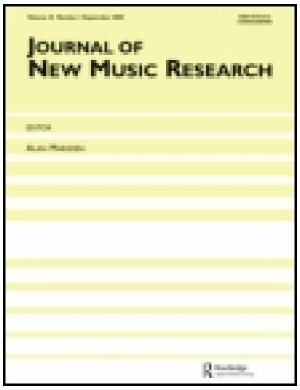

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Preserving Musical Cultural Heritage at MIRAGE

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Abstract

The preservation and restoration of the information contained in musical documents (sounds, scores, images) are very delicate but necessary operations in order to safeguard an immense cultural patrimony from irreversible degradation. The re-recording of audio documents onto digital carriers and their processing on computerized systems require the coordination of several technical-scientific and musicological competences: from the audio signals processing to the chemistry of the carriers, from archive-keeping to the history of electronic music and musical technology. Such a complex professional interdisciplinary training is repaid by the accomplishment of more rapid systems and more sophisticated methodologies of information retrieval and processing. Moreover, the opening of archives and libraries to a wide telecoms community, which is made available through the integration of the Internet web, gives a further impulse to education and cultural development. The choice of establishing a university laboratory for the preservation and processing of musical knowledge and materials is inspired by these strategic aims.

1. Activities

Founded in 1998 at the DAMS: Operatore dei Beni Culturali – Musica e Cinema Degree Course of the University of Udine in Gorizia, the musical informatics laboratory MIRAGE is a centre for the research, production and educational experimentation of musical disciplines. Its interdisciplinary and interuniversity scientific works have national and international importance and are carried out in the various sectors of the application of informatics technology to music:

1) teaching of contemporary music (sound analysis and synthesis, editing and audio production systems, MIDI protocol applications) and of computer-aided composition;
2) preservation and restoration of sound documents;
3) digital processing of musical documents: electronic editing of musical scores; digitalisation of scores; OMR recognition techniques of the musical text; preservation in MIDI formats; multimedia database systems.

2. Teaching and seminars

Laboratory activities are a consistent part of the DAMS: Operatore dei Beni Culturali – Musica e Cinema Degree study course.

Studios seminars, lectures, and lab activities are held by composition teachers and worldwide famous experts in the field: musical acoustics, electroacoustics, digital processing of signals, techniques and instruments for sound analysis and synthesis, sound recording techniques, sound direction in "Live Electronics", architectonic acoustics of theatres and concert halls, history and techniques of electronic music, chemistry of audio carriers, re-recording methodologies, sound restoration techniques and methods. Moreover, MIDI protocol advanced applications, the editing of scores, and computer-aided composition are also lab subjects.

MIRAGE, directed by Angelo Orcalli, also thoroughly investigates the History of Contemporary Music, by organizing specialized conferences and workshops such as:

- XII Colloquium on Musical Informatics (CIM), organized in collaboration with the Associazione Informatica Musicale Italiana (AIMI) and the Faculties of Lettere e Filosofia and of Scienze M.F.N. of the University of Udine in September 1998 [Argentini et al., 1998];
- Computer-aided Composition: *Experimental Compositive Techniques and contemporary aesthetic thought*, held by Marco Stroppa, in September 1999;
- Piano Concert: *A piano itinerary toward contemporary music*, played by Pierre-Laurent Aimard; sound director: Marco Stroppa; music by Liszt, Skrjabin, Boulez, Stroppa; September 1999;

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- The restoration of contemporary sound documents: *The Restoration of Luigi Nono's works*, held by Alvise Vidolin, University of Padua; *The Study of the Phonology of Rai-Milano*, held by Maddalena Novati, RAI Milano, May 1999;
- Theories and Techniques of Sound Direction: *Architectonic Acoustics in theatres and concert halls*, held by Prof. Pompoli, University of Ferrara; *Sound Direction in "Live Electronics"*, held by Alvise Vidolin, University of Padua, September 2000;
- II International Biennial Meeting on Audio Restoration; workshop, September 2000.

3. Preservation and restoration of audio documents

3.1. Introduction

The rapid evolution in sound recording and reproducing technology has developed in only a hundred years from mechanical recording to digital on optical carriers through constant changes of mediums and several audio formats. The even more rapid degradation of the carriers induce archivists to intervene promptly in order to save an immense cultural heritage and to reproduce with historical-philological faithfulness, sound documents which would otherwise be lost, by transferring without errors the information they contain onto more stable carriers.

