Annotated Resources

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# Articles

**E. Benetos, S. Dixon, Z. Duan, S. Ewert, “Automatic Music Transcription”, in IEEE SPS Journal Vol. 36 January**

* General introduction to AMT

[1] A. Klapuri and M. Davy, Eds., Signal Processing Methods for Music Transcription. New York: Springer-Verlag, 2006.

* General overview of field
* Errors present in current models
* Characteristics of musical notes
* Description of unpitched sound problem Ch. 5

[2] E. Benetos, S. Dixon, D. Giannoulis, H. Kirchhoff, and A. Klapuri, “Automatic music transcription: Challenges and future directions,” J. Intelligent Inform. Syst., vol. 41, no. 3, pp. 407–434, 2013.

* General overview of field
* Future challenges
* Polyphonic instruments challenge
* Problems with current models

[3] M. Müller, D. P. Ellis, A. Klapuri, and G. Richard, “Signal processing for music analysis,” IEEE J. Sel. Topics Signal Process., vol. 5, no. 6, pp. 1088–1110, 2011.

* Relation to source separation
* Basic music fundamentals

[4] M. Schedl, E. Gómez, and J. Urbano, “Music information retrieval: Recent developments and applications,” Foundations Trends Inform. Retrieval, vol. 8, pp. 127–261, 2014. doi: 10.1561/1500000042.

* Relation to Information Retrieval tasks like music similarity

[5] N. Boulanger-Lewandowski, Y. Bengio, and P. Vincent, “Modeling temporal dependencies in high-dimensional sequences: Application to polyphonic music generation and transcription,” in Proc. Int. Conf. Machine Learning, 2012, pp. 1159– 1166.

* Relation to Information Retrieval tasks like music similarity
* Neural Network (NN) and Music Language Model (MLM)
* NN MNE does not consider note interactions
* NN MNE considers note interactions
* Polyphonic music detection via RBM machine with RNN to postprocess the acoustic output of an AMT system
* Modelling high dimensional sequences with deep learning methods

[6] T. Virtanen, M. D. Plumbley, and D. P. W. Ellis, Eds., Computational Analysis of Sound Scenes and Events. New York: Springer-Verlag, 2018.

* AMT and sound event detection (SED)
* Similarity of methodologies used in SED with AMT methods

[7] L. Su and Y.-H. Yang, “Escaping from the abyss of manual annotation: New methodology of building polyphonic datasets for automatic music transcription,” in Proc. Int. Symp. Computer Music Multidisciplinary Research, 2015, pp. 309–321.

* Way to circumvent lack of ground truth transcriptions using music performers
* Lack of annotated datasets

[8] Z. Duan, B. Pardo, and C. Zhang, “Multiple fundamental frequency estimation by modeling spectral peaks and non-peak regions,” IEEE Trans. Audio, Speech, Language Process. (2006–2013), vol. 18, no. 8, pp. 2121–2133, 2010.

* Probabilistic MPE modelling

[9] Z. Duan and D. Temperley, “Note-level music transcription by maximum likelihood sampling,” in Proc. 15th Int. Society Music Information Retrieval Conf., 2014, pp. 181–186.

* Spectral likelihood model for MNE considers note interactions

[10] Z. Duan, J. Han, and B. Pardo, “Multi-pitch streaming of harmonic sound mixtures,” IEEE/ACM Trans. Audio, Speech, Language Process., vol. 22, no. 1, pp. 138–150, 2014.

* MPS instrument tracking

[11] V. Emiya, R. Badeau, and B. David, “Multipitch estimation of piano sounds using a new probabilistic spectral smoothness principle,” IEEE Trans. Audio, Speech, Language Process. (2006–2013), vol. 18, no. 6, pp. 1643–1654, 2010.

* MPE using traditional Signal Processing techniques
* Largest dataset of several hours of piano music
* Challenges to NN

[12] L. Su and Y.-H. Yang, “Combining spectral and temporal representations for multipitch estimation of polyphonic music,” IEEE/ACM Trans. Audio, Speech, Language Process., vol. 23, no. 10, pp. 1600–1612, 2015.

* MPE using traditional Signal Processing techniques
* MNE with median filtering does not consider note interactions

[13] P. H. Peeling, A. T. Cemgil, and S. J. Godsill, “Generative spectrogram factorization models for polyphonic piano transcription,” IEEE Trans. Audio, Speech, Language Process. (2006–2013), vol. 18, no. 3, pp. 519–527, 2010.

