Artificial Intelligence in the Concertgebouw

Andreas Arzt[(1,2)], **Harald Frostel**[(1)], **Thassilo Gadermaier**[(2)]
Martin Gasser[(2)], **Maarten Grachten**[(2)], **Gerhard Widmer**[(1,2)]
[(1)]Johannes Kepler University, Linz, Austria
[(2)]Austrian Research Institute for Artificial Intelligence, Vienna, Austria
andreas.arzt@jku.at

Abstract

In this paper we present a real-world application (the first of its kind) of machine listening in the context of a live concert in a world-famous concert hall – the Concertgebouw in Amsterdam. A real-time music tracking algorithm listens to the Royal Concertgebouw Orchestra performing Richard Strauss' *Alpensinfonie* and follows the progress in the sheet music, i.e., continuously tracks the most likely position of the live music in the printed score. This information, in turn, is used to enrich the concert experience for members of the audience by streaming synchronised visual content (the sheet music, explanatory text and videos) onto tablet computers in the concert hall. The main focus of this paper is on the challenges involved in tracking live orchestral music, i.e., how to deal with heavily polyphonic music, how to prepare the data needed, and how to achieve the necessary robustness and precision.

1 Introduction

Real-time music listening is a big challenge for machine perception and AI. While 'listening' is a broad concept, involving various aspects of structure comprehension and abstraction (e.g., perceiving and tracking beat and tempo, identifying the melody, recognising voices, instruments, style, genre, etc.) – all of this is the domain of the Music Information Retrieval (MIR) research field –, even the more specialised task of listening to a live performance and synchronously reading along in the printed music score (e.g., for the purpose of page turning) is a big challenge [Arzt *et al.*, 2008]. This task is generally called *score following* or *music tracking*. What it involves is listening to a live incoming audio stream, extracting higher-level features from the raw audio that somehow capture aspects of the 'sound' of the current moment, and tracking the most likely position in the score that the sound seems to correspond to – regardless of the specific tempo chosen by the musicians on stage, of continuous or abrupt tempo changes due to expressive timing, and robust to varying sound quality and instrument sounds.

Real-time music tracking, which started in the 1980s (see [Dannenberg, 1984; Vercoe, 1984]), has attracted quite some research in recent years [Raphael, 2010; Cont, 2009; Arzt *et al.*, 2008; Korzeniowski *et al.*, 2013]. While there still are many open research questions (such as on-line learning of predictive tempo models during a performance), real-time score following is already beginning to be used in real-world applications. Examples include Antescofo[1], which is actively used by professional musicians to synchronise a performance (mostly solo instruments or small ensembles) with computer realised elements, and Tonara[2], a music tracking application focusing on the amateur pianist and running on the iPad.

In this paper, we lift the problem to a new level of complexity: we wish to track an entire orchestra playing complex polyphonic music. This presents specific challenges to a music tracking algorithm. First and foremost, it has to deal with heavily polyphonic music, with many different instruments – and sometimes very unusual ones. Furthermore, a long piece like a symphony challenges a music tracking algorithm with many different situations (e.g. very soft and quiet sections, immensely powerful, dynamic and fast parts, solo sections for different instruments). The music tracking algorithm has to cope with all these situations and has to be able to track all the instruments, be it a trumpet, a violin or an organ. All of this is done live, in contrast to studies like e.g. [Miron *et al.*, 2014], where orchestral recordings are aligned to a score off-line in a non-causal way. Tracking can only work if a good representation of the score of the underlying piece is provided. While this process is relatively straightforward for e.g. a solo piano piece, it is far from trivial for a complicated classical symphony.

In addition to describing how we solved these challenges, we report on the first public live demonstration of our system in a regular concert in a famous concert hall, and provide a quantitative evaluation of the precision and robustness of our algorithm in solving this task.

The paper is organised as follows. Section 2 explains the general idea, context, and setup of the experiment. In Section 3 the requirements on the internal score representation and the audio features are discussed. Sections 4 and 5 give a description of the tracking algorithm. In Section 6 we present a qualitative analysis of the tracking during the live concert, and Section 7 gives a detailed quantitative evaluation.

