The Methodology of Automated Decoding of Znamenny Chants

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Abstract. The paper considers problems of applying information technology to the processing of ancient music manuscripts. We propose to use automated component methodology, which applies machine translation methods and allows decoding Znamenny Chants into a linear notation. The present work describes basic stages of the methodology. In order to implement the methodology steps, the work develops and describes an automated system of research studies - "Computer Semiography". The system consists of a module of the chants' input into the database, review of the manuscripts in electronic form, formation of a linguistic model of ancient musical chants, translation models, and decoding of the chants. Music editor module allows users to play the resulting melodies, while input of chants and translation rules makes it possible for users to conduct researches without a reference to a particular manuscript. As a result, these web services have been developed to assist researchers, historians and musicians to process a wide variety of musical manuscripts written in Znamenny notation.

Keywords: musical information technologies, decoding automatization, statistical machine translation, linguistic model, semiography, ancient manuscripts, visualization of Znamenny chants

1 Introduction

The modern system of linear notation of musical compositions provides us with a method to describe the pitch and duration of notes with high accuracy. However, in the XVII century, before the acceptance of this system, in ancient Russia there was a widespread distribution of another method of tunes recording - "Znamenny notation". In this method, melody was recorded with the use of semiographic special characters - "znams" (Fig.1).

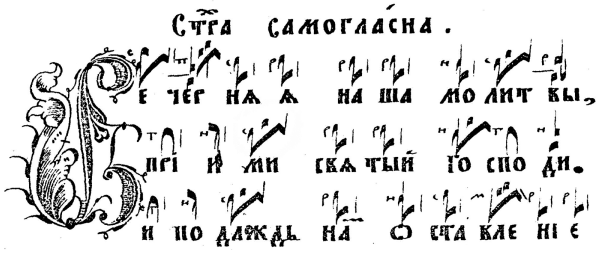

Fig. 1. Fragment of a znamenny manuscript

Musical manuscripts of the XVII century can be transferred to the modern notation. There were special books at the turn of the transition to the new records system– alphabets and dvoyeznamenniks, which contained translation rules for certain znams and chants in two notations (znamenny and linear) correspondingly. Unfortunately, earlier manuscripts (XI-XVI centuries) do not contain special tips and the currently developed tips cannot be fully applied to them. To offer a variant of translation of such manuscripts, it is necessary to conduct thorough researches of the development of the Znamenny chant system. Complexity of the translation is caused by a significant amount of factors – not only lack of sufficient alphabets, but also existence of special structures in chants (popevka, fita and others), which represent sequences of znams with special interpretation. They can be decoded only by means of special "instructions" (kokiznik, fitnik, etc.), like phraseological units in a language.

Many famous scientists dealt with the study of Znamenny Chants. In the XVIII-XX centuries D. V. Razumovsky (1818-1889) [1], S. V. Smolensky (1848-1909) [2], M. V. Brazhnikov (1902-1973) [3] and other researchers worked on drawing up specialized alphabets and the description of rules of znamenny chants' execution. Some scientists were engaged in collecting the remained musical manuscripts. Research of the znamenny chants is still a pressing question. Modern scientists pay great attention to it: B. G. Smolyakov [4], B. P. Kutuzov [5], E.G. Meshcherina [6], G. A. Pozhidayeva [7] and scientific schools (projects), e.g. "Fund of znamenny chants" [8], "Dyache oko" [9], and others [10]. Some researches are conducted with assistance of grants from scientific funds in Russia (RGNF and others).

As a part of “Computer semiography” project [11], since 2000, scientists have worked on solving problems of Znamenny Chants visualization [12]. They have also conducted statistical researches [13], and investigated a possibility of development of znams’ automated recognizer [14], aspects of musical semiotics, and a structure of musical language [15, 16]. In 2011-2013 the researches were supported by RGNF Grant No. 110412025v "The automated system of scientific researches in the field of a computer semiography (ASNI KS)".