* Bayesian MPE

[14] P. Smaragdis and J. C. Brown, “Non-negative matrix factorization for polyphonic music transcription,” in Proc. IEEE Workshop Applications Signal Processing Audio and Acoustics, 2003, pp. 177–180.

* NMF MPE

[15] E. Vincent, N. Bertin, and R. Badeau, “Adaptive harmonic spectral decomposition for multiple pitch estimation,” IEEE Trans. Audio, Speech, Language Process. (2006–2013), vol. 18, no. 3, pp. 528–537, 2010.

* NMF MPE
* Supervised NMF narrow-band sub templates to enforce harmonic structure for all NMF templates
* Remove interference from templates by extracting templates from recordings with only one note

[16] E. Benetos and S. Dixon, “Multiple-instrument polyphonic music transcription using a temporally-constrained shift-invariant model,” J. Acoust. Soc. Amer., vol. 133, no. 3, pp. 1727–1741, 2013.

* NMF MPE
* MPS instrument tracking
* Shift invariant dictionaries can represent multiple F0s
* Sharing parameters between pitches
* Markov process to model note evolutionary phases

[17] B. Fuentes, R. Badeau, and G. Richard, “Harmonic adaptive latent component analysis of audio and application to music transcription,” IEEE Trans. Audio, Speech, Language Process. (2006–2013), vol. 21, no. 9, pp. 1854–1866, 2013.

* NMF MPE
* Shift invariant dictionaries can represent multiple F0s
* Sharing parameters between pitches

[18] S. Sigtia, E. Benetos, and S. Dixon, “An end-to-end neural network for polyphonic piano music transcription,” IEEE/ACM Trans. Audio, Speech, Language Process., vol. 24, no. 5, pp. 927–939, 2016.

* NN MPE
* MLM considers note interactions
* Long range dependencies between notes using an acoustic front end with a symbolic level module resembling an MLM
* Use of MIDI data a recurrent NN was trained to predict active notes in the next frame given those in the past
* NADE architecture and WaveNet
* RNN-RBM MM combined with acoustic predictions using a probabilistic graph model

[19] R. Kelz, M. Dorfer, F. Korzeniowski, S. Böck, A. Arzt, and G. Widmer, “On the potential of simple framewise approaches to piano transcription,” in Proc. Int. Society Music Information Retrieval Conf., 2016, pp. 475–481.

* NN MPE
* Large scale hyperparameter search describing individual system components
* Performed well against other models

[20] J. Nam, J. Ngiam, H. Lee, and M. Slaney, “A classification-based polyphonic piano transcription approach using learned feature representations,” in Proc. Int. Society Music Information Retrieval Conf., 2011, pp. 175–180.

* HMM MNE does not consider note interactions

[21] M. Marolt, “A connectionist approach to automatic transcription of polyphonic piano music,” IEEE Trans. Multimedia, vol. 6, no. 3, pp. 439–449, 2004.

* MNE interonset interval approach considers note interactions
* Marolts Sonic System based on NNs
* Analyzing the output of adaptive oscillators to track and group partials in the output of a gammatone filterbank

[22] A. Cogliati, Z. Duan, and B. Wohlberg, “Context-dependent piano music transcription with convolutional sparse coding,” IEEE/ACM Trans. Audio, Speech, Language Process., vol. 24, no. 12, pp. 2218–2230, 2016.

* MNE considers note interactions through unifed framework that estimates pitch,onset and offset together
* Context specific transcription : single instruments have become much more accurate

[23] S. Ewert and M. B. Sandler, “Piano transcription in the studio using an extensible alternating directions framework,” IEEE/ACM Trans. Audio, Speech, Language Process., vol. 24, no. 11, pp. 1983–1997, 2016.

* MNE considers note interactions through unifed framework that estimates pitch,onset and offset together
* Markov process to model note evolutionary phases
* Comparison to Marolt’s Sonic System
* Limitations of NNs: cold start problem
* Context specific transcription : single instruments have become much more accurate

[24] C. Hawthorne, E. Elsen, J. Song, A. Roberts, I. S. C. Raffel, J. Engel, S. Oore, and D. Eck, “Onsets and frames: Dual-objective piano transcription,” in Proc. Int. Society Music Information Retrieval Conf., 2018, pp. 50–57.

* MNE considers note interactions through unifed framework that estimates pitch,onset and offset together
* Google Brain general purpose piano transcription
* Two networks: one focuses on note onsets and informs the network focused on perceiving note lengths
* Limitations of NNs: cold start problem

[25] V. Arora and L. Behera, “Multiple F0 estimation and source clustering of polyphonic music audio using PLCA and HMRFs,” IEEE/ACM Trans. Audio, Speech, Language Processing, vol. 23, no. 2, pp. 278–287, 2015.