[1] `repmus.ircam.fr/antescofo`
[2] `tonara.com`

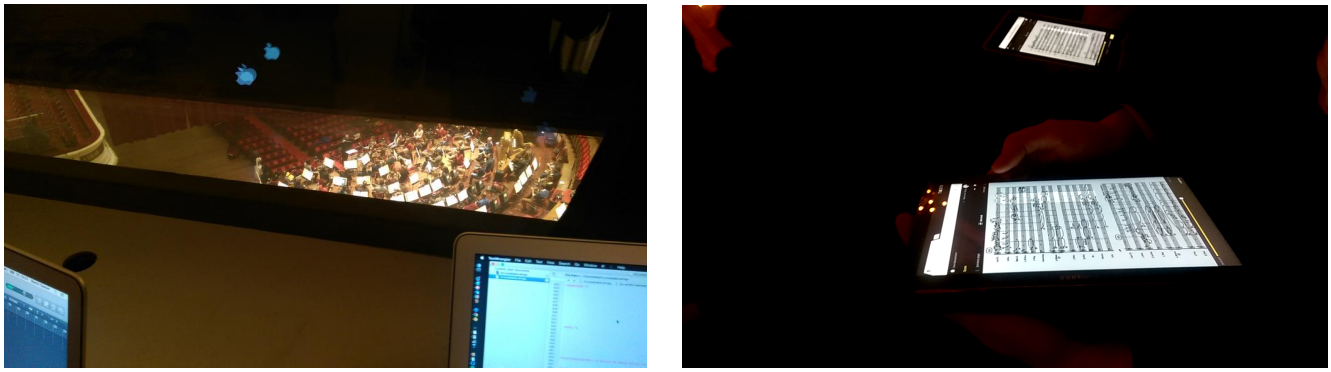

Figure 1: Left: View from the control room onto the stage (during orchestra rehearsal); right: synchronised score display in the audience during the concert.

2 The Challenge: Tracking the Concertgebouw Orchestra

The multi-national European research project PHENICX[3] provided us with the unique opportunity (and challenge) to demonstrate our score following technology in the context of a big, real-life symphonic concert. The general goal of the project is to develop technologies that enrich the experience of classical music concerts. In the experiment to be described, this was done by using the live performance tracker to control, in real time and via WiFi, the transmission and display of additional visual and textual information, synchronised to the live performance on stage. The user interface and the visualisations were provided by our project partner Videodock[4].

The event took place on February 7th, 2015, in the Concertgebouw in Amsterdam. The Royal Concertgebouw Orchestra, conducted by Semyon Bychkov, performed the *Alpensinfonie* (Alpine Symphony) by Richard Strauss. This concert was part of a series called 'Essentials', during which technology developed within the project can be tested in a real-life concert environment. All the tests during this concert series have to be as non-invasive as possible. For the demonstration during the concert in question, a test audience of about 30 people was provided with tablet computers and placed in the rear part of the concert hall.

The setup was as follows. Two microphones were placed a few meters above the conductor, in an AB-setup, picking up the music, but also a lot of noise, e.g. coughing in the audience and noise made by orchestra members, and a fair amount of reverberation from the hall. In a control room behind the scenes a regular consumer laptop was receiving the audio signal and feeding it to a music tracking algorithm, computing at any point during the performance the current position in the score. This information was sent to the tablets of the test audience and triggered pre-prepared visualisations at the appropriate times. The audience could choose between 3 different kinds of synchronised visualisations: the sheet music (with synchronised highlighting of the current bar, and automatic page turning), textual information and explanations, and an artistic video, visualising the story of the symphony (which is 'Program Music' *par excellence*). Two pictures with impressions from the live setup are shown in Figure 1.

