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Abstract:
This document reports the applications and practices in the domain of coding images of music sheets (music imaging), which include music sheet digitisation, recognition, restoration, and others. It reports hardware and software related to music imaging, with discussions on main obstacles and approaches to evaluate state of the art OMR system.
Keyword List:
Music imaging, music digitisation, sheet music, image processing, scanner, optical music recognition, OMR, optical music restoration, multimedia, image

Table of Content

1 Executive Summary and Report Scope

This document reports the applications and practices in the domain of coding images of music sheets (music imaging), which include music sheet digitisation, optical music recognition (OMR) and optical music restoration.

With a general background of Optical Music Recognition (OMR), the report discusses typical obstacles in this domain and reports currently available commercial OMR software. It reports hardware and software related to music imaging and discusses steps required to evaluate the state of the art OMR system.

Besides the main focus on the transformation from images of music scores to symbolic format (for printed and handwritten music notation), this document also reports music image restoration and the application of music imaging techniques for graphical preservation and potential applications for cross-media integration.

2 Introduction

The document explore issues on the digitisation, restoration and automatic transcription of music documents; converting paper-based music document into machine readable formats, in order to explore effective use of the latest interactive and multimedia technologies for cultural heritage restoration and preservation of musical documents, such as printed music scores, handwritten manuscripts and ancient music scores.

With the advancements of digitisation and information technologies, document analysis and optical character recognition technologies are now widely used, from form processing to handwritten address recognitions. As we know, document imaging, analysis and understanding is extremely complex, not to mention the additional complexities inherent to Music notation.

There are a vast amount of invaluable paper-based heritage, including printed music scores and handwritten manuscripts that are deteriorating over time due to natural decaying of paper and chemical reaction (e.g. printing ink and paper). This situation is a similar challenge to many other paper-based items in library and museum archives. In order to introduce interactive multimedia music capabilities and functionalities, machine readable representation is required. Hence one of the main steps is to create digital version of these paper-based heritage materials for further processing (restoration, encoding, recognition etc) in order to allow long term preservation and wider and more effective distributions. Various efforts have been focused on this issue in order to preserve the record of our heritage. For example, manual and highly skill *paper-splitting* technique used to conserve Bach's manuscripts [Porck & Teygeler, 2000; Wächter *et al.*, 1996] and others.

3 Background

Digitisation has been commonly used as a possible tool for preservation. Although the digital copy may not conserve the original document, it can preserve the data in the document, with the advantage of easy duplications, distribution and digital processing.

Optical Music Recognition (OMR), also commonly known as OCR for Music (Optical Character Recognition for Music) was first attempted in the 60s, and since then there have been a wide range of research and developments in this interdisciplinary domain. Currently there are various commercially available products as well as research systems for OMR. OMR system transforms paper-based printed music scores and handwritten music manuscripts, into a machine-readable symbolic format, and an optical music restoration system to reconstruct small discontinuities and imperfection in the musical writings, including broken stems and stave lines. An idealise system which could reliably "read" and "understand" music notations could provide a wide range of applications for interactive multimedia music, bringing paper-based music to the new multimedia era.

OMR was first attempted over thirty years ago [Pruslin, 1966]. It has received much attention over the last fifteen years [Bainbridge & Wijaya, 1999; Bellini et al., 2001; Bruno & Nesi 2002; Ng & Boyle, 1992; Ng, 1995; Ng et al., 1999; Ng, 2002; etc, see Section "OMR Bibliography"], and there are currently a number of commercially available packages, such as capella-scan [capella-scan], Optical Music easy Reader [OMeR], PhotoScore [PhotoScore], SharpEye [SharpEye], SmartScore [SmartScore] and Vivaldi Scan [Vivaldi Scan]. However there are still much room for improvements in many aspects. Reviews and background on the development of various OMR systems can be found in Bainbridge & Carter [1997], Blostein & Baird [1992] and Selfridge-Field [1994]. An online bibliography on OMR can be found at the Interactive MUSICNETWORK website (http://www.interactiveMUSICNETWORK.org) and http://www.kcng.org/omrbib/

4 Obstacles, Music Notation

Optical Character Recognition (OCR) is perhaps the best known related document image processing problem, but OMR can be critically different. The visual problem might seem simple since writing is normally black on white paper. However, OMR introduces an additional layer of complexity due to the wide range of possible shape variation resulted from inter-connections and groupings of symbols. Furthermore there may be other symbols (e.g. expressive signs, fingerings, bowing, texts, etc.) that are positioned around and sometime overlaid part other music symbols (for example, a tie crossing a stem or touching a note-head).

Music Notation is inherently opened ended. Even if generally considered as stable for the period of XVIIIth and XIXth centuries in the Western world, there are several exceptions, such as "unmeasured notation" (for cadenzas and so on), approximate rhythmic notation (several examples can be found in works of authors like Chopin, Schumann or Mendelssohn), or slight enhancements to traditional notation (slurs without ending note, non canonical time signatures…). In the earlier centuries, with neumatic or Gregorian notation, music notation was very far of a standardized system, and in the XXth century, music notation has exploded, and is noticeably far from that model commonly known as Common Western Music Notation.

Direct recognition of musical symbols is difficult due to the design of the notation. In general, OMR system uses divide-and-conquer approaches to separate musical features before recognition. For example, stave lines are detected and marked before/after note-head in order to separate one feature from the other.

Basic musical syntax (e.g. time-signature) and domain-knowledge enhancement such as rhythmical analysis have been explored to improve recognition performance. Fahmy & Blostein [1998, 1994] propose a graph-rewriting approach for OMR enhancement. Stückelberg et al. [1997] propose an architecture for OMR with high-level domain knowledge and Stückelberg & Doermann [1999] explore probabilistic reasoning for musical score recognition. Coüasnon [2002] comments that existing OMR software is not suitable for industrial context due to time consuming and tedious manual proof reading, and proposes a system that is capable of self-diagnostic to detect error [Coüasnon and Rétif, 1995]. The paper discusses the application of musical knowledge of music writing to enhance OMR processing and recognition using DMOS (Description of MOdification of Segmentation), a generic recognition approach for structured document analysis with grammatical formalism EPF (Enhanced Position Formalism).

5 Music Digitisation

5.1 Hardware

Nowadays, document digitisation systems such as optical flatbed scanners are widely available. There are a wide range of commercial products from manufacturers such as Fujitsu, Agfa, HP, Cannon, Epson, UMAX, Microtek, Visioneer and many more. Currently available commercial products are equipped with USB, parallel or SCSI interfaces. Some of these products support dual-interfaces.

Many of these products are capable of more than 600 d.p.i. (dot per inch) optical scan resolution with grey or up to 48-bit colour depth which surplus general requirement for OMR processing.

Increasingly digital photo-copiers are also equipped with optical scanner which provides high-speed digitisation. Examples include products from Ricoh and Canon.