Archival needs are matched by an increasing interest on the part of the public for historical performances and past documents. The high quality of audio carriers such as the compact disc or the DAT and the *perfection* reached in audio recordings have increased expectations on sound quality and have determined progressive changes in auditive sensitivity. The desire for high fidelity and the longing for historical performances are united in the sought-after possibilities of digital sound processing. The ideal to transcend the limits of a historically faithful reproduction in order to reconstruct the "true sound of an artist" seems a near objective, even if its accomplishment can be hypothesized only in an asymptotic sense.

New fields of research are necessary in the restoration sector owing to the existence of a remarkable patrimony of pieces of electronic music. Conceived and made on magnetic tapes with concrete materials or synthesis sounds, electronic pieces do not really offer the traditional aid of confronting scores and executions and the restoration work on the timbral texture acts directly on the formal structure.

All this is only a representative outline of the problems involved in the preservation and restoration of sound documents. Yet, although it clearly has a specificity of its own, audio restoration can be inserted into the more general issues which are common to all types of restoration work and which can be summarized by the question already posed by art historians: whether restoration is a moment of pure preservation of the works which have come down from the past or whether it should rather be oriented toward their "adaptation" to the new uses and tastes of an ever-growing public, to the diverse cultural policies adopted and to the new social contexts. We have to understand if and to what extent we can remove ourselves from the habits of perception and sensitivity, which are inevitably different from those of the original. These aspects interweave on a technical and historical-critical level, and indicate new works within which multiple competences converge: those of music, acoustics, computer science, and archiving.

3.2. Preservative re-recording: the historically faithful reproduction

After the imperative to safeguard the musical culture heritage contained in sound documents and after the obsolescence of the carriers, it consequently follows that it is necessary to individuate re-recording protocols coherent with the ethics of a *reproduction historically faithful* to the audio content. At the moment, the indications given by the international archive community prescribe that preservative re-recordings be done directly from original sources. These operations must then be backed up by operations aimed at obtaining a quality signal close to the one originally recorded or to the one that could have ideally been recorded if the conditions of recording moment and of the technology available at the time were at their best. The compensations of the intentional signal alterations (such as, for example, equalization or noise reduction techniques available at the time of the original recording) and of unintentional alterations due to errors deriving from an imperfect calibration of the devices used are operations normally accepted by the international archive community.

Within this methodological framework, signal alterations and reproduction of defects are characterized on the basis of the technical data relative to the recording equipment and the carriers. If the information retrieved from the signal and/or the carrier is not exhaustive, the aid of historical and musicological knowledge becomes essential. Moreover, the praxis of making a historically faithful copy by reading the original with equipment which has been up-dated to the current professional standards is accepted in order to avoid further distortions in the re-recording phase.

Although in carrying out these operations we also use knowledge which is *external* to the recording and the historical and technical knowledge of the document is called into question, this type of information is partly retrievable from the history of audio technology and/or experimentally inferable with a certain margin of correctness. This restoration work can, therefore, be carried out with a good degree of "objectivity" and thus represents an optimal level within which to define the standard for an archive preservative copy.

3.3. Restoration work for access copies

Within the archive field, more caution is instead needed to compensate for unintentional alterations of the recorded signal, to clean the signal from disturbances that even the best technology of the time would have introduced (see, for instance, the degrees of non-linear distortion or the noise/signal relations which are no longer acceptable according to current standards).

In this methodological asset interest lies in the realization of other copies which can eventually be accessed for study purposes and on which we can test signal processing systems dedicated to audio restoration and carry out operations aimed at improving the quality of the signal without however producing real artistic remakes. The signal processing algorithms dedicated to noise reduction are not neutral; they derive from a modelling of the sound among the many possibilities and thus bring about that certain degree of relativism which burdens the restorer with further responsibilities.

3.4. Research activity

The research is aimed at:

a) defining preservation and re-recording protocols founded on the characteristics of the various types of audio documents;
b) individuating a restoration methodology guided both by "objective" knowledge inferred from the signal analysis and by external knowledge obtained through a historical-critical investigation on the evolution of recording techniques and on all the information produced by a musicological analysis.

The following fields are developed:

- history of recording and reproducing techniques;
- evolution of equalization techniques and of noise-reduction systems in analog technology;
- preservation and restoration of the carriers;
- analysis of the formats and of the characteristics of the audio document;
- analysis of the signal;
- creation of environment software for the comparison of audio restoration systems.

In collaboration with the CSC of the University of Padova, the MIRAGE laboratory is engaged in the experimentation of signal processing algorithms which are created purposely for the electronic music restoration.

In 2000 the laboratory concluded an interuniversity project called "The Preservation and Philological Restoration of Audio Documents of Bruno Maderna" [Canazza et al., 2000].