This specific application of music tracking poses some unique challenges. Most importantly, so far the focus of music tracking has mostly been on solo or small ensemble music, like solo violin or flute, solo piano or string quartets, but nothing comparable to a full sized orchestra (according to Strauss' notes the optimal size of the orchestra for the Alpensinfonie is 129 or more musicians!). This level of polyphony and of variety of instruments has to be considered when choosing the internal representation of the score and the features used during the on-line alignment process.

Furthermore, this piece challenges the music tracking algorithm with a vast range of musical situations: very quiet and slow parts without a clear melodic line (only a sound texture), very sparse parts with long pauses, energetic, loud and fast parts and even solo sections. Ideally, the tracker has to do equally well in all these situations, or at least well enough to not get lost completely. Thus, the main focus of our music tracking algorithm is placed on robustness. It actually does not matter much if an event is detected with a short delay, but it is very important that the algorithm does not get lost during this long piece (a typical performance takes about 50 minutes and contains no breaks).

3 The Score: Data Representation

To make the live tracking possible some internal representation of the musical score is needed. In most cases in music tracking the score is provided in symbolic form (e.g. MIDI or MusicXML). For the tracking, some kind of features are computed from the score representation that can be compared to the audio signal of the live performance.

Furthermore, for our task the content to be visualised has to be linked to the symbolic score, ideally via bar and beat numbers. For each video and every text snippet timing information is needed. Additionally, for the score visualisation also the area to be highlighted in the sheet music for each point in time needs to be known. We decided to provide this information at the level of musical bars.

The most natural approach (and most common in music

[3] http://phenicx.upf.edu
[4] http://videodock.com

Conductor	Orchestra	Year	Length	Data Type
Jansons	Royal Concertgebouw Orchestra	2007	52:51	Manual Annotations
Haitink	London Symphony Orchestra	2008	50:20	Off-line Alignment
Previn	Philadelphia Orchestra	1980	49:09	Off-line Alignment
Karajan	Berlin Philharmonic Orchestra	1980	51:05	Off-line Alignment
Luisi	Staatskapelle Dresden	2007	50:42	Off-line Alignment
Haitink	Royal Concertgebouw Orchestra	1985	49:29	Off-line Alignment
Järvi	Royal Scottish National Orchestra	1987	49:33	Off-line Alignment

Table 1: Performances annotated to be used as alignment basis ('score representations')

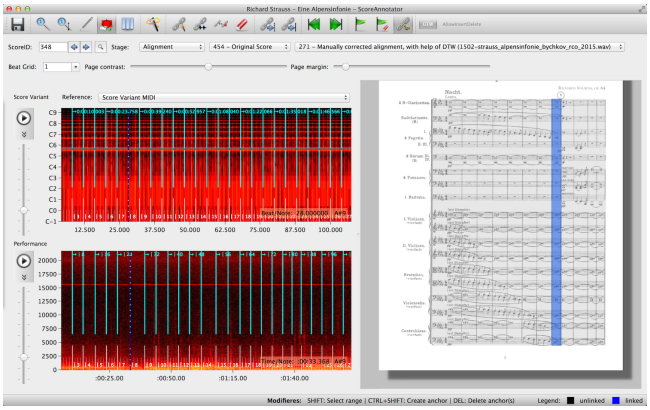

Figure 2: The annotation tool, used for identifying the timings of downbeats in the performance and for linking them to the corresponding areas in the sheet music.

tracking) is to start from the symbolic score representation and compute features for the tracking process. But in doing so we ran into both practical and theoretical problems. First of all, it is far from easy to get good quality symbolical representations for orchestral pieces. In the case of the Alpensinfonie we found some MIDI files on the internet, but in the end all of them turned out to be unusable because of grave mistakes and missing parts. We also contacted a music publishing house, but they could not provide us with a symbolic version for this particular piece. In theory one could try to scan a printed score – those are of course readily available – and try to convert it to a symbolic representation. Unfortunately, optical music recognition (OMR) algorithms are still not good enough to cope with the complexity of an orchestral score fully automatically, and the manual correction of their output would take an immense amount of time.