* MPS instrument tracking

[26] E. Cambouropoulos, “Pitch spelling: A computational model,” Music Perception, vol. 20, no. 4, pp. 411–429, 2003.

* Notation level pitch Spelling

[27] H. Grohganz, M. Clausen, and M. Mueller, “Estimating musical time information from performed MIDI files,” in Proc. Int. Society Music Information Retrieval Conf., 2014, pp. 35–40.

* Notation level timing quantization

[28] I. Karydis, A. Nanopoulos, A. Papadopoulos, E. Cambouropoulos, and Y. Manolopoulos, “Horizontal and vertical integration/segregation in auditory streaming: A voice separation algorithm for symbolic musical data,” in Proc. Sound and Music Computing Conf., 2007, pp. 299–306.

* Notation level voice separation

[29] A. Cogliati, D. Temperley, and Z. Duan, “Transcribing human piano performances into music notation,” in Proc. Int. Society Music Information Retrieval Conf., 2016, pp. 758–764.

* Notation level method to convert MIDI to music notation with comparison to commercial packages and performance transcription

[30] R. G. C. Carvalho and P. Smaragdis, “Towards end-to-end polyphonic music transcription: Transforming music audio directly to a score,” in 2017 IEEE Workshop Applications Signal Processing Audio and Acoustics, 2017, pp. 151–155.

* End-to-end proof of concept work audio-to-music notation

[31] D. D. Lee and H. S. Seung, “Algorithms for non-negative matrix factorization,” in Proc. Advances Neural Information Processing Systems, 2001, pp. 556–562.

* Deriving update rules for descent-based minimization of divergence in NMF between V and DA (spectro temporal representation and matrix product of the Dictionary and Activation matrices
* Explanation and advantages of NMF algorithms

[32] S. A. Abdallah and M. D. Plumbley, “Unsupervised analysis of polyphonic music by sparse coding,” IEEE Trans. Neural Netw. (1990–2011), vol. 17, no. 1, pp. 179–196, 2006.

* Challenges of NMF including correlation of sound objects and inharmonicity
* Sparse coding approach to obtain solutions that are dominated by activations that are few but substantial
* Unsupervised NMF

[33] I. Goodfellow, A. Courville, and Y. Bengio, Deep Learning. Cambridge, MA: MIT Press, 2016.

* NNs learning nonlinear functions and optimization methods
* Stochastic gradient descent
* Convolutional networks in the time direction
* Long Short-Term Memory Layers
* Interpolation of templates and valid spectra manifolds in NN

[34] S. Böck and M. Schedl, “Polyphonic piano note transcription with recurrent neural networks,” in Proc. IEEE Int. Conf. Acoustics, Speech, and Signal Processing, 2012, pp. 121–124.

* NNs revival
* Two spectrograms for high time and frequency resolution
* Benefits of LTSMs to model long range dependencies
* Probability of measuring a particular chord sequence

[35] S. Wang, S. Ewert, and S. Dixon, “Identifying missing and extra notes in piano recordings using score-informed dictionary learning,” IEEE/ACM Trans. Audio, Speech, Language Process., vol. 25, no. 10, pp. 1877–1889, 2017.

* Score informed transcription

[36] X. Serra, “A multicultural approach in music information research,” in Proc. 12th Int. Society Music Information Retrieval Conf., 2011, pp. 151–156.

* Non-Western music problem

**M. Müller, D. P. Ellis, A. Klapuri, and G. Richard, “Signal processing for music analysis,” IEEE J. Sel. Topics Signal Process., vol. 5, no. 6, pp. 1088–1110, 2011.**

Gouyon, F., & Dixon, S. (2005). A review of automatic rhythm description systems. Computer Music Journal, 29(1), 34–54.

* Beat tracking and rhythm parsing research

Kirchhoff, H., Dixon, S., Klapuri, A. (2012). Shift-variant non-negative matrix deconvolution for music transcription. In Int. conf. audio, speech, and signal processing (pp. 125–128).