3.5. Description of the project

The preservation and restoration work of the magnetic tapes containing Bruno Maderna's compositions falls within the project for a critical edition of his works. The project is co-financed by the Ministry for the University and Scientific and Technological Research (MURST) and is achieved thanks to a collaboration between the universities of Udine, Bologna and Trento.

3.6. Objectives of the project

a) Preservation and restoration of the purely electronic pieces composed by Maderna at the Studio di Fonologia della RAI in Milan.
b) Preservation and restoration of the recordings of instrumental pieces directed by the author and belonging to the Bologna archive.

The project considers two representative subgroups of Maderna's production and musical experimentation: the first subgroup is made up of two tapes of electronic pieces whose saving – essential to the survival of the pieces – involves an audio restoration field which is quite unexplored and analytically complex owing to the nature of the electronic materials and their timbral structure. The second subgroup has a particular historical relevance since it offers both the recording of the works and a witness of Maderna's directing technique.

3.7. Methodological criteria for preservative re-recording: archive copies

With a re-recording operation for preservative aims we intend to transfer all the information content presents in the original historical carriers onto new (optical or magnetic) carriers in order to safeguard it form obsolescence and guarantee, thanks to digital coding, the fidelity of future copies.

In producing the preservative copy, our methodology is inspired by the ethical criteria of a historically faithful reproduction of the document: the objective is to preserve the audio content of the original recording as it has come down to us. For this aim:

1) the re-recording is extracted from the original carrier;
2) if necessary, the carrier is cleaned and restored in order to repair the chemical degradations that can put at risk the quality of the signal;
3) the reproducing instruments are chosen among current professional instruments, while readings with equipment of the time are avoided in order not to introduce further distortions during the re-recording phase;
4) intentional alterations are compensated for through a correct equalization of the reproducing system and the de-codifying of possible intentional noise reduction operations.

The re-recording of the electronic pieces has been carried out at the RAI laboratories in Milan by the technicians of the Audio Laboratory in collaboration with the technicians of the University of Udine according to the above-described criteria and in conformity with the procedures co-ordinated by the responsible of the University of Udine research group, Angello Orcalli, and the artistic consultant of the project, Alvise Vidolin.

3.8. Restoration: the access copies – methodological criteria

We come to a different concept of the level of a historically faithful reproduction when, to the above-mentioned compensation operations for the preservative copy, we add further removal operations of unintentional alterations produced by an incorrect use of the recording and reproducing mediums or by technical defects present in the equipment used. The objective is to create an access copy for study purposes.

The restoration work we have carried out is inspired by the following concept: to give back to the recording a sound quality considered optimal according to the standard procedures of the time, without transcending the technological level historically reached by the Studio di Fonologia. What we wanted to reproduce, therefore, is a copy restored according to a degree of audio quality technologically comparable with that which could have been realized by using the equipment and techniques of the time in ideal ways and conditions.

This methodology aims at preserving the results of the creative process which are specific to the electro-acoustic assembling technology of the fifties, such as the tape junctions (provided that they are carried out well) and the mixing and editing procedures. It follows that the characterization of the degradations cannot derive only from the analysis of the digitalised signal, but also implies some *external* knowledge which includes musicological notions and, more precisely, the history of electronic composing techniques and the history of audio recording and reproducing systems.

The collaboration with the RAI technicians in Milan has also been useful under this aspect, since it offered both an exchange of experiences relative to the procedures and operational techniques of analog systems which derive from the history of the RAI laboratories, and a knowledge of the technical data and the procedures used in Fonologia at the time of the recordings.

3.9. Comparison of the editions on tape of the electronic pieces coming from other archives

With the intent of offering a basic contribution for future formal analyses of Maderna's pieces, we have carried out an accurate comparison between the RAI originals and the various recordings on tape which belong to the archives of Casa Suvini Zerboni and of Centro Tempo Reale, and to the Maderna Archive in Bologna (for completeness' sake, the analysis was also extended to the editions present on the market). In the first place, the comparison has allowed us to differentiate the numerous versions of the piece *Dimensioni II – Invenzioni su una voce*; from the analysis of the other works meaningful deformities among the existing recordings have emerged. Examples are: in the edition of *Notturno* published together with n.3 of "Electronica" of 1956, and in the recording owned by the Casa Suvini Zerboni there is a short sound of which there is no trace in the RAI original; a segment of 2.5 seconds on the tape of *Syntaxis* of the Casa Suvini Zerboni presents material which in the RAI original is reduced and inversely cut with the effect of turning over the trace.