Even given a complete and correct symbolic representation, it would be difficult to align audio to this representation. Most music tracking algorithms convert the symbolic note sequence to some kind of representation that is similar to the audio signal – either by using a MIDI synthesiser or by learning tone models and applying them and estimating what the spectrum of a real performance will look like for every point in the score. This approach works well for specific instruments like the piano, but far less so for orchestral music. In addition, the Alpensinfonie is a very special case and includes instruments like cowbells, a wind machine and a thunder machine.

Thus, we decided to try a different approach. Instead of a symbolic score and synthesised features, a recording of the same piece is used as the basis for the music tracking. This version – we selected a performance by the Royal Concertgebouw Orchestra from 2007, conducted by Mariss Jansons – is manually annotated beforehand, so that the timing for each downbeat (the first beat in a bar, and thus the start time of a new bar) is known and the performance can be used as a direct replacement of the score (all the visual information shown to the audience is timed at the bar level). The features for the score can be computed in the same way as for the live performance, as both are the same kind of data. Figure 2 shows a screenshot of the tool used to prepare the annotations.

We strongly believe that from a practical point of view this is the best approach for tracking music of this complexity (regarding number of instruments / polyphony). The resulting score features are of very high quality, while the amount of time spent on annotating the performance (about 12 hours) was acceptable – especially compared to the amount of time it would have taken to either repair one of the MIDI files or produce a digital version of the score from scratch.

The absence of symbolic scores in the system also means that theoretically it can be used for *any* piece of music for which a recording exists. This immensely extends the repertoire for which music tracking can be used.

Another important point is that the amount of annotations actually depends on the specific usage scenario. We decided to show the sheet music synchronised at the bar level, and thus needed to annotate the timing of every downbeat. As the piece consists of 1154 bars, we had to find each of these points in the audio file. Then we linked all the remaining information (the text and the videos) to these time points.

Had we decided to only turn the pages automatically, the annotation work would have been reduced to about 190 time points (160 pages plus about 30 additional events for the videos and textual information).

The downside of this approach is that without the symbolic score there is no information about specific notes. While this is not important for our task, it might be important if the computer's role is a more proactive one and predicts the timing of certain events before they are being played, or makes use of the symbolic information to actively take part in the performance (e.g., by synthesising an accompaniment).

As now both the 'score' and the live performance to track are in the same format – both are audio signals – it is possible to use the same kind of feature computation for both

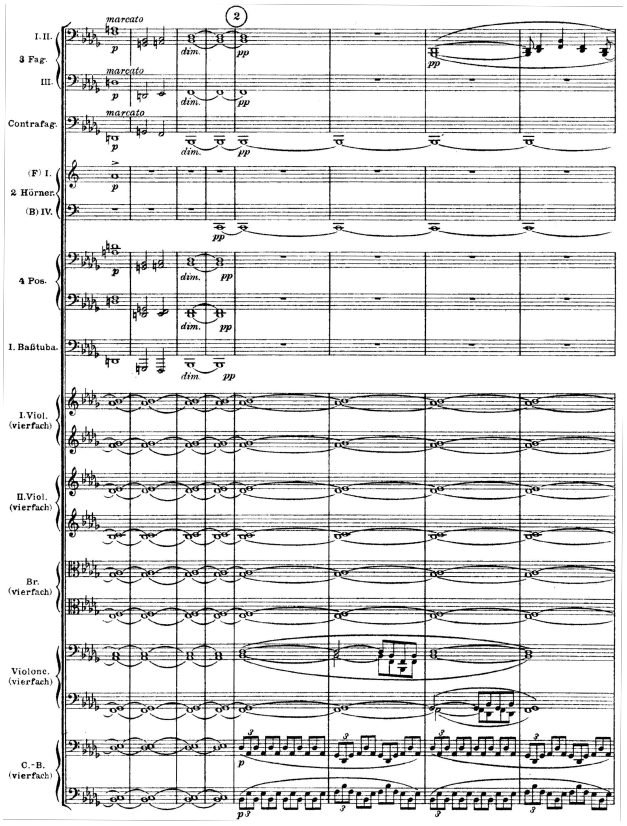

Figure 3: Excerpt from the score. This part is played very slowly and softly (note the p and pp dynamic markings), without a distinct melody (sustained notes in the strings, horns and the contrabassoon). The triplet figures in the bass section are so soft that they don't stand out but add to the overall sound texture.