Now researchers in the field of musical medieval studies tend to use modern information technologies for accumulation of remote sources, their

systematization and automation of routine operations. However, these practices are heterogeneous, demand generalization and development. This defines relevance of the general component technique development of the Znamenny Chants transfer into a linear notation. This would allow tracking transformation of the manuscript from image to a melody, and combining the accumulated knowledge of the studied manuscripts.

One of the most important requirements to a technique is a possibility of the stage-by-stage and autonomous solution of separate tasks: the translation of manuscripts in electronic form, drawing up electronic dictionaries, playing of chants in Znamenny and musical notations.

2 General scheme of the technique

The proposed methodology of the automated decoding of Znamenny Chants includes some components (stages), which can be realized both consecutively and selectively, depending on the input data and research purposes. The technique is schematically presented in Fig. 2, and below are its main stages:

1. Selection of basic data. Decoding of chants can be made depending on the chosen chants.
2. Transfer of manuscripts into electronic form. Scanning and input of chants, processing and saving of the information in the databases.
3. Development and setting up of the translated dictionary. Choice of structuring methods and sources for creation of decoding rules; carrying out necessary researches.
4. Transformation (decoding) of the manuscript by means of the dictionary.
5. Preparation of the manuscript, materials and results of research for electronic representation and playing in the web environment.

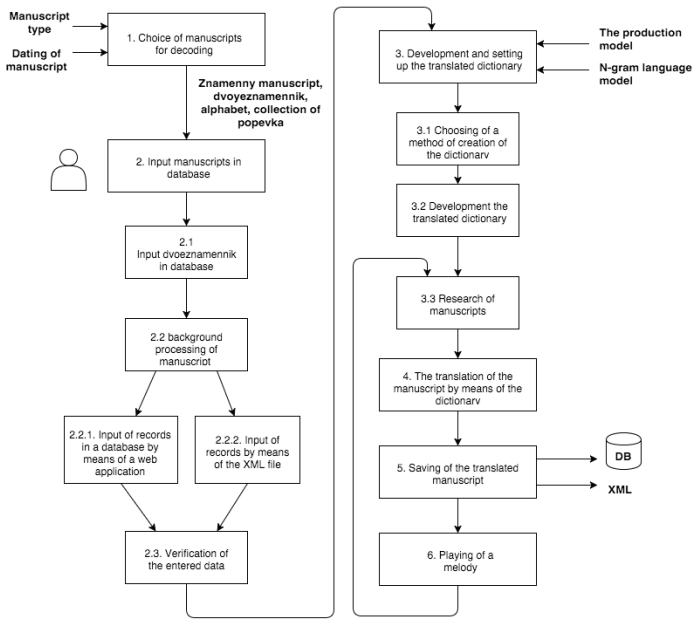

Fig. 2. The flowchart of the automated Znamenny Chants decoding technique

3 Selection of the source data

At this stage, it is necessary to define musical manuscripts and reference materials, by means of which it will be possible to form translated dictionaries. Ancient musical manuscripts are diverse, thus we need different materials to evaluate and decode them. In simplified form, musical manuscripts with Znamenny notation can be divided into the following groups:

A – alphabets (manuscripts, where certain znams correspond to certain notes (one or several))
D – dvoyeznamennik (manuscripts with chants in two notations: znamenny and linear)
K – kokiznik and fitnik (manuscripts, which represent a set of popevkas in the Znamenny notation, grouped in chapters with the indication of each popevka's name)
Z – znamenny manuscripts (manuscripts, where chants are presented in the Znamenny notation)
Sb – collections of popevkas (manuscripts, where popevkas are listed in the Znamenny or linear notation)

Choice of the basic data usually depends on availability of sources and possibility to use them for automated processing. In the future, it will be possible to develop recommendations on how to choose certain manuscripts to assess their completeness, reliability, and other parameters. Technically, the problem of manuscripts selection for research (a set of IshRuks) can be described with the following procedureφ_1:

$IshRuks = \varphi_1(Ruks) = \{r_1, r_2, \dots, r_m\}$, where
Ruks – all set of available manuscripts,
r_i – certain manuscripts,
m – number of the chosen initial manuscripts.