Drum scanners are less commonly being used in this domain. Besides professional flatbed scanners (such as Creo Scitex, Heidelberg and others), industrial music imaging applications for archiving (bitmap images) also use a digital-camera-back or digital-camera with a copy-stand setup which range from a simply board for document placement to include fully pneumatically controlled book cradle system as well as complex robotic control automatic page-turning system. Examples of overhead-scanning products include:

Company	Product	Notes	URL
Kirtas Technologies, Inc. (USA)	APT BookScan 1200	World's first automatic book scanner	http://www.kirtas-tech.com
4DigitalBooks	"DIGITIZING LINE"	Automatic digitizing system	http://www.4digitalbooks.com
Zeutschel GmbH	various MONISCAN models	Large format colour scanner OMNISCAN9000	http://www.zeutschel.de
Solar Imaging Systems, UK	M3 & M5 digital camera systems	Maximum optical resolution 8192x12000 pixels	http://www.solar-imaging.com
Icam Archive Systems, UK	GUARDIAN	Various models including Guardian which uses Phase One camera backs	http://www.icamarchive.co.uk
Konica Minolta	Minolta PS7000 book scanner	Up to A2, 256 greyscales	http://www.minoltaeurope.com/...
InfoSys GmbH	alpha librae	Up to 900 pp/hour, greyscale & colour model	http://www.infosys-scanner.de/indexE.html
ImageWare Components GmbH	Bookeye products	Oversize formats up to 350 x 720 x 470 mm	http://www.bookeye.com
Imaging Business Solutions	SMA ScanFox	A1 and A2	http://www.imagingbusiness.co.uk
Lumiere Technology	Jumbo Scan	30000x12000 pixels	http://www.jumboscan.com/
Cruse Digital Equipment	Various models including Synchron Table Scanners	CS 175P which accepts originals as large as 40"x60"	http://www.crusedigital.com/scanners.html
Zeutschel GmbH	Zeutschel Omniscan 10000	Bbooks, newspapers and large format documents (maps, drawings, posters) 871x 610 mm (A1) = 10424x 7300 pixels and 24 bit/pixel	http://www.zeutschel.de

Table 1: sample document digitising hardware

With increasing pixel count, one-shot digital camera systems are increasingly usable for this domain. For example:

- PhaseOne, www.phaseone.com
- BetterLight, www.betterlight.com
- Imacon, www.imacon.dk
- Fujitsu, http://www.fujitsu.com and

- others

With high-end digital camera or scan-backs system, copy-stand is necessary. Examples of copy-stand include:

- Bencher, http://www.bencher.com/copystands.html
- Beseler, http://www.beselerphoto.com/Product_Catalog/o1.pdf
- Kaiser, http://www.kaiser-fototechnik.de
- Linhof, http://www.linhof.de/english/zubehor/repro/repro.html
- Testrite, http://www.testrite.com/CopyStands.htm
- Tarsia Technical Industries, http://www.ttind.com

The section has presented some sample hardware for the digital acquisition of musical documents. This is a fast moving market and hence it is simply as a guide, with some special mention on relevant hardware such as the book scanner and high quality large format digitiser which are important for music manuscripts preservation, to provide general information. More up-to-date information is to be maintained on the project website.

In addition to hardware system, the following sub-section discusses digitisation guidelines and relevant issues for digitising musical documents.

5.2 Digitisation

There are many digitisation related projects and institutions which have produced good set of guidelines or publications related to these issues. These include:

- MINERVA, http://www.minervaeurope.org
- PULMAN, http://www.pulmanweb.org
- AHDS (Arts and Humanities Data Service), UK, http://www.ahds.ac.uk
- British Library, http://www.bl.uk/services/preservation/freeandpaid.html
- DFG (Deutsche Forschungsgemeinschaft, German Research Council, www.dfg.de) 'retro-digitisation'
- CLIR (Council on Libraries and Information Resources), Building and sustaining digital collections: models for libraries and archives, http://www.clir.org
- DLF (Digital Library Federation), *Digital library standards and practices,* http://www.diglib.org/standards.htm
- Library of Congress, A Framework of Guidance for Building Good Digital Collections , http://www.nap.edu/catalog/9940.html
- UNESCO/ICA/IFLA, Guidelines for digitization projects for collection and holdings in the public domain, particularly those held by libraries and archives http://www.ifla.org/VII/s19/pubs/digit-guide.pdf
- DI.MU.SE project (*Ministero per i Beni e le Attività Culturali* and Palatina Library of Parma) provided guidelines for the digitalisation of 150.000 music manuscript pages. http://www.bibpal.unipr.it
- and others

As with other document imaging processes such as Optical Character Recognition (OCR), OMR is not particularly demanding on currently available optical document scanners. Typically, for sheet music, 300 d.p.i optical resolution and 8-bit grey is sufficient for the purpose of OMR [Selfridge-Field 1994]. Fujinaga & Riley (2002) reported that 600dpi is a sufficient resolution for all significant details. The paper suggested that further increase in resolution is not necessary for OMR since it will not provide any additional information.

Generally, the first process in a document analysis system is to threshold a given grey input image into a binary image. Some systems used binary input images produced by the digitiser.
Regarding the Italian DI.MU.SE project, the digitalisation parameters for the music manuscript was fixed for the master copy in 300 d.p.i optical resolution with colour depth at 24 bit RGB, TIFF format.

6 OMR

This section discusses the development of the OMR providing information and discussions on both commercial and research OMR systems.

6.1 Commercial OMR Systems

Current, there is a number of commercially available OMR software. No comprehensive comparative study has been carried out, and hence this is urgently required. In order to provide unambiguous comparative study between different software, terminology for all musical primitives (e.g. note-head, stem, etc) has to be standardise. For a non-bias survey of OMR software, a representative and sufficiently large ground-truth dataset of music sheets containing different style of fonts, density, sizes and page layout has to be collected. Simple recognition rate (as in Optical Character Recognition) does not offer good/meaningful measure for OMR system due mainly to the complex musical notation which may change (visually) depending on the contexts, and hence a good assessment matrix is require to provide meaningful assessment for OMR system. Current proposal include a 3 level approach with measurement at primitive-level, note-level and interpretation- (score-) level.

Commercially available OMR systems include:

- capella-scan
- Optical Music easy Reader (OMeR)
- SharpEyeMusic Reader
- SmartScore
- Neuratron, PhotoScore
- BraeburnSoftware, Music Publisher system
- Vivaldi Scan (derived from SharpEye)
- Musitek, SmartScore
- Scorscan of NPCImaging http://www.npcimaging.com/scscinfo/scscinfo.html
- MIDI-Connections Scan, http://www.midi-connections.com/Product_Scan.htm

6.2 Research OMR Systems

6.2.1 OMR Granularity

This section presents a range of research OMR systems, with discussions on techniques and approaches. For more research OMR systems, please see the "OMR bibliography" at the end of this document or from the project website.