sequences. We decided on using the features presented in [Arzt *et al.*, 2012] – alternatives approaches can be found in [Joder *et al.*, 2010]. These are well tested and reliable for audio to audio alignment tasks. Originally they were developed for tracking piano music, but as they try to combine two important properties of musical tones (the attack phase and the harmonic content), they are also well suited for a wider range of instruments.

Specifically, two different types of features are combined. 1) onset-emphasised features (an onset is the start time of a tone), which work particularly well for instruments and playing styles that produce sudden increases in the amplitude at onset times, and 2) harmonic features, which model the spectral content. As both features map the spectral data to the semitone scale, they are relatively robust to differences in timbre.

4 Following Live Orchestral Music: Tracking Algorithm

The music tracking algorithm we used is based on an on-line version of the dynamic time warping (DTW) algorithm, making it suitable for real-time music tracking (see [Dixon, 2005]). As input it takes two time series consisting of feature vectors – one known completely beforehand (the score) and one coming in real-time (the live performance) –, computes an on-line alignment, and at any time returns the current position in the score. In contrast to the standard dynamic time warping algorithm the alignment is computed incrementally, and it has linear time and space complexity due to the fact that instead of the whole alignment matrix, in each step only a small window centered at the current position is considered for computation.

Subsequently, improvements to this basic algorithm were proposed. This includes an extension called the 'backward-forward strategy' [Arzt *et al.*, 2008], which reconsiders past decisions and tries to improve the precision of the current score position hypothesis, and relatively simple tempo models [Arzt and Widmer, 2010] which are used to stretch or compress the score representation dynamically and therefore reduce differences in absolute tempo between the score representation and the live performance.

5 Adding a Safety Net: Multi-agent Tracking

While in preliminary experiments the presented combination of score representation, features and tracking algorithm generally gave robust and accurate results, we also witnessed some problems in specific circumstances. In the Alpensinfonie there is a part early in the piece (see Figure 3), starting around bar 14, that is played very softly and slowly. There is no distinct melody, only a relatively monotonic sound texture. Given sub-optimal sound quality (some noise, some distracting sounds), the tracker sometimes got lost or recovered very slowly.

Furthermore, a brief comparison of tracking results shows that, given multiple performances of a piece of music, some pairs of performances are 'easier' (i.e. more accurately and robustly) to align to each other, than others. Generally the features and the tracking algorithm are very robust to differences in tempo, timbre, tuning and even instrumentation, but the tracking process works best when the selected performances are similar to each other in these respects. In case an unsuitable pair of performances is selected, more inaccuracies will occur, and in very rare cases the tracking process might even fail at some point. To alleviate this problem, in [Wang *et al.*, 2014] an off-line music alignment algorithm was presented that improved the quality of pairwise alignments by also taking into account the additional information provided by alignments to all the other performances. Inspired by this we came up with a simple way to increase the robustness in the on-line case.

Instead of using one single instance of the tracking algorithm aligning the live performance to a 'score performance', multiple instances are initialised as independent agents, each using a different performance as its score representation (see Figure 4). The performances used for the Alpensinfonie are