3.10. Characterization of the defects starting from the signal and comparisons of restoration algorithms

Today digital processing allows us to distinguish two classes of signal degradations: global disturbances and local disturbances. The first class includes:

1) broad-band noise;
2) frequency modulations introduced by the fluctuations of the speed of the recording and reading devices;
3) amplitude distortions generated during the recording phase;
4) the presence of external stationary signals, introduced by a bad system isolation;
5) the print-through effect;
6) the degradation of tape magnetization induced by external agents.

In the second class there are impulsive noises generated by electrical disturbances, by low-frequency transient noise caused by alterations and deformations of the carrier, and by dropout.

Signal processing algorithms dedicated to the noise reduction and the improvement of the quality of the signal derive from a hypothesis on the nature of sound in relation to the signal and imply a modelling of the sound; they thus reflect that degree of relativism which pervades all research founded on the construction of models. This epistemological consciousness, together with the specificity of the electronic materials that have to be treated, has induced us to compare various models as a function of their effectiveness from a perceptive point of view.

In collaboration with the CSC of the University of Padova we have carried out a series of experiments with the aim of obtaining:

1) a definition of the criteria of qualitative comparison for audio restoration;
2) a comparison between the various algorithms of audio restoration on the basis of the criteria established. We were able to evaluate the differences among the various approaches used by broadband noise suppression algorithms.

The method followed to define the evaluation criteria was elaborated starting from the perceptive experiments described in the protocols of the International Communication Union for the determination of the digital audio signal quality [ITU-R BS.1116 and ITU-R BS.708]. In this way it was possible to highlight the most important acoustic parameters from a perceptive point of view.

Thanks to the results of the perceptive experiment, we selected the algorithms which gave the best results in perceptive tests. We, therefore, proceeded to the phase of investigating and developing these algorithms. We also applied the traditional Short Time Spectral Attenuation (STSA) methods in relation to the psycho-acoustic modelling of the signal.

The results obtained from the perceptive experiment of qualitative comparison between the various audio restoration algorithms and the consequent analysis of the best restoration methodologies which came out also suggested to investigate more deeply the study of innovative algorithms which operate in the time-domain, based on the Extended Kalman Filter (EKF) theory. This filtering method is potentially able to restore simultaneously disturbances of a local nature (impulsive type) and those of a global nature (broadband noise).

From the perceptive experiments carried out and from the objective comparisons made, it follows that the methods frequently used are more robust and of a more general valence. We have therefore used the NoNoise system of the Sonic Solution, which implements a refined method of spectral subtraction. The technique used can be seen as a discrete approximation of the Wiener filter in the frequency domain. We hypothesize that we know an estimate of the noise power spectral density. The method consists in analysing the corrupted signal through a filter bank, weighing the various spectral components in relation to the noise estimate made. The re-synthesized signal is the result of a subtraction made on every frequency component between the corrupted signal and the power spectral density estimate.

3.11. Restoration work on electronic pieces

For each piece a time-frequency analysis was carried out in order to individuate in *objective*, as well as perceptive, terms the sound materials of Maderna's compositions and highlight their morphological characteristics. In compliance with our theoretical line, we carried out the following operations on the re-recordings of Maderna's electronic pieces:

1) Reduction of broadband noise:
in order to restore a Signal-Noise Ratio (SNR) close to the values considered optimal in Phonology at the time of the recording, we reduced the broadband noise by exploiting the spectral subtraction algorithm available on the Sonic System (which MIRAGE is equipped with). In compliance with the methodology previously exposed we chose a noise print and a setting of the NoNoise parameters apt to attack a noise level which is not far from that produced by the normal aging of the tapes; on the contrary, the incremental relations between the noise print which stratified diversely owing to recording and editing operations on analog tape typical of the technology of time were left unaltered. We did not therefore intervene on the noise level discontinuities present at times in many pieces, and we also respected the sudden sound variations audible in certain junction points of the tape (see, for example, *Notturno* or *Continuo*).

2) Survey and removal of impulsive disturbances:
they are local disturbances which appear with a quite varied morphology, isolated or not. They are caused by micro-degradations of the carrier, or by an imprecise tape junction, or still by unintentional signal alterations introduced during the recording phase (micro-impulses of an electric and electrostatic nature). In the case of electronic music their removal cannot be carried out with an automatic procedure, since the usual detecting algorithms (included in Sonic System) are not able to distinguish the involuntary impulses from those conceived by the composer and recorded on purpose as an integral part of the composition.