Generally, OMR systems make use of the following main processes:

(i) segmentation, to detect and extract basic symbols or primitives from a given image of the document
(ii) recognition
(iii) reconstruction, which builds the logical description of the notation, and they can be categorised by the granularity of recognition, by mean of he fundamental symbol units that are considered.

There are generally two levels of granularity:

(i) fundamental units as remaining connected components after staff lines removal (e.g. chord, notes with their stem and flag, etc.), or
(ii) fundamental units as the lower-level graphical primitives such as note heads, rests, flags, dots, that can be used to make up of music symbol [Ross, 1970, Blostein and Baird, 1992, Bellini, Fioravanti and Nesi, 1999, Ng 2005].

In the first case, the symbols can be easily isolated or segmented. However, the number of different type of symbols is very high. In the second case, it has to process a large number of primates segmented and required reconstruction for the semantic. This leads to increase complexity.

6.2.2 On-line and Off-line OMR

In addition to the different levels of granularity, OMR systems can further be dichotomised into two categories, as in OCR, on-line and off-line systems.

The on-line systems analyse the writing (input) directly, using input systems such as pen-based input systems [Anstice et al. 1996, Ng, Bell and Cockburn, 1998] that allow a user to use a pen to write the music as in the traditional paper-based approach. Typically these systems consist of a tablet, which is normally a touch-screen display, with an electronic pen (or stylus) which is used to write on the tablet. This is aimed at minimising the input time for data entry into a computer. Similar challenges remained on the issues related to the complexity for the recognition of the writing. On-line systems require the generation of symbolic music representation interactively, recognising each fundamental units of the music score locally. In comparison to the off-line systems, the on-line systems can make use of the stroke information (e.g. direction of writing, overlapping, etc) that is not available for the off-line systems.

The off-line systems analyse an image of a given music sheet which has been digitised by a scanner (e.g. normal flat-bed document scanner). Typically the processing time is not the key issues but the overall recognition rate is. Off-line systems generally make use of global information since the system access to a section or a full page (or pages) at a time working forward and backward extracting and enhancing the results with additional information from the surrounding contexts.

6.2.3 OMR Research and Development

This section briefly discusses several key OMR systems presenting the trend and practises on the system architectural and processes.

Prerau [1970] introduced the concept of music image segmentation to detect primitive elements of music notation. Prerau proposed a fragmentation and assembling approach to identify the staff lines, to isolate fragments of notation and to rebuild the fragments into music symbols. In summary the overall processing can be divided into the following stages:
- Staves lines are scanned to detect parts of music symbols (fragments) lying inside and outside the lines.
- Fragments are recombined to build complete symbols. Overlapping rules drive the assembling phase: two symbol fragments that are separated by a staff line are connected if they overlap horizontally.
- Dimensions of bounding box are measured for each symbol. Prerau proposed that the height and width of the symbols are sufficient features to identify the symbols.
- Symbols are classified by comparing their dimensions with a table where topologic features for each symbol

Carter [1989] proposed an image segmentation process uses the Line Adjacency Graph (LAG). It analyse the image vertically and horizontally to search for paths of connected foreground pixels, called segments. Graph nodes correspond to unions of adjacent and vertically overlapped segments (sections) while arcs define the overlapping of different segments in an adjacent column (junctions). The resulted graph is analysed to detect the staff lines and symbols lying on it. This technique is able to support the identification of staff with the following features:
- empty areas of staff (areas without music symbols); in this way it is possible to detect and label the section containing single music symbols or groups of symbols (beamed notes);
- supporting image skew up-to ten degrees;
- supporting stave lines that are slightly bent or broken, and/or with variable thickness.

The main stages of this system consist of:
- segmentation based on the LAG approach to identify the empty areas of stave lines and to isolate the symbols, and groups of overlapped or connected symbols;

- classification of the segmented objects, using the bounding-box size. Specific algorithms are proposed for overlapped or superimposed symbols, and for objects that are not linked to the staff system.

Fujinaga [1988] proposed an OMR system which is based on projection method. Staff are identify for their position, but not removed. Notation syntax knowledge are applied for the analysis of the projections to identify and classify the symbols. Fujinaga proposed a context-free grammar based on the syntax of the music notation. The main stages of the system can be summarised as followed:

- Staff system is identified by analysing the Y-projection of the image to find groups of five peaks, with a graphical consistent contribution;
- Symbols are identified by using the X-projection. Values greater than the background noise caused by the staff lines suggest the presence of music symbols. Syntactic rules, mainly based on the position of notation are applied;
- Symbol classification is performed by using the X- and the Y- projections. Classification features include width, height, area, and number of peaks in projection. First and the second derivative of projection profiles have also been suggested.

Roth [1994] proposed a method to remove both the horizontal and vertical lines in order to attack the problem of objects that are touching with each other, and broken-symbols caused by staff lines removal. Main stages of the system include:

- Statistical analysis of vertical paths: The average length of vertical paths for black and white pixels is used to estimate the thickness of staff lines and the inter-stave space;
- Staff lines detection and removal: The detected staff lines (by searching groups of five peaks in the Y-projection profile) are removed by erasing lines having thickness less than the detected value;
- Vertical lines detection and removal: X-projection profile is used to detect all vertical lines (e.g. bar-lines, stems, vertical lines in accidentals, etc.);
- Objects labelling: Label each object found together with the features information such as dimensions, number of pixels and centre of mass;
- Symbol recognition: Symbols are recognised by using the information provided by the labelling step and graphical rules.

Ruth [1994] reported the first version of the system which provided modest results and worked with a limited set of symbols. It also presented an improved system with a feedback based on the semantic control. The improvements include further graphic analysis and allow changes of various threshold levels that control the process.

Couasnon and Camillerap [1995] reported that the musical knowledge is very important in the recognition process. A grammar which describes syntactic rules representing both the musical and graphical context is introduced to separate the definition of the musical rules. With this approach, the segmentation and labelling stages of basic symbols are controlled by the proposed grammar. Basic symbols are not labelled during the extraction phase since the labelling phase depends on the verification of the consistency of the syntactic rules. Using this approach, the reconstruction and classification stage of the system is immediate since the consistency of position and sequence of primitives have been preserved. The resulted reconstruction is further verified to enhance the results using the music domain knowledge to control the overall process. It is believe that this system is capable of scaling up to manage more complex score since it is possible to define new grammars to formalise the music notation in different level of complexity. Good results with polyphonic music score were reported.

Ng (1992, 1994, 1996, 2002, 2005) proposed a reverse engineering approach which reverse the process of the musical writing. Consider a normal ordering of writing a passage of musical notation: a composer or copyist typically draw the note-head first, follow by the stem, beam and finally adding structural elements such as slurs and ties. In this way composite and complex music symbols are decomposed in primitive symbols. The system is divided into different sub-systems as follows:

1. The pre-processing sub-system consists in a list of automated processes including:
    - Thresholding, to convert the input grey image into a binary image;

- Deskewing, the image is rotated whether any correction of the skew, usually introduced during the digitisation, is needed. This step is necessary because the orientation of the input image affects any further process where the projection method is used.
- Staff lines detection and definition of a constant value obtained by adding the average highness of a staff's black line with the distance between two lines. The constant value so calculated is used as fundamental unit in further processes and as general normalisation factor.