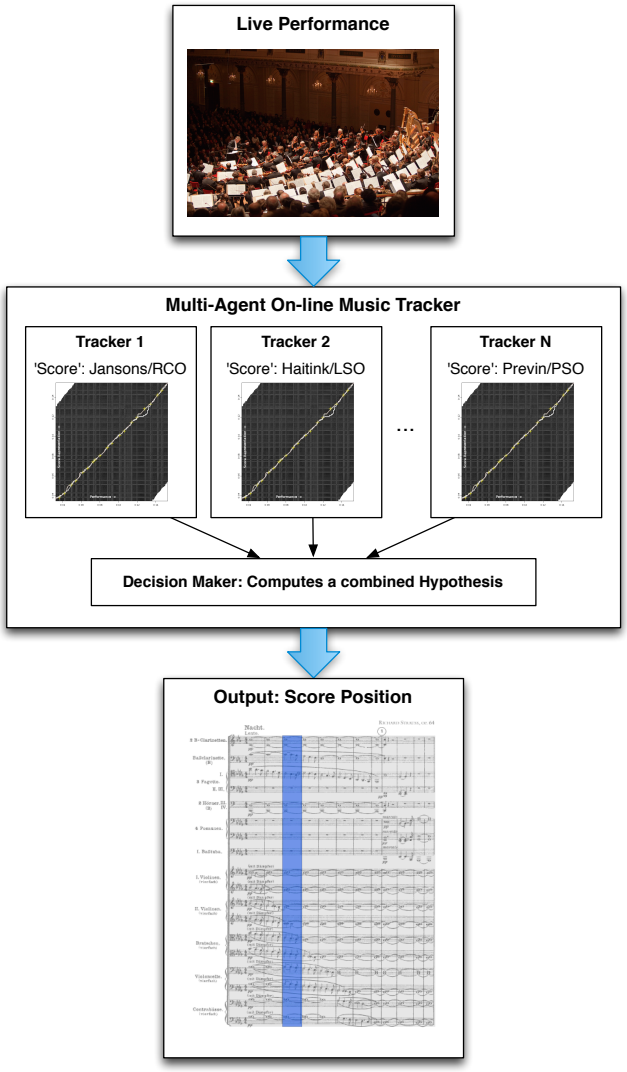

Figure 4: The Multi-agent Tracker. The live input is fed to N independent instances of the tracking algorithm. Each aligns the input to its own score representation, based on different performances of the same piece. Then, the individual hypotheses are combined and the estimate of the current position in the score is returned.

given in Table 1 – thus we had 7 trackers in total. As can be seen, only 1 performance was actually annotated manually while the other 6 were then aligned to it with the help of an off-line audio alignment algorithm (see [Grachten *et al.*, 2013]; other approaches to this problem include [Hu *et al.*, 2003] and [Ewert *et al.*, 2009]) to produce the information about the location of the downbeats. This means that these 6 additional 'score performances' were produced without any additional manual effort. Off-line alignment generally is much more accurate than on-line tracking, although it will still lead to some (but for our case acceptably small) inaccuracies.

During the concert the trackers run in parallel and each tracker tries to align the incoming live performance to its score representation, each producing its own, independent hypothesis of the current position in the score. In the end the hypotheses are combined to form one collective hypothesis of the music tracking system.

Generally, many different ways of combining the hypotheses would be possible, e.g. based on voting or on the current alignment error of the individual trackers. As we had a clear goal in mind – robustness to single trackers getting lost – we decided on a very simple method: taking the median of the positions that are returned by the individual trackers. In our case this effectively allows us to come up with the a good estimate of the score position even when 3 out of 7 trackers get lost.

6 The Event: Live Tracking in the Concertgebouw

The event on February 7, 2015 in the Concertgebouw was a big success. The tracking went smoothly and there were no glitches, only some minor inaccuracies. An obvious mistake happened at the quiet section in the beginning that was already discussed above. The sound texture here essentially consists of a very soft and repeating pattern. In cases like this the trackers sometimes tend to 'wait', because they try to align newly incoming instances of the pattern to past positions in the score (that also represent the same pattern). This resulted in a perceived delay of roughly 1 bar, for a period of about 5 bars. As soon as the texture changed and more distinct sounds could be recognised, the trackers recovered quickly. There were no further noticeable problems and in the end all of the trackers could follow the whole concert, and there was never any concern that the system might fail.

The general opinion amongst the project staff and the test audience was that the tracking worked very well and the accuracy was more than sufficient to trigger the visualisation in time. Only a few inaccuracies were noticed.