In order to test the technique, we have chosen three trustworthy sources, which represent different types of singing manuscripts:

Z: "A Circle of church ancient Znamenny chants in six parts" under D. V. Razumovsky's edition. This manuscript is znamenny, which means that the melody there is written down by means of znams, supplied with pometas. (1367 pages, 6 volumes).

A: Collection "Singing alphabets of Ancient Russia." Shabalin D.S. [18]

Sb: "Collection of popevkas of the Solovki meeting". This manuscript is a collection of the popevkas, which are written down in the Znamenny notation.

Some of them are determined by words. The book is the fullest collection of popevkas, classified by chapters (213 pages).

D: "Irmology" –dvoyeznamenny manuscript, where the melody is presented in two notations: linear and znamenny (68 pages).

4 Technologies for manuscripts transfer into electronic form

Technologies for transferring musical manuscripts into electronic form could be based on widespread approaches. To make chants visual in the web environment, it is possible to scan, process and upload them on a web site in a graphic format or PDF files. However, having a big amount of materials, there will be tasks of creating an effective system of navigation and indexing of graphic files.

Computer fonts. For research purposes, the manuscripts have to be entered in a symbolic form, applicable for machine processing. At early stages of the Computer semiografiy project (in 2000), it was decided to develop special computer fonts, which would allow to set up chants in widespread text editors. Within the following 5-10 years, there were also other znamenny fonts, the main objective of which was visual representation of znamenny manuscripts.

A peculiarity of an AndrewSemio font is its orientation on maximum functionality – convenience of input and the subsequent machine processing. Fonts have undergone some stages of completions, from an experimental version up to elaboration of an ergonomic component. In the final version, similar znams settle down on one letter with a different tracing (normal, **bold**, and *italic*). In the course of the researches, there have also been some replenishments of znams – up to now scientists have revealed and presented fonts of 202 znams.

Online editor of Znamenny Chants (IPSM) [20]. Initially, students entered Znamenny Chants in a text editor of MS Word. However, special editor programs were developed in the process of obtaining statistical data and further expansion of a number of znams. At first, the programs were desktop, and then they became web-oriented (IPSM).

Development of input technologies and updating of fonts required improvements of data formats: in order to store the texts of chants users switched from a simple *.doc format to, at first, Word tables and then to Excel and XML. To realize the search queries or other resource-intensive operations, it was also necessary to develop formats for data storage in Database Management System (DBMS). The editor of Znammeny Chants (IPSM) was developed to increase the efficiency of the input process and to continue analyzing the entered manuscripts. This editor was made in the Python language with the help of Django framework.
All znams in this editor are decoded by sequence of seven figures and grouped according to their tracing similarity. At the first level, six main groups are allocated, and each group has a maximum number of seven subgroups.

A special research was conducted before forming special groups [13, 15, 17, 18]. This research analyzed statistics of occurrence of znams in the previous manuscripts. Figure 3 shows that the occurrence of znams is distributed unevenly, therefore optimization of the web forms (Figure 4) allowed to increase the speed and convenience of the input dramatically.

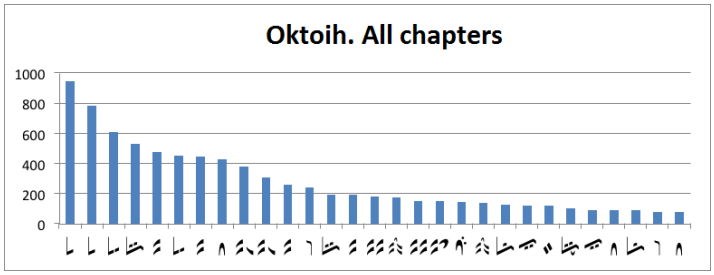

Fig. 3. Statistics of znams occurrence.