2. In the sub-segmentation process, the composite music symbols are divided into lower-level graphical primitives such as note heads, vertical and horizontal lines, curves and ellipse. From the initial segmentation, each block of connected features is passed into the classification module. If the object is not classified confidently, and it is too large as a feature, it is passed into the sub-segmentation module to be broken into two or more objects.
3. In the classification process, primitives are classified using a k-Nearest-Neighbour (kNN) classifier based on simple features such as the aspect ratio and normalised width and height, being graphical features of the primitives relatively simple. After recognition, sub-segmented primitives are reconstructed and contextual information is used to resolve any ambiguities. To enhance the recognition process, basic musical syntax and high level musical analysis techniques are employed for instance: automatic tonality detection, harmonic and rhythmic analysis.

The pre-processing task for the recognition of printed music has been re-used for hand-written manuscript analysis in (Ng, 2002). The sub-segmentation approach relies on the vertical orientation of the musical features and performs unsatisfactorily for hand-written music due to the characteristically slant and curve line segments. For hand-written manuscript, the sub-segmentation module adopts a mathematical morphology approach, using skeletonisation and junction points to guide the decomposition of composite features, and disassembles them into lower-level graphical primitives, such as vertical and horizontal lines, curves and ellipses.

Fujinaga (1997, 2001) presents the *Adaptive Optical Music Recognition* system with the functionality to learn new symbols. The adaptive feature allows the system to evolve. The system consists in a database of symbols and three inter-dependent processes: (i) a recogniser detects, extracts and classifies music symbols using a k-Nearest-Neighbour classifier. The recognition is based on an incremental learning of examples. It classifies unknown symbols by locating the most similar feature which the system has in its database. An editor for music notation allows the user to make correction and a learning process improves the performance and the accuracy of any further recognition sessions, updating continuously the database and optimising the classification strategies.

The system consists of the following main stages:

1. The staff lines removal is performed without removing music symbols. To determine the height of lines and white spaces between two lines, the *vertical run-lengths* is used. Staff lines are selected by means of a projection along the vertical axis; the presence of more than one staff and the left and right margin of the page are established by projecting the page along the horizontal axis.
2. The text location and removal tasks are performed by using heuristics. An OCR allows recognising the word; letters as dynamic symbols are not removed since they are not inside a word. This task fails for instance when letters are connected to each other or touched the staff lines; a note touching the staff could be recognised as a letter.
3. In the segmentation task, the image is decomposed in disjoined image segments; each segment contains an object to be classified. For each symbol, measurable features (height, width, area, etc…) are extracted and the *feature vector* is calculated by means of *genetic algorithms*.
4. The classification is performed using a k-Nearest-Neighbour. The classifier decides the class the symbol belongs to on the account of its feature vector. The k-NN does not require the knowledge a priori of the symbol distribution in the space of features; this property allows learning new class of symbols.
5. Reconstruction of the score is performed by using a Prolog based grammar.

This system was chosen as the basis for of the Levy OMR system, called Gamera, and expanded with an Optical Music Interpretation system (Droettboom and Fujinaga, 2002).

Luth [2002] proposed a system for the recognition of hand-written music manuscripts. The work is based on image processing algorithm such as edge detection, skeletonisation, etc, with the following main stages:

- Pre-Processing: to obtain a binary image with minimal disturbances using an adaptive thresholding approach; with automatic estimation of optimal threshold value for small regions.
- Image Analysis: The thresholded image is decomposed into 5 layers: (i) horizontal lines (stave lines); (ii) vertical lines (bar, stems); (iii) small circular filled structures (note heads); (iv) line structures (clefs, note flags or accidentals); and (v) other structures (textual information).
- Object Recognition: based on an *a-priori* knowledge and structuring rules of abstract models (staff lines, note stem, note heads) to assign contextual meanings to the extracted structures. This task also generates a special Notation Graph. It involves a syntactic level of handwriting for the description of relationships among structures in terms of geometry, metrical and features.

Identification: A tree of features is built to collect two forms of structural descriptions: the structure of the abstract object features and the appearance of the features as primitives in the image. Once object features are given in the form of structural descriptions, a graph matching algorithm determines which image primitives belong to the same object feature.

The Object Oriented Optical Music Recognition System (O^3MR) is under development at the Department of System and Informatics of the University of Florence, Italy, in relation to the following EC IST projects: IMUTUS (Interactive Music Tuition System) and WEDELMUSIC (Web Delivery of Music, www.wedelmusic.org) [Bellini, Bruno and Nesi, 2001]. The general architecture of the O^3MR can be summarised as followed:

- Segmentation: extracts basic symbols and their positions. The actual classification is performed later at the reconstruction stage.
- Basic Symbol Recognition: recognises basic symbols using a neural network using the segmented basic symbols. On the basis of the set of basic symbols a feed–forward neural network has been set and trained to perform the recognition. The output of this module is mainly symbolic. For each recognised basic symbol, the image segment co-ordinates and the confidence value of recognition are produced. When bar lines are recognised, the corresponding image segment is further elaborated in order to estimate the position of staff lines.
- Music Notation Reconstruction: maps the recognised basic symbols onto the elementary components of music notation symbols. For example, a short horizontal line segment may be part of a beam or a rest, etc. This is the stage to finalise the recognition using the context, with a set of Visual Rules of the Music Symbols for the reconstruction. With this process, each basic symbol is assigned a set of probable elementary symbols. These elementary notation symbols estimate the probability to be a basic symbol on the basis of the context.
- Music Notation Model: once the basic notation symbols are identified they are composed with a set of Music Notation Rules.

7 OMR Evaluation

7.1 Obstacles

The Optical Music Recognition task is more complex than OCR. Although there are several OMR packages that are commercially available, e.g. SharpEye2, SmartScore, Photoscore, CapellaScan, etc., none of them are satisfactory in terms of precision and reliability. The efficiency stated by each distributor is typically close to 90%, but this value is obtained only when quite regular music sheets are processed and the estimation is not always objective. In the character or face recognition field, there are many ground truth databases that enable recognition results to be evaluated automatically and objectively. At the present time, there is neither a standard database for music score recognition nor a standard terminology. If a new recognition algorithm or system were proposed, it could not be compared with the other algorithms or systems since the results would have to be traditionally evaluated with different scores and different methods. Taking these facts into consideration, it is indispensable to make a master music score database that can be used to objectively and automatically evaluate the music score recognition system. At the same time a set of rules and metrics are needed in order to define what aspects have to be considered in the evaluation.

In general, the currently available commercial OMR systems are linked to a music notational software. For example, PhotoScore outputs directly into Sibelius. It is not easy to access the performance of the OMR system alone without interaction with the interface provided by the notational software. That is to say, it is not always possible to output from the OMR system itself. This problem is even complicated by the lack of a commonly accepted standard for musical notation.