A formal in-depth evaluation, based on questionnaires the test audience had to fill out after the concert, will be published at a later point. This does not directly cover the tracking part as a technical process, but focuses on the user experience and on the value added by the provided additional information.

7 Evaluation

To be able to perform quantitative experiments the concert was recorded and annotated in the same way as the score representation above. Thus, the correct times of the down beats in the performance are known, and can be compared to the output of the music tracker. For the evaluation the error for each aligned downbeat is computed as the absolute value of the difference between the point in time given by the algorithm and the actual time according to the ground truth.

The results are presented in Tables 2 and 3. As can be seen, there are only slight differences in the results for the single tracker and the multi-agent approach. Keeping in mind that the goal of the multi-agent approach was to increase the robustness – the tracker would still produce similar results even when 3 out of 7 trackers fail –, this is a good result: extra robustness and a slight increase in accuracy were achieved

Err. (sec)	Single	Multi-agent
≤ 0.25	78.25%	81.80%
≤ 0.50	92.20%	93.24%
≤ 0.75	95.57%	96.44%
≤ 1.00	97.49%	98.01%

Table 2: Real-time alignment results for the single tracker and the multi-agent tracker, shown as cumulative frequencies of errors of matching pairs of downbeats. For instance, the first number in the first row means that the single tracker aligned 78.25% of the downbeats with an error smaller than or equal to 0.25 seconds.

	Single	Multi-agent
Average Error	0.20 sec.	0.19 sec.
Standard Dev.	0.35 sec.	0.36 sec.
First Quartile	0.06 sec.	0.05 sec.
Median Error	0.11 sec.	0.10 sec.
Third Quartile	0.22 sec.	0.19 sec.
Maximum Error	5.33 sec.	5.38 sec.

Table 3: Real-time alignment results for the single tracker and the multi-agent tracker.

without any extra manual efforts as the additional data was prepared by automatic methods.

Generally the results were more than sufficient for the task in question. The median error for the multi-tracking approach is about 0.1 seconds. Only in very rare cases did the tracker make major mistakes. Specifically the section already discussed above (see Figure 3) still causes problems, culminating in a maximum error of 5.38 seconds at bar 24 (which translates to about 1.5 bars, as this part has a relatively slow tempo). Actually the extent of the problem was not as apparent during the concert itself, also because even for humans it is very hard to follow the orchestra during this part.

8 Conclusions and Future Work

In this paper we presented a real-world application of machine-listening in the context of an actual concert in a world-famous concert hall. A music tracking algorithm was listening to the on-going live performance and was used to synchronise additional content (the sheet music, textual information and an artistic video), provided to the audience on tablet computers, to the live music.

The general impression during the concert was that the live tracking worked very well. This was confirmed later by a detailed quantitative evaluation.

As discussed above, our algorithm still runs into problems during soft and slow passages with very little structure or information. We are planning to solve this problem by both looking at additional features and by making stronger use of the tempo model at these parts.

A common problem of real-time music tracking and audio to score alignment are structural differences between the score and the performance. For example, if a piece has some repeated sections, the performers might decide to play the repeat or to leave it out. For the Alpensinfonie this was not an issue, but in the future we will try to cope with this fully automatically – in the preparation phase via the technique used in [Grachten *et al.*, 2013], and in the live tracking phase with the approach presented in [Arzt *et al.*, 2014], extended to orchestral music.

We will also further investigate the multi-agent approach and will evaluate its merits in two scenarios: 1) in more noisy surroundings, and 2) for music of different genres, e.g. romantic piano music, where extreme differences in performing one and the same piece exist. Ultimately, we would like to use the multi-agent approach not only to increase the robustness, but also the accuracy of the tracking process.

In the future we wish to continue using the system in concert halls, possibly also on other genres. Specifically, we are considering opera – which would also lead directly to an additional use case: most opera houses provide subtitles for the audience, which so far are synchronised manually. Tracking an opera is a very challenging task, due to it being a combination of music (including singing voice), spoken language and acting and thus the best approach might be to combine multiple modalities (audio and video) within the tracking process.

Acknowledgments

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