The impulsive disturbances were thus surveyed and examined for an inspection of the signal through both listening and direct observation of the waveform. Their removal was carried out thanks to interpolation algorithms (available on the Sonic System) chosen on the basis of the morphology of the disturbances surveyed.

3) Removal of stationary signals introduced by parasite currents:
the frequency analysis of the electronic pieces revealed the presence in all of the recordings of a 50 Hz signal with harmonic components, of low intensity, probably due to a not sufficiently shielded circuit current. It is therefore an involuntary signal, produced by the recording instruments, whose reduction belongs to the typology of operations contemplated in our theoretical premises; therefore the NoNoise parameters for the reduction of this disturbance were set in the process of background noise removal (point 1).

3.12. The recordings of the Maderna's Archive in Bologna: methodological criteria for restoration

The tapes of the Bologna archive are copies coming from various radios and many of them present a poor audio quality. This can be attributed to the recording conditions of the original copy, to the duplication methods and probably even to an use of the tapes on non-professional equipment. For the recordings of the Bologna archive we therefore adopted an intervention strategy which is completely different from the preceding one: to characterize the degradations only by starting from the signal and to exploit to the highest degree the potentialities of intervention of the Sonic System in order to make access copies in which both intentional and unintentional alterations were compensated for. We cleaned the signal from disturbances that were introduced by the technology and praxis used as much as possible and, where possible, we reduced the degradations due to natural decay and to the abuse of the tapes. In live recordings, we left the hall and scene noises whose removal would have meant a complete remaking: an inappropriate operation in the case of copies for study purposes rather than for the record market.

4. Digital processing of musical documents

In the field of multimedia database systems and in the sector of score recognition techniques, the MIRAGE laboratory collaborates with the Department of Mathematics and Computer Science of the University of Udine at the realization of "An innovative system for representing and analysing heterogeneous music documents with public access retrieval functionalities through automatic recognition and indexing" (ARMIDA) [Argentini et al., 2000]. Two research groups work at this interdisciplinary project, which is co-financed by the Region Friuli-Venezia Giulia. The researchers working in the first group, namely Gian Luca Foresti, Marco Frailis and Claudio Mirolo, are developing a system for automatic recognition of printed scores. The people working in the second group, i.e., Carlo Combi, Angelo Montanari and Adriano Peron, are engaged in the design of a database system for music documents, which can be used in remote way and which integrates the acquisition of musical documents and audio sources (in numerical formats), restoring them if necessary.

4.1. Automatic recognition of printed scores

The Optical Music Recognition (OMR) has as its purpose the digitalisation of music scores, usually paper documents, with a minimum of human intervention, thus reducing the time of operations which, if done manually, would be long, repetitive and costly. Furthermore, the digital information can be manipulated more easily both syntactically and semantically. However, the main problem we still face is that the systems available are not fairly reliable. In order to increase their reliability, it is necessary to improve the recognition of the optical image and to use musical knowledge to check and recover them from possible errors. After a brief sketch of a few optical music recognition techniques, we will address a set of crucial OMR problems and outline some proposals in order to solve them. Finally, a few preliminary results will be presented.

The focus of this work is to find new ways to solve some of the difficulties inherent in the optical acquisition of scores and in their conversion into a format suitable for digital processing and storage. Until now the digital processing of documents has been mainly concerned with the recognition of textual characters (OCR), and only recently the problem of the automatic recognition of music (OMR) has been studied in some depth. The papers published in the last years, however, show few important achievements in the field.

The existing OMR systems are still unsatisfactory, especially in the case of complex (e.g., orchestral) scores. One of the main problems to be solved is the high percentage of errors and lack of systematic information on their occurrences. Also inconsistencies that are easy to detect are not reported; as a consequence, it is very difficult, time-consuming and expensive to correct them manually. Frequent errors are: loss of staves within a brace; notes placed far out of the staff (above or below it) are hard to recognize correctly; signs of chromatic alteration introduced for single notes or measures tend to be read without enough accuracy.