All the currently available OMR systems offer capture facilities to communicate directly with the scanner. This is another complication since it is not easy to make sure that the input images for all OMR systems are exactly the same (pixel perfect). For the OMR assessment, file input is clearly preferred, however the complications here include:

- different input format support
- different optimum resolution
- different image depth requirement (e.g. 2-bit, 8-bit etc.) and different pre-processing approaches.

Besides differences of input and format representation, differences in output formats, due to the lack of a commonly accepted standard for musical notation, present another layer of complication. Generally output can only be obtained in the proprietary format of the music notation software – that is, the ".mus" or the Enigma format for the Finale software, the Sibelius format for the Sibelius software, and so on. Some of these formats, such as the ".mus" format, are undocumented, and some partially documented format such as the Enigma format are perpetually evolving and suffering of lacks of documentation.

The NIFF format, which was designed at the very origin for the purpose of exchanging music notation between different music notation software, noticeably OMR and music notation software, is now used by very few notation software (see the MUSICNETWORK deliverable DE4.1.1, "music notation coding"), and some OMR software are not able to export in this format.

In general, all music notation software could export in the MIDI format, but this format doesn't capture all features of music notation, thus that format can be used only in a first approach. Noticeably, the MIDI format doesn't capture rhythmic features, and output in MIDI from different music notation software could be slightly different depending on the music software. It would however be possible to set up a methodology based on the MIDI format, with a first step of export in MIDI, followed by an import in a reference software.

It is not easy to compare results outputted in different formats due to their individual designs and capabilities. Due to these complications, "scan once, use many" methodology may not be easily applied.

Moreover, complexity of music notation is a supplementary challenge: the fundamental unit of music notation (the note) is itself a complex object, made of a note head, a stem, a flag or a beam, possibly an accidental and dynamic markings such as staccato dot. This complex object can be modified in its fundamental meaning **-** pitch and duration **-** by its environment (clef, key signature, time signature…).

The results of the comparison could be distorted by errors introduced by the context (notation software, music format, etc…). Therefore, a good methodology for comparing results must involve definition of different ratios for each kind of error. An error of clef, for example, would produce an error for each note in the MIDI output, while being easily corrected by just one correction in the notation format. These errors must be detected and corrected at the earliest step possible, since they could induce wrong automatic corrections and artefacts performed by the software at a later stage (for example, error in time signature could generate an automatic completion of measures in the notation software, by introducing incorrect rests for completing measures). In the same manner, a normalisation must be done at an earlier stage to correct possible errors of non-significant features such as tempo markings which could introduce differences in the final output.

A proposed methodology for comparing OMR software would then involve the following steps:

1. Input of scan with different resolutions, different format support, different image depth
2. First step of correction for context errors: clef, time signature, key signature.
3. Normalization of context for non tested features: tempo marking

4. Output in music notation software
5. Second step of correction for context errors: clef, time signature, key signature (if not possible at an earlier stage)
6. Normalization of context for non tested features: tempo marking (if not possible at an earlier stage)
7. MIDI export
8. MIDI import in a reference software – Normalization of context (tempo markings – dynamics – MIDI instruments and parts) – first evaluation of rates
9. Correction of errors on the first-rated result, and generation (MIDI export) of a reference file
10. MIDI export

The comparison tests must be made:

- By manual, human detection of errors at step 8 (MIDI import) described above.
- By automatic, software-based comparison of the results obtained at step 10 with the reference file obtained in 9.

This methodology can only be applied to those basic features which are part of the MIDI standard, and cannot be applied to features which are not part of the standard, such as dynamic markings (hairpins, staccato, tenuto…).

As a quick test to find out the capability of an OMR package, this project has design an OMR "Quick-Test" typical musical features specially layout and grouped for a simple and clear confirmation of the OMR package under survey. This is presented and discussed in the following subsection.

7.2 The OMR Quick-Test

As mentioned earlier, there are no standard benchmarking resources for OMR and hence this project introduced a "Quick-Test" in order to provide a simple but informative approach to find out the capability of an OMR system. The features included in the "Quick-Test" are typical symbols on various different types of musical scores. Some parameters and expressive signs are also included to test the functionalities supported. Grouping (e.g. beam), time- and key-signature changes are inserted at various position to allow a confirmation of such support by the OMR system. It is a purely made-up score not for musical expressivity but purely to test the capabilities and functionalities preserving musical syntax and logic to minimise any "correction" that could be enforced by the musical editor after the OMR process.

The OMR "Quick-Test" (version 0.1) contains three pages of basic musical features including:

- time signatures
- notes
- beams
- key signatures
- clefs
- note heads
- accidentals
- articulation
- text
- bar lines
- flat beams
- sloping beams
- stave types
- dynamics
- hairpins
- rests
- slurs and ties
- triplet and tuplets
- octava lines
- pedal symbols

- pedal lines

As mentioned above, most OMR systems use notational software front-ends. Notational software tends to use domain knowledge to interpret the data e.g. the number of beats in a bar given a known time-signature. To try and eliminate as far as possible the difficulties that misreading of this kind produces, the "Quick-Test" is designed with "correct" time to occupy each bar.

The data gathered from the "Quick-Test" should result in a list of recognition problems allowing us to target features which consistently prove problematical for the software. This will then lead to a priority list of these features.

Solving these problems will lead to more accurate initial interpretation of symbols and features, and therefore to less user-intervention.

We also look forward to input from the content providers that have supplied us with images, as well as from the OMR system developers. Their comments will help in identifying areas that are important to address if OMR software is to become more commercially viable.

Further details and information are available online at the Imaging WG section at the project website: http://www.interactiveMUSICNETWORK.org

The proposed Quick-Test dataset is available for download at the Imaging WG section.

7.3 Evaluation of performance based on complete music symbols and relationships reconstruction

Beside the Quick-Test, the WG is also working on an approach for the assessment of OMR system intending to take into account the "importantness" of the each music features and planning to offer a representative measure to measure the performance of OMR system. For further details, please see "Assessing Optical Music Recognition Tools" by I. Bruno, P. Bellini and P. Nesi available online at http://www.interactiveMUSICNETWORK.org/wg_imaging/upload/assessingopticalmusicrecognition_v1.0.doc. Three applications have been selected in order to compare the performance in the score recognition: SharpEye2 (Visiv), SmartScore (MusiTek) and O^{3}MR (developed at the DSI – University of Florence).

The set of complete symbols and relationships are listed and described in Table 2. This evaluation set is not exhaustive for all genre of music score, it could be extended in order to include more aspects (structural, symbolic, etc…). The proposed list is able to describe the monophonic music score and relationships, and the most important and frequent symbols. The relevance of each category is represented by a value of weight. A questionnaire was prepared and submitted to a group of experts and users of Optical Music Recognition tools and Symbolic Music Notation Software, in order to estimate the weights expressing the relevance of the identified categories of symbols. To each category of symbol the expert was asked to provide a relevance vote in the range from 1 to 10. The weights have been collected by interviewing a group of 13 people at the second MUSICNETWORK workshop who are experts in music notation.