* User identification of instruments act as labels for better supervised learning

Ryynänen, M., & Klapuri, A. (2005). Polyphonic music transcription using note event modeling. In IEEE workshop on applications of signal processing to audio and acoustics (pp. 319–322)

* HMMs used to estimate musical key and note transition probabilities
* 3-state HMMs which model the attack, sustain and noise/silence states of each sound
* Best results for the MiReX note tracking task 2008
* Keys impose probability distributions on the pitches

Ryynänen, M., & Klapuri, A. (2008). Automatic transcription of melody, bass line, and chords in polyphonic music. Computer Music Journal 32(3), 72–86

* Use of dynamic Bayesian Network

O’Hanlon, K., Nagano, H., Plumbley, M. (2012). Structured sparsity for automatic music transcription. In IEEE international conference on audio, speech and signal processing (pp. 441–444).

* Structured sparsity: groups of atoms active

Bertin, N., Badeau, R., Richard, G. (2007). Blind signal decompositions for automatic transcription of polyphonic music: NMF and K-SVD on the benchmark. In IEEE international conference on acoustics, speech, and signal processing (pp. 65–68)

* No training on monophonic data needed

Stanislaw Raczynski, Emmanuel Vincent, Shigeki Sagayama. Dynamic Bayesian networks for symbolic polyphonic pitch modeling. IEEE Transactions on Audio, Speech and Language Processing, Institute of Electrical and Electronics Engineers, 2013, 21 (9), pp.1830-1840. ffhal-00803886f

* Python / R software for symbolic pitch modelling

M. McVicar et al, "Automatic Chord Estimation from Audio: A Review of the State of the Art," IEEE/ACM Transactions on Audio, Speech and Language Processing (TASLP), vol. 22, (2), pp. 556-575, 2014.

* Seems pretty interesting
* Tried an open source package and thought it worked great

Junqi Deng & Yu-Kwong Kwok (2018) Large vocabulary automatic chord estimation using bidirectional long short-term memory recurrent neural network with even chance training, Journal of New Music Research, 47:1, 53-67, DOI: 10.1080/09298215.2017.1367820

* Automatic chord estimation with NNs

# Datasets

[Accessed 3/8/2019]

<https://staff.aist.go.jp/m.goto/RWC-MDB/AIST-Annotation/>

* chorus annotations for RWC recordings

<http://hil.t.u-tokyo.ac.jp/software/KSN/>

* functional harmony annotations

<http://labrosa.ee.columbia.edu/projects/piano/>

* MIDI ground truth dataset

<http://c4dm.eecs.qmul.ac.uk/rdr/handle/123456789/27>

* classical and jazz trios

<http://www.tsi.telecom-paristech.fr/aao/>

* piano models database

<http://theremin.music.uiowa.edu/MIS.html>

* Musical Instrument Samples

<https://staff.aist.go.jp/m.goto/RWC-MDB/rwc-mdb-i.html>

* dynamics samples

<http://dml.city.ac.uk/vis/>

* music analysis library

<https://www.musicxml.com/music-in-musicxml/>

* Great resource for musicXML files
* [Accessed 15/8/19]

<https://staff.aist.go.jp/m.goto/RWC-MDB/AIST-Annotation/SyncRWC/>

* Music synchronization for RWC Music Database
* Classical music

# Societies

<https://www.music-ir.org/mirex/wiki/MIREX_HOME>

* society for task tracking and MIR
* Here are the most recent results
* <https://www.music-ir.org/mirex/wiki/2018:MIREX2018_Results>

<https://www.ismir.net>

* International Society of Music Information Retrieval

<https://dcase.community/>

* Classification of music events

# Software

## mir\_eval

<http://craffel.github.io/mir_eval/>

* Metrics for MIR evaluation

## JAMS

## <https://pythonhosted.org/jams/index.html>

* Python library for annotation tasks

## Librosa

[Accessed 20/8/19]

<https://librosa.github.io/librosa/>

* Python library for music analysis

## Sonic Visualiser + Vamp Plugins

[Accessed 11/8/2019]

[https://www.sonicvisualiser.org](https://www.sonicvisualiser.org/)

* Great tool for use with vamp plugins which have a number of open source packages for MIR

[https://vamp-plugins.org](https://vamp-plugins.org/)

* Access to some great plugins

## Music Analysis Library

[Accessed 19/8/19]

<http://dml.city.ac.uk/vis/>

* Music Analysis Library

# Tutorials

Z. Duan, E. Benetos, “Automatic Music Transcription”, Tutorial at ISMIR 2015, available: <http://c4dm.eecs.qmul.ac.uk/ismir15-amt-tutorial/> [Accessed 3/8/2019]

* society for task tracking and MIR
* slide 60, list of AMT academic open source software
* slide 61, list of AMT commercial software
* slide 61, demo of Silvet Vamp plugin

E. Benetos, ‘Automatic Music Transcription’, Tutorial at the Department of Computer Science, National University of Singapore, available: <http://c4dm.eecs.qmul.ac.uk/nus-amt-tutorial/> [Accessed 19/8/2019]

* General overview
* Challenges and future directions

# Textbooks

Oppenheim, A., Schafer, R. and Oppenheim, A. (1989). Discrete-time signal processing. Englewood Cliffs, N.J.: Prentice-Hall.