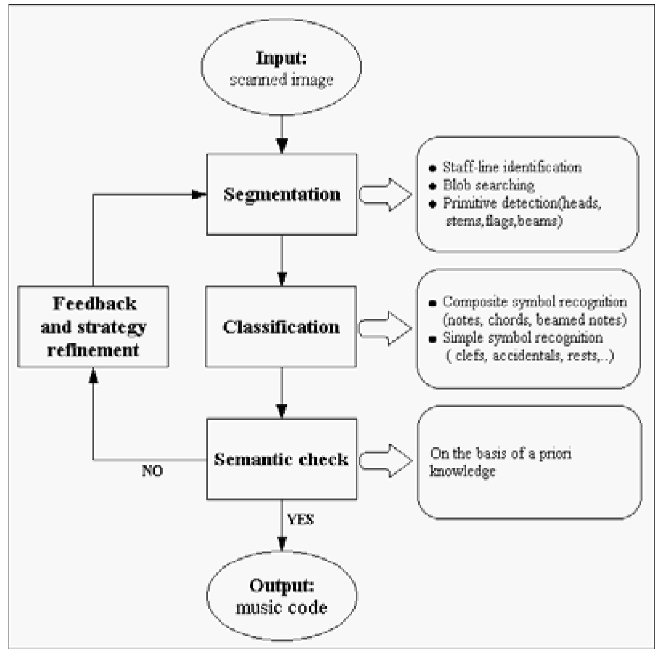

Fig. 1. Main functional modules for the optical recognition of music scores.

From the realization of a reliable OMR system we may expect several benefits, including the development of tools for automatic music transposition and/or production of special-purpose (e.g., Braille) scores, as well as the integration of digital scores within multimedia databases. In order to increase the reliability of the OMR systems we can improve image-processing (segmentation, classification, etc.) by exploiting both standard techniques and innovative techniques such as neural networks and neural trees. Moreover, we should use a-priori knowledge on the document (e.g., music grammar, composition rules, etc.) to check and correct possible inconsistencies.

A consolidated approach to the recognition of a great variety of documents can be decomposed into the following three phases (see also Fig. 1):

1) Image acquisition and pre-processing: the source (paper) document is converted into a digital image by using either a scanner or a camera; then the image is processed by special purpose tools (pre-segmentation).
2) Image segmentation: the elementary components that best represent the content of the document are recognized (musical notes, characters, other graphic symbols). This is a crucial phase in recognition.
3) Classification of the musical notation: the elementary components are processed and classified (e.g., by neural networks). The outcome of this step can then be interpreted at a higher level and any inconsistencies relative to

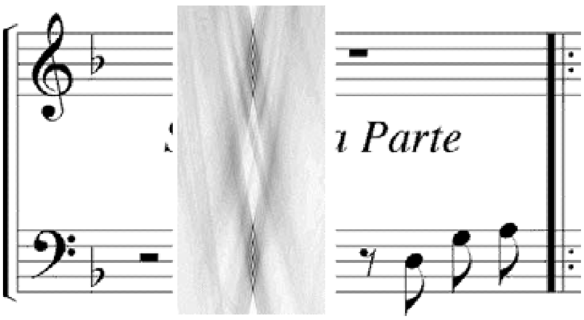

Fig. 2. Staff recognition in the *Hough* space.

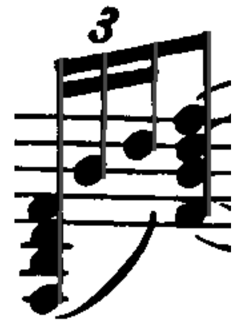

Fig. 3. Stem localization.

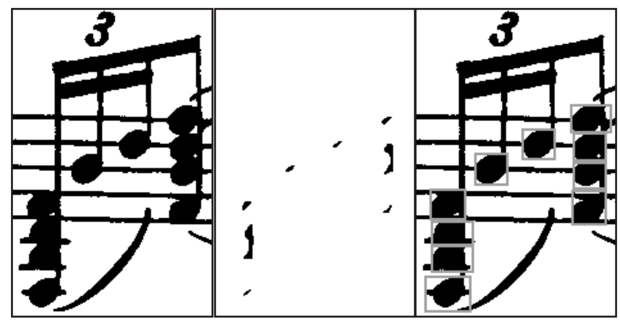

Fig. 4. Head identification.

the available a priori knowledge can be exploited in a feed-back loop in order to improve the results of the previous phases.

The feedback module referred to in the third point above consists of two main components: (i) a *diagnosis unit*, aimed at detecting incorrect symbols or structures based on higher level information on the rules of written music, and (ii) an inventory of *error recovering tools*, each devoted to solve some specific problem. Ideally, this module should be endowed with an extensible database containing the required high level information (music grammar and rules, description of the most frequent sources of error, specific diagnosis and correction techniques).

In our recent work, we have mainly been concerned with the development of segmentation techniques (step 2) and classification techniques (step 3) for a set of significant symbols of the musical notation.

In what follows, we discuss in more detail the main recognition steps and we outline some relevant techniques we have experimented.