Definition of test set – The lack of a ground truth databases conditioned the choice of tests, to cope with this lack, seven images have been selected from the archive of collected images at the DSI. The test-cases can be found online at http://www.interactiveMUSICNETWORK.org/documenti/view_document.php?file_id=475 and could be used as a reference set by any other research group or by OMR builders for their self assessment. The chosen music scores have the following features:

- Monophonic music.
- Font variability.
- Music symbols frequently used in the classic music repertory.
- Variable density of music symbols.
- Irregular groups (triplets, etc.).

- Small note with or without accidentals (grace notes).
- Different barlines (start and end refrain, end score, single barline and double barline).
- Clef and time signature change.
- Ornaments (mordent, turn, and trill).
- Slurs: single and nested.

Categories	Weight	Aim
Note with pitch and duration	10	Evaluate the note reconstruction correctness in terms of pitch and duration.
Rests	10	Evaluate the recognition of rests.
Note with accidentals	7	Evaluate the association of accidentals (sharp, flat, double sharp, natural, double flat) with a note.
Groups of beamed notes	10	Evaluate the capability in reconstructing beamed notes
Time signature and time change	10	Evaluate the capability in identifying and reconstructing the time indication by recognised numbers involved in the fraction.
Key signature and key signature change	10	Evaluate the capability in identifying and reconstructing the key signature (tonality). The tonality is linked to the number of accidentals used in representing the key signature.
Symbols below or above notes	5	Evaluate the capability in identifying and linking ornaments symbols and accents (staccato, accent, turn, mordent, trill, tenuto, etc…).
Grace notes	5	Evaluate the capability in recognising grace notes: acciaccatura and appoggiatura are related to a single symbol while multiple grace notes define a group of notes. The multiple notes are considered a unique symbol.
Slurs and bends	7	Evaluate the reconstruction of horizontal symbols: slurs (and ties) and bends.
Augmentation dots	10	Evaluate the augmentation dots linking to notes.
Clefs	10	Evaluate the recognition of clefs and clef changes.
Irregular notes groups	10	Evaluate the capability in recognising tuplets.
Number of measures	10	Evaluate the capability in recognising the bar line and the number of measures.
Number of staves	10	Evaluate the capability in recognising staves.

Table 2: List of complete symbols and relationship considered in the performance

All images were digitised by means of a HP ScanJet flat scanner with: 300 dpi resolution, 8-bit depth (grey scale). They are stored in GIF format. All images were submitted as input files to the OMR applications and the corresponding recognised scores were printed and analysed.

Evaluation and result analysis **-** In order to assess the recognition rate in terms of complete symbols, a set of metrics has been defined to count several categories of recognised, fault and missed complete symbols, for each of the above possible complete symbols category. These metrics are estimated both on the original score image and the reconstructed one when the latter is compared with the original score. They consider:

1. $NECS_i$: number of expected complete symbols of type i^{th} counted directly in the original music score image.
2. $NTCS_i$: number of correctly recognised (true) complete symbols of type i^{th} counted in the reconstructed score while comparing it with the original music score image.
3. $NFCS_i$: number of wrongly recognised (fault) complete symbols of type i^{th} counted in the score while comparing it with the original music score image.
4. $NMCS_i$: number of not recognised (missed) complete symbols of type i^{th} counted in the score while comparing it with the original music score image.
5. $NACS_i$: number of wrongly added complete symbols of type i^{th} counted in the score while comparing it with the original music score image.

For the category of complete symbols i the following equation is valid:

$$NECS_i = NTCS_i + NFCS_i + NMCS_i$$

Table 3 shows evaluations of accuracy on the test set respectively of SmartScore, O^{3}MR and SharpEye2, where:

- The **Total** column reports the number of collected/ expected occurrences for each category.
- The **True** column reports the percentage rate for correct symbols
- The **Add** column reports the percentage rate for added symbols
- The **Fault** column reports the percentage rate for incorrect symbols
- The **Miss** column reports the percentage rate for missed symbols

The table shows that:

- SmartScore introduces errors in notes reconstruction and adds notes. It detects tuplets, but the main tendency is to make mistakes. It has difficulty with slurs, time signature change and key signatures.
- SharpEye 2 does not introduce notes, it has some problems with tuplets. In the grace notes detection, it does not discriminate appoggiatura from acciaccatura, it considers only grace notes as appoggiatura.
- The main limits for O^{3}MR are due to the recognition of slurs, tuplets, grace notes and ornaments symbols. It introduces wrong slurs due to a incorrect decomposition of symbols, whereas it adds less symbols than SmartScore. It obtained the best score in Time Signature, Key Signature and Clef recognition.

Complete Music symbols & Relationships	**Total**	**SmartScore**				**SharpEye2**				**O^{3}MR**			
		% True	% Add	% Fault	% Miss	% True	% Add	% Fault	% Miss	% True	% Add	% Fault	% Miss
Notes' shape with right pitch & duration	1923	95.68	2.44	2.29	2.03	96.67	0.26	1.20	2.13	97.97	0.68	1.46	0.57
Note with right associated accidental	171	88.89	5.26	2.34	8.77	95.32	0.00	0.58	4.09	80.12	2.34	2.92	16.96
Groups of Notes (Number)	446	98.65	0.22	0.22	1.12	96.64	0.00	0.22	3.14	98.21	0.00	0.90	0.90
Rests	192	38.54	8.85	0.00	61.46	81.77	0.00	2.60	15.63	95.31	5.73	0.00	4.69
Time Signature and Time Change	41	31.71	2.44	14.63	53.66	63.41	4.88	4.88	31.71	68.29	0.00	2.44	29.27
Key Signature	74	32.43	0.00	35.14	32.43	90.54	10.81	9.46	0.00	93.24	0.00	6.76	0.00
Markers	117	33.33	13.68	0.00	66.67	70.09	0.85	0.00	29.91	37.61	1.71	0.00	62.39
Grace note	31	0.00	0.00	0.00	100.00	12.90	0.00	67.74	19.35	0.00	0.00	0.00	100.00
Slur, Tie and Bend	440	61.82	9.32	9.77	28.41	82.05	0.00	8.18	9.77	60.23	3.86	19.77	20.00
Augmentation Dots	123	89.43	66.67	0.00	10.57	91.06	11.38	0.00	8.94	80.49	2.44	0.00	19.51
Clefs and Clef change	145	75.17	5.52	0.00	24.83	66.21	3.45	18.62	15.17	96.55	1.38	0.69	2.76
Tuplets	87	34.48	26.44	0.00	65.52	33.33	1.15	9.20	57.47	0.00	0.00	0.00	100.00
Number of measures	275	100.00	2.18	0.00	0.00	99.27	1.45	0.00	0.73	99.64	1.45	0.00	0.36
Number of Staves	74	100.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00

Table 3: Evaluation tables: SmartScore, SharpEye2 and O^{3}MR.