* DSP topics

<http://www.dspguide.com/pdfbook.htm>

* DSP guidebook for engineers

# YouTube Videos

### Technical Concepts

<https://www.youtube.com/watch?v=yWqrx08UeUs>

* [Accessed 20/8/19]
* Sampling, Aliasing and Nyquist Theorem

<https://www.youtube.com/watch?v=mkGsMWi_j4Q>

* [Accessed 18/8/19]
* Discrete Fourier Transform

<https://www.youtube.com/watch?v=g1_wcbGUcDY>

* [Accessed 20/8/19]
* STFT DSP
* Frequency tiling

<https://www.youtube.com/watch?v=1JnayXHhjlg>

* [Accessed 18/8/19]
* Fourier Transform video

<https://www.youtube.com/watch?v=FjmwwDHT98c>

* [Accessed 21/8/19]
* Intuitive understanding of FFT

<https://www.youtube.com/watch?v=NA0TwPsECUQ>

* [Accessed 20/8/19]
* Short Time Fourier Transform / Spectrogram
* Filterbank interpretation

<https://www.youtube.com/watch?v=qS4H6PEcCCA>

* Fourier series and epicycles

<https://www.youtube.com/playlist?list=PLX2gX-ftPVXVTT3qpUeHVxbmJx9D1vGhC&fbclid=IwAR0Sle6SZggWXvFcs5roOZnVoU7AFe74Z0zcKHLUjUye0rWIL2gAIQxWr0c>

* **Accessed 25/8/19**
* Michel Van Biezen Fourier transform basics

<https://www.youtube.com/playlist?list=PLB24BC7956EE040CD&fbclid=IwAR2sdIqFLPoC418xPVCS0pUrBpRPkg8bMeSwQiOpX_A-NuerQ-TdNVMDiXk>

* Stanford Fourier Transform lecture series

### Music concepts

<https://www.youtube.com/watch?v=rc30HFVNedQ>

* [Accessed 8/8/19]
* Great explanation of partials, harmonics and fundamental frequencies

## Music Information Retrieval

<https://www.youtube.com/watch?v=9boJ-Ai6QFM&t=95s>

* [Accessed 19/8/19]
* Anna Wszeborowska - Music transcription with Python
* Example of simple python application for real time transcription
* Monophonic real time transcription

<https://www.youtube.com/channel/UCn4iMJjVktUb6SgprG4Eijw/videos>

* [Accessed 19/8/19]
* Fantastic channel for ISMIR tutorials and lectures

<https://www.youtube.com/watch?v=oGGVvTgHMHw&feature=youtu.be&fbclid=IwAR1RjW7ukpOYZArS9frHZzZlUcT0U-6I94euWpMF9-YcaJA2aZyFmUqzvXY>

* Scikit-learn Steve Tjoa MIR algorithms

# Lectures

Librosa Audio and Music Signal Analysis in Python

* Brian McFee
* <https://www.youtube.com/watch?v=MhOdbtPhbLU&feature=youtu.be&fbclid=IwAR3gAHYv8AbgnfwC5QuB0kZghzOd-AelPdBAyxZBKkJfAsgAk8diEnHH42s>
* [Accessed 25/8/19]

Signal Processing Methods for Sound Recognition

* Emmanouil Benetos
* <https://www.youtube.com/watch?v=tAECqx5i4oc>
* [Accessed Online : 19/8/19]

Automatic Music Transcription by Dr. Emmanouil Benetos at NUS

* Emmanouil Benetos
* <https://www.youtube.com/watch?v=HXGv_zL6V7w>
* [Accessed Online : 19/8/19]

# Websites

<https://musicinformationretrieval.com/index.html>

* Notebooks in python for music analysis
* Includes some machine learning

<https://betterexplained.com/articles/an-interactive-guide-to-the-fourier-transform/>

* Fourier Transform explained

<http://www.dspguide.com/pdfbook.htm>

* DSP guidebook

[https://allsignalprocessing.com](https://allsignalprocessing.com/)

* Online library for DSP

[IEEE Referencing Generator: Citation Generator by Cite This For Me](http://www.citethisforme.com/ieee)

* Referencing tool