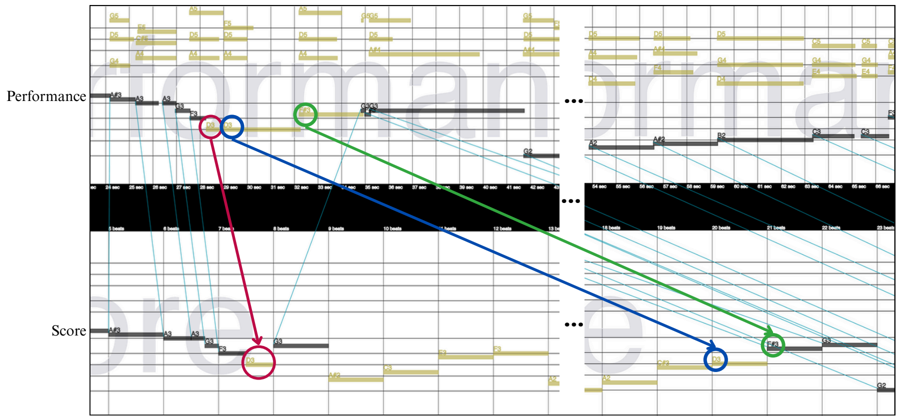

Fig. 3. Illustration of an example where performer error resulting in a skipped line in performance creates challenges in the first step of alignment. The image consists of screenshots of two sections in the piece's timeline that are separated by some time in between (this gap is marked by '...' in the image). The notes circled in red mark the end of a line of music in the piece, following which the subsequent line of music was skipped in the performance, resulting in the subsequent score notes remaining unaligned or incorrectly aligned. The blue and green lines with their circled notes represent the ideal alignment, which was not achieved by the current state-of-the-art alignment algorithm.

relative parallelism of the alignment connectors of the preceding and following notes.

Ornaments One is also expected to face challenges when the bass line is ornamented by the performer, for example with a trill that is not written in the basso continuo score. The ambiguity in ornament alignment lies in several aspects. It is necessary to determine whether a single bass note within a trill is to be aligned to the score note, or if the entire trill needs to be considered as a single entity that is aligned to the score note. Moreover, ornamentation is not always notated in a basso continuo score, which can make it challenging to distinguish an ornament from a mistake or improvisation in the bass line.[6] Ornament alignment is an open problem even in strongly notated scores [11, 21].

Note Skips Some performers mistakenly skip notes or even entire passages during a performance. While current state-of-the-art alignment algorithms are known to handle skips in the performance [22, 11, 14], the presence of the improvised realization notes complicate the automatic alignment process, resulting in incorrect alignments between the performance and score. An example related to

[6] Duration is not a sufficient indicator: slow ornaments like *appoggiatura* are common in baroque music.

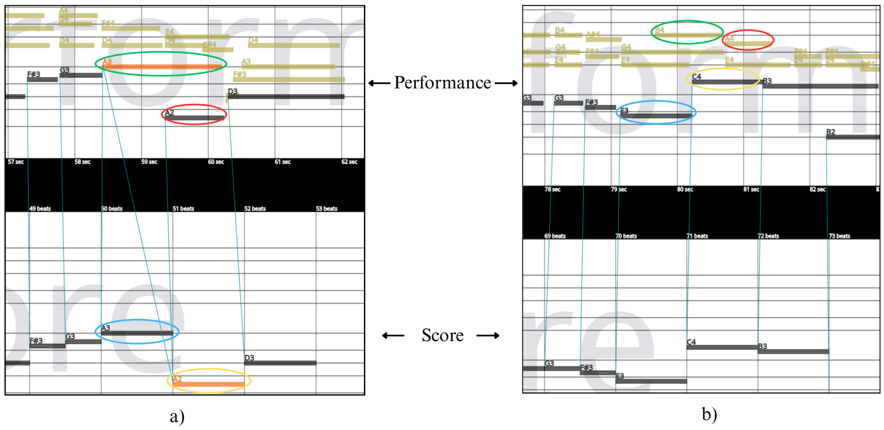

Fig. 4. Examples that illustrate two different challenges a) and b) faced in the manual alignment annotation of the realization notes to the score. See Section 3.2 for details.

a performance with two long skipped passages is shown in Figure 3. The performance and score notes D3 (highlighted with red circles) indicate the conclusion of a musical line within the piece. However, during the performance, the line of music that was supposed to follow this point was inadvertently skipped. As a result, the corresponding notes in the score that should have aligned with the performance became misaligned or improperly synchronized. In contrast, the blue (corresponding to the note D3) and green (corresponding to the note F$\#$3) lines, along with their circled notes, illustrate the correct or intended alignment between the performance and the score—an alignment that the current state-of-the-art algorithm failed to achieve.