1) A vertical scan of the score image allows us to estimate the average width and spacing of the staff lines.
2) We extract the staff lines and localize them in the score image. It is important to know where the staff lines are drawn with high accuracy, since they represent the suitable reference frame for all the information in the score. To this aim, we apply the Hough transform, to each single staff and we can use the result of the previous step in order to detect the coordinates of the five staff lines (see Fig. 2). This kind of approach seems more accurate than others based on projections, on line adjacency graphs, or on Kalman filters.
3) After localizing all the staffs, the staff lines are removed from the image, in order to separate the musical symbols, and most of the subsequent operations are relative to a single staff.
4) The next steps are meant to localize all the vertical lines, namely the note stems and the bar lines. The tools we use to this purpose are the Sobel gradient, to extract the edges of the music objects, and again the Hough transform (see Fig. 3).
5) The heads of the notes are focused and cleaned by means of morphological operations (i.e., erosion, followed by dilation), the structural element being a disk of suitable size (see Fig. 4).
6) The relative positions of the candidate stems and heads are then analysed, on the basis of the rules of music notation, in order to detect inconsistencies.
7) Once the notes have been reconstructed, the bar lines are also processed. In this respect we proceed differently from most standard approaches to reduce the possibility of confusing stems and bar lines, which is a common source of errors.
8) In the following step we search each single bar unit to recognize beamed notes; the notes and the beams are classified with respect to their features and to their relative position in the staff (an example is shown in Fig. 5).
9) Even the symbols which have been recognized in the previous steps, namely, stems, heads, beams and bar lines, are then removed from the score image in order to better isolate the remaining musical objects (see Fig. 6).
10) Finally, the heterogeneous symbols left in the score image are classified by means of specific tools, based on Zernike's moments and neural networks, already exploited for optical character recognition.

As all previous experience shows, this phase of verification of the consistence of the results is unavoidable. In case of inconsistence, the system will have to process again the digital document until a coherent classification is obtained.

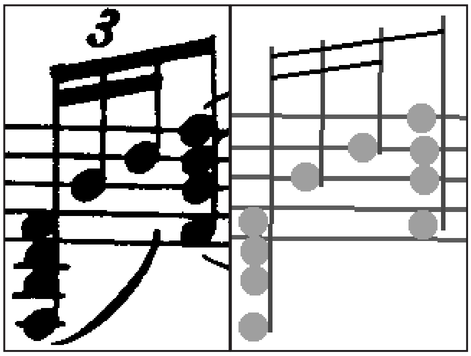

Fig. 5. Beamed notes recognition.

Fig. 6. Removal of notes, beams and bar lines.

This may require some finer tuning of the recognition strategies. At least, the critical areas of the document should be isolated for a localized manual intervention. In order to reprocess a document for error recovering, we have to exploit any a-priori knowledge at the level of the image-processing phase.

In the score image, the staff lines are usually rotated and distorted (curved). The Hough transform allows us to solve the problem of rotated lines, but, as a result, the staff lines are forced to be approximated by straight lines. This may be a serious source of errors in the presence of distortion, since the notes are then referred to a scarcely accurate reference frame. To solve this problem, we compute the Hough transform within image windows whose width is smaller than the whole length of the staff lines and we represent each line by a set of contiguous straight line segments. Different techniques to deal with distortion have also been proposed, e.g., by Bainbridge.

The information obtained through the Hough transform to recognize the stems and the bar lines is less accurate than in the case of staff lines since the vertical lines are shorter; as a consequence, indeed, the maximum in the Hough space are more difficult to detect. To overcome this problem, the Hough transform is applied to the symbol edges, extracted through the Sobel gradient. Moreover, the information that stems and bar lines are perpendicular to the staff lines is taken into account to reduce both the search space (in the Hough space) and the computational costs.

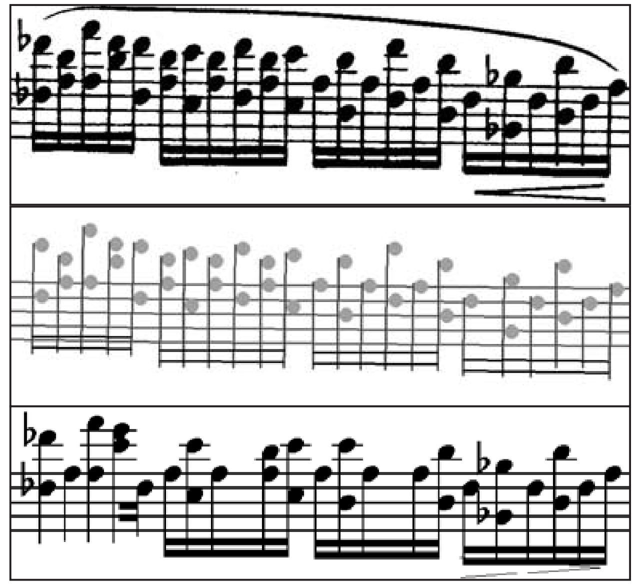

Fig. 7. Sample results. The upper staff is the source image, in the bottom is the output of the commercial product, and in the middle staff is the output of our product.