The recognition of notes and rests is the most important requirement that an OMR system has to respect. They are considered the most important music symbols, and their recognition has to be robust and to provide a high performance. Tables show the O^{3}MR capability in recognising notes and rests. In particular, the recognition rate for rests is the highest, with a relative difference of 14.2% with SharpEye2 and 59.56% with SmartScore. Rests, added by O^{3}MR (4.69%), are due to segmentation errors. This is a limit for the actual version of the O^{3}MR system (relative percentage: (OM3R – X) * 100 / OM3R)

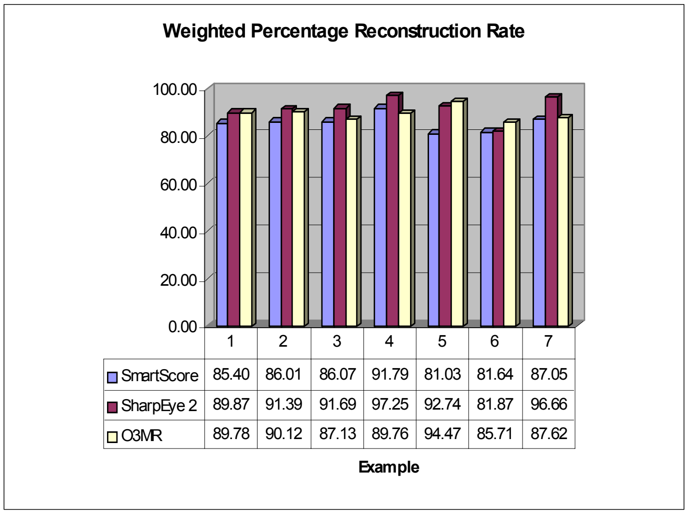
Finally, the graphics reported in Fig.1 shows a global evaluation associated with each example. They represent respectively:

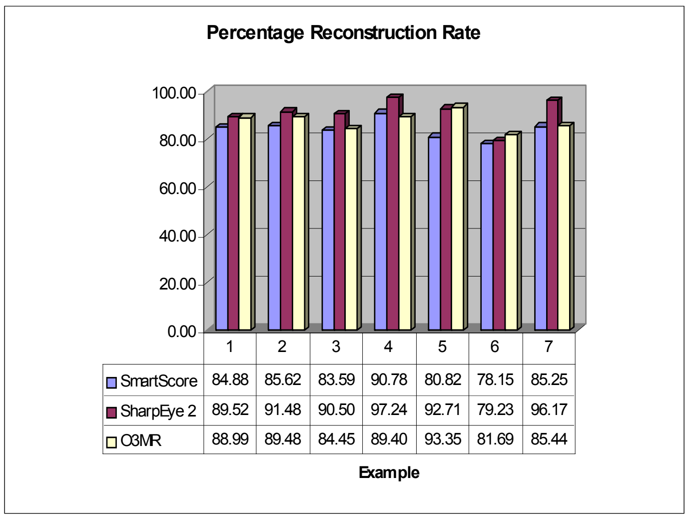
(i) The *Weighted Percentage Reconstruction Rate*: it takes into account weights associated with each music symbol and relationship.

(ii) The *Percentage Reconstruction Rate*: in this case music symbols and relationships have the same relevance.

(iii) The *Percentage Reconstruction Error*: it considers missed, added and fault symbols. For this reason it represents a measure of the work has to be done to correct the reconstructed score.

This evaluation shows that SharpEye provides in general the best performance, whereas the O^3MR is comparable with Smartscore. The O^3MR obtained the best score with the example 5 (93.35%).





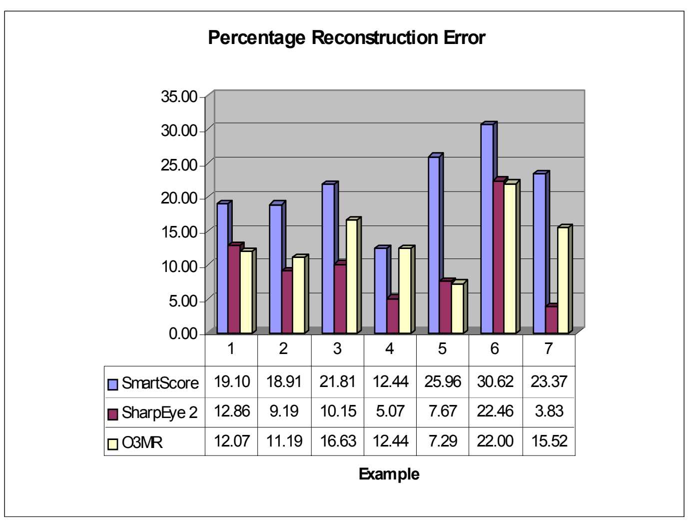


Figure 1: Evaluation of complete music symbols and relationships reconstruction: graphics of performance.

8 Music Image Restoration and Preservation

8.1 Music Image Restoration

Besides recognition and translation into machine-readable symbolic representation, graphical representation of music scores and manuscripts can also be useful for various applications, including digital preservation and cross-media integration. The idea is to digitise, extract and encode the music graphically to preserve the look and feel of the original image from the paper-based input.

This is particularly important for handwritten music manuscripts, since this approach preserves the writing style and enables scalable reconstruction and visualisation. Suitable vector graphics formats include:

- SVG (Scalable Vector Graphics),
- MPEG 4 BIFS,
- Postscript
- Adobe PDF
- Flash
- and others

SVG (for Scalable Vector Graphics) is a standard (a recommendation) of the World Wide Web Consortium. SVG is a language for describing two-dimensional graphics and graphical applications in XML.

Postscript is a language for description of a printed page. Developed by Adobe in 1985, it has become an industry standard for printing and imaging. The PDF (Portable Document Format) is based on Postscript, and on the ability of almost all software on major operating systems such as Windows or MacOS to generate postscript using their widely available Postscript printing device driver.

The Flash format, developed by Macromedia, is mainly based on a vector graphics format, similar in functionalities to the Freehand format of the same vendor. It is a proprietary format, even if the specifications are available.

MPEG BIFS (Binary Format for Scenes Description) makes possible to define so-called ”scenes“ consisting of several audiovisual objects which can be part of complex interactive multimedia scenarios. The individual objects are encoded and transmitted separately in a scene which is then composed after decoding of individual objects. Objects can be simple shapes such as circles, rectangles, text, or media such as AudioClip or MovieTexture, or even scripts.

SVG and BIFS can be considered as something equivalent: SVG is XML-based, while BIFS, even if not XML-based, owns an equivalent in the XMT format which is the XML translation of BIFS. As mentioned earlier, Flash is a proprietary format. Although the specification is publicly available (with some restrictions), it is subject to evolve without notice from the owner (Macromedia). Postscript, even if being page-based, can be a good choice since translation tools are available from Postscript to SVG (Adobe Illustrator), thus to BIFS by the mean of XMT. **However,** Postscript is proprietary, while the SVG standard is absolutely free of patents or royalties, like every W3C standard.