3.2 Performance Realization Notes Alignment

A many-to-many structure was adopted for annotating the alignment between score notes and performance realization notes. This approach allows multiple realization notes to be linked to a single score note. Often, a single realization note must be aligned with multiple score notes as well when its duration extends beyond the duration of its first associated bass note and across subsequent performance bass notes. This is especially relevant to tied notes on the organ, prepared dissonances, etc. Table 1 shows that a majority of continuo alignment challenges are of this type.

Bass notes as realizations. Situations where a performance bass note itself stretches in duration partially or completely over the length of the next performance bass note(s), occur more than once in every ten notes (see Table 1. In such cases the overlap between these notes helps determine whether the first note becomes reinterpreted as a realization note of the following bass note(s). As illustrated in Figure 4a, in such cases, the performance bass note (green) is aligned with its own score note (blue), and it is also aligned as a realization note with the next score note (yellow); i.e., the score note corresponding to the next performance bass note (red).

Sustained realization notes. A challenging case that occurs almost once every third note during the process of realization note alignment is when a realization note stretches in duration partially over the subsequent performance bass note. On the one hand, since the realization note continues to be sounded over the next bass note, one can argue that it must be aligned with the following bass note's corresponding score note. However, sometimes the performer's articulation can hold a realization note to linger longer than intended (*overlegato* articulation on the harpsichord [17]), and therefore cannot be aligned with the following score note. Again, duration can help disambiguate: if a realization note stretches beyond a certain proportion of the duration of the subsequent bass note, it must be aligned to the corresponding score note as well.

A specific case can be observed in Figure 4b. The performance realization note B4 (green) is clearly played towards the end of the performance bass note E3 (blue). Given that the piece is in G Major/E Minor, B4 pairs well with E3, since they form a perfect fifth interval; all the more so due to the existence of the G4 below it. It can therefore be aligned with the score note corresponding to the E3 performance bass note. The B4 then, however, partially stretches in duration over the next bass note, C4 (yellow). In this case, even though the note B4 forms a major 7th interval with the performance bass note C4, it is still annotated as being aligned with the C4 as well because of the fact that the B4 stops sounding at the same time as the G4 below it, which is a perfect 5th to the C4 bass note. Immediately after the B4 note ends, the realization note A4 (red) is observed to begin halfway through the duration of the same C4 bass note. The E4 begins along with the A4 as well, and together with the C4 bass note, they form the A minor triad. Therefore, both the E4 and A4 are aligned with the C4 bass note. It is then observed that both these realization notes continue to sound over the next performance bass note, B3. Similar to how the B4 formed a major 7th interval to the C4 bass note earlier, the A4 forms a minor 7th interval with the B3 bass note. In this case, however, the A4 ends well before the E4 does, covering only a fraction of the duration of the B3 performance bass note. For this reason, the A4 was chosen to not be aligned to the B3 bass note.

4 Conclusions

Manual alignment annotations in ACoRD have revealed ways in which aligning basso continuo realizations to their scores differs from the traditional symbolic performance-to-score alignment task. These challenges arise because for continuo realizations, the expectation that the written score and performance contain roughly the same tonal content is *not* met: while one should play what is written, one also should play much that is *not* written, as opposed to e.g., a score of a Chopin Etude, which clearly indicates also everything that one should *not* play (anything besides the notated tones would be a mistake). For Chopin, the expected relationship between score and performance at the symbolic level is an *equivalence*. For continuo, this relationship weakens to an *implication*: on top of the score, many unwritten notes must be played.

For such traditions, we propose the term **weakly notated** music. Many traditions have this weaker relationship between a “work” and its tonal content, leaving great freedom to performers to determine what is performed: jazz lead sheets, chord sheets for popular modern music, or church organists’ practice of harmonizing hymn melodies. These are traditions that generally emphasize stylistic knowledge, improvisation, performance practice, and collaboration. Notably, despite the freedom performers are afforded, they are still constrained: each tradition has its rules of style, and other musical constraints—such as a melody—apply. Indicating different kinds of mistakes would be an important contribution computational methods could make, also in support of its performers.

The “extra content” in weakly notated music is at the same time still closely related to the written score, or rather: we want to study this content in relation to the score, so it must be aligned. But the distance function for these notes might not be the same as for notes where the score-performance relationship is an equivalence, such as matching properties of pitch, onset, or duration. Hence, weakly notated music presents a structurally separate alignment challenge.

For the case of *basso continuo*, we have tried to reduce this problem to familiar “strongly notated” alignment by splitting it across two steps: bass notes alignment, and realization notes alignment. However, a majority of the challenges we have observed stem from the second step as well as the interaction between these two steps; notably, the high dependence of the second step on the accuracy of the first step. Future work can aim to address these challenges faced in this two-step process, or alternatively reinterpret the entire continuo alignment task as a single-step approach of a one-to-many (one score note to many performance notes) alignment.

We focused on continuo, but all these semi-improvised keyboard practices are a fascinating and under-researched area of music, uniquely suited to study in the digital domain. Most musicking [24] likely happens today in weakly notated traditions, and with robust tools for alignment they present a great opportunity to broaden the scope of computational musicology. We hope this work helps bring them more into the spotlight.

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