To give an idea of the state of the art of the system we are developing, in the following figures our results (relative only to the recognition of notes and beam notes) are compared with the results achieved by a commercial OMR application. In figures 7 and 8, the upper staff is the source image and that in the bottom is the output of the commercial product.

4.2. Database of music documents

The main activity related to the database field consists in designing and implementing a multimedia database system allowing the integrated management of textual data, musical scores in an image format or in a symbolic format (e.g., MIDI, NIFF, Enigma or others), and sound documents. The integration among different data types allows the user to navigate among sounds, related texts and musical scores in a simple way. Associations among data are not built-in: when entering data, the user can define associations among data depending on the data content.

In order to model musical information, a temporal multimedia object model is being designed; the research focus in applying this model to music data consists in allowing the management of temporal aspects of (multimedia) data with regard to both "intrinsic" features (e.g., the decomposition of a musical piece in temporally related subparts) and "extrin-

Fig. 8. Sample results. The upper staff is the source image, in the bottom is the output of the commercial product, and in the middle staff is the output of our product.

sic" features (e.g., time-varying data related to a specific music piece, history of comments on a musical execution, . . .).

Another research topics related to multimedia (musical) database deals with non-conventional indexing techniques that will permit the retrieval of documents not only with key words obtained by standard (manual) techniques of classification, but also with multi-dimensional indexes based on non-elementary parameters and musical patterns (such as theme cells, rhythms, harmonic figures etc.) retrieved from the documents with automatic or semi-automatic techniques. The implementation of prototypes, based on the above research topics, is based on the use of advanced object-relational technology (DBII and Oracle database management systems) and object-oriented technology (Java and persistent objects). Further research will focus on the internet-based access to multimedia musical data.

From the database perspective, two main directions are original in the lab activity: the first one is related to the refinement and application of an object-oriented multimedia temporal model in designing music databases. The emphasis in modeling multimedia music data is twofold. The first focus in on allowing the user to logically divide a music score in different subparts, to compose multimedia music documents as sequences of different pieces/executions: in other words, the goal is to define a data model, by which the user is able to compose and navigate among music data. The second focus of the data model is specifically on integrating music data with other related multimedia data, as, for example, audio or text comments on a part of a piece execution, information about the players, the images of the scores of the considered piece for different instruments, and so on. Temporal features of relationships among multimedia data will be extensively studied.

The second research direction deals with the definition and experimentation of index structures/algorithms for music databases, where the retrieval of interesting information must be done on the basis of several features: e.g., rhythm, melody, intensity, related observations describing the author, the piece, the players and so on. A similar situation arises in music database also when there is the need of retrieving scores containing some specific parts (or similar ones). Indexing techniques for multidimensional databases have been extensively studied in the literature but they have to be suited and tested for the special application domain of musical data.

5. Conferences and collaborations

MIRAGE organized two international workshops on audio restoration. The first one was held in September 1998 within the *XII Colloquium on Musical Informatics*; the Chairman of the session was Dietrich Schüller, from the Phonogrammarchiv in Vienna.

The *II Biennial International Meeting on Audio Restoration* took place on September 30, 2000. Among its participants there were the most important researchers on digital restoration systems (Andrzej Czyzewski – Technical University of Gdansk, Simon Godsill – University of Cambridge, Gianni De Poli and Gian Antonio Mian – University of Padova) and on the ethical and technical aspects of the re-recording and archiving of sound documents (Marc Leman – Ghent University, Drago Kunej – Slovenian Academy of Sciences and Arts, Maia Caral Sotgiu – Discoteca di Stato, Alvise Vidolin – CSC University of Padua, Nadja Wallaszkovits – Phonogrammarchiv of Vienna, Angelo Orcalli – University of Udine).

MIRAGE has also stipulated conventions and started relationships with both Italian and foreign private and public bodies, in particular with: Mediateche RAI – Radiotelevisione Italiana, Rome; the State Record Library, Rome; the Academy of the Sciences, Vienna; Centro di Sonologia Computazionale, University of Padova; Phonogrammarchiv, Vienna. It also collaborates with public bodies and institutions for the preservation and restoration of sound archives of historical-artistic and ethno-musicological interest.

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