The SVG standard seems to be the best choice, for the following reasons;

- It can generate BIFS (and even Postscript, PDF or even Flash content).
- SVG is an open standard, free of patents and royalties
- Being developed by Adobe, the format is at the level of the state of the art.

For more information about vector graphics formats, please refer to the MUSICNETWORK deliverable 4.3.1, “multimedia standards for music coding”.

Typical enhancements and restorations process include reconstructing broken stave lines and stems, and removing ink spillage and noise (see Figure below). Working at this level allows minor alteration such as this. However, this is not an effective approach for modifications involving larger interconnected features or alteration affecting multiple staffs.

The advantage of optical music restoration is that the processes do not jeopardise the original layout of the scores, which have been optimised by the engravers, and normally represents the ideal visual configurations. Since the original spacing of the music is untouched, there is no large modification and hence it does not require extensive proof reading. However, the process is only concerned with small and local modifications. Larger adjustments, for example insertions or deletions of a group of symbols cannot be fully automated without altering the original layout. No full recognition is necessary for this process and hence it does not provide multimedia functionalities such as playback or search. This process is robust and it can improve the visual qualities of the scores and manuscript for reprinting and archiving.

Example inputs **After processing**

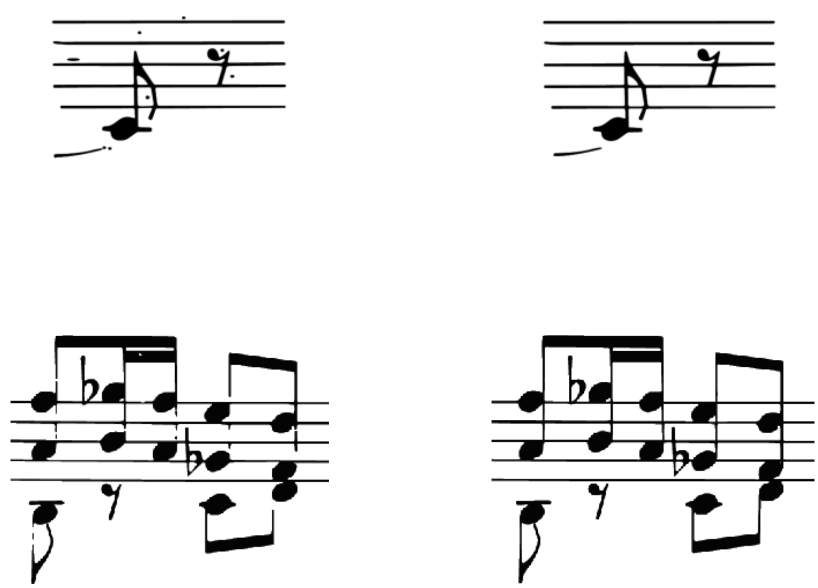


Figure 2: music restoration

8.2 Music Paper Preservation

As mentioned earlier, there are many invaluable paper-based artefacts which represent our cultural heritage and knowledge including music manuscripts. Unfortunately these priceless objects are decaying due to natural processes. There are now various important digitisation projects and important works on digitisation guidelines and standards, such as MINERVA [MINERVA], PULMAN [PULLMAN], AHDS [AHDS], which evaluate and propose national and international guidelines for the digitisation process, capturing the visual aspect of these objects for preservation. However, current general digitisation processes focus on the visual aspects of the surface and rarely capture and analyse the artefacts beyond the surface data.

Paper-based watermark designs are not part of the music, but it is part of the heritage and could be important historically and scholarly for its preservation, together with the music which is printed/written on the surface of the paper. Typically, paper-based watermark design extraction techniques have been using radio-active sources which are time-consuming, expensive and not easy to be used. Recently [Ng *et al*. 2004, Hiary and Ng 2005] has proposed to use a back-lighting technique with automated image segmentation technique to capture and extract paper-based watermark. This project focuses on easy application of back-lighting on typical input with foreground interference (ie foreground writing) and uses multiple inputs to enhance the watermark segmentation.

From the segmented pixels, various image processing techniques are used to analyse the pattern found. The foreground could be processed by an optical music recognition system, an optical character recognition system or other relevant processing. The background, which includes the decolourisation and other stains, could be preserved untouched. This project focuses on the automatic watermark tracing using edge detection and border tracing techniques, converting the segmented bitmap into a graphical description to be stored in a vector format, such as PostScript or SVG.

Figure 3: The top image shows a typical digitisation of a music manuscript, and the bottom image illustrates the hidden watermark design using back-lighting technique.

It is hoped that this kind of techniques will provide an additional level of preservation, providing information that may be important for different purposes. It is believed that digitisation and preservation is an important issue to widen the accessibilities and cultural understanding for the huge amount of knowledge.

9 Applications and Future Directions

With an effective and robust OMR system, it can provide an automated and time-saving input method to transform paper-based music scores into a machine readable representation, for a wide range of music software, in the same way as OCR is useful for text processing applications. Besides direct applications, such as playback, musical analysis, re-printing, editing and digital archiving, OMR would enable efficient translations, for example, to Braille notations [Dancing dots] or other non-western musical notations. It could provide better access and widen participation of music and at the same time introduce new functionalities and capabilities with interactive multimedia technologies and provide digital preservation of this invaluable paper-based cultural heritage.

With graphical reconstruction processes, paper-based music sheets can be digitised with the original visualisation with the capabilities of cross-media integration , extending useful functionalities for usages and applications in edutainment, long term preservation and archiving as well as widening accessibilities and participations.

Typical applications in the field of cross-media (multimedia) integration include the following:

- Association of scores and audio performance, with automatic synchronization.
- Association of scores and video excerpts (showing details on execution)
- Association of scores and other visualisations, such as musical summaries, sonagrams…
- Hyperlinking (adding links to graphic symbols in scores)
- Convergence with audio technologies (remix, spatialisation…)
- Content-based queries, and web-based access to music (query by humming, query by example…)
- Use of the score as a reference point for studies on expressive rendering (comparison of renderings from different performers), and use of score for expressive rendering using audio synthesis software.

"Expressive rendering" refers to the interpretation of a performer of a musical piece which generates musical expression. This process of understanding and interpreting a piece, deriving a performance plan, and expressing it musically, are the main focuses of the performance rendering systems. Association of scores and musical performance can actually be made manually, but in the case of a vector-graphics based score, an automatic process can be envisaged, in the near future for monophonic audio, and in a mid-term future for polyphonic music, with the progress of automatic voice separation. All these applications have direct application in the field of education as well as in the field of music practice.

For more details on cross-media integration, see the MUSICNETWORK deliverable 4.3.2, "multimedia standards for music coding"

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