The developed application allows entering Znamenny Chants into the database page-by-page. At the same time, the current page of the manuscript is entered in the form of an image in a separate block on the page, where the current line of the chant is largely displayed. If a user needs to upload a dvoyeznamennik, the page will contain a special menu with the keyboard layout, which would allow inputting the notes with the help of Odnoglas font [8].

Apart from the studied manuscripts, users can upload any chants (each record in the database will correspond to one znam) and dictionaries (each record will contain sequence of znams and notes corresponding to it in the database).

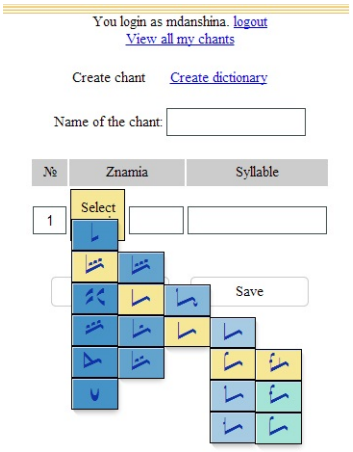

Fig. 4. Scheme example of the application for inputting chants.

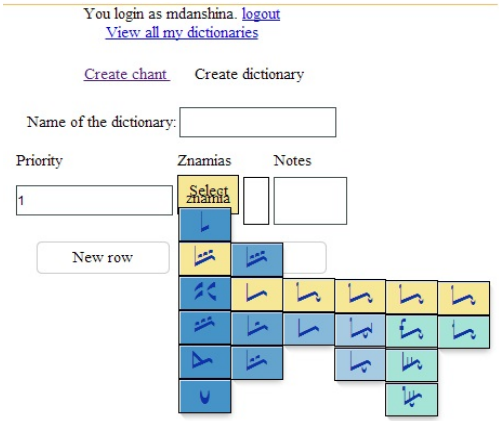

Fig. 5. Scheme example of the application for inputting a translation dictionary.

Checking of the entered records is carried out visually, comparing the initial table with the electronic version. A special module is used to check that the Znammeny Chants have been entered correctly. Based on the previously conducted language module, this module checks probability of occurrence of the entered znams sequences in the Znamenny manuscript [17].

Formally input procedure (φ_2) can be presented as a transfer of the manuscript (r) to the sequence of znams (RZ) :

$$RZ = \{z_1, z_2, \dots, z_m\} = \varphi_2(r), \text{ where}$$

z_i – manuscript znams,

$r \in IshRuks$ - the chosen manuscript,

m – quantity of znams in the r-manuscript.

5 Development and setting up of the translated dictionary

This stage assumes drawing up a dictionary, which would contain rules for the translation of chants from Znamenny notation into a linear one. Several methods can be used to form the dictionary:

- Creation of the dictionary on the basis of popevkas (productive model),
- Creation of the dictionary on the basis of a dvoznamennik (n-gram model),
- Combined method.

Decoding of chants is ambiguous, and all variants of the Znamenny Chants transfer of the XI-XVI centuries are only assumptions. Therefore, it is important for the researcher to receive, analyze and compare the transferred chants by means of various methods.

Formation of the dictionary based on popevkas. In the first case, the dictionary is based on popevkas. Previously prepared collection of popevkas forms a set of rules. Each rule has a translation, based on a dvoznamennik or alphabets.

$$Sl(r) = \varphi_3(RZ, r) = \{p^3\} = \{\langle z_i, z_{i+1}, z_{i+2}\rangle, \langle n_i, n_{i+1}, n_{i+2}\rangle, p\}$$

In order to provide independence of the translation from the initial sound and to check a hypothesis of translation similarity for popevkas in different chapters, it is necessary to keep interval sequence for each popevka in the database. This code is not a designation of a note, but amount of half tones (intervals), based on which the current sound differs from the previous one. Transformation of the musical dictionary into the interval one can be presented as follows:

$$ISl = \varphi_4(SL) = \{\langle z_i, z_{i+1}, z_{i+2}\rangle, \langle Intr_i, Intr_{i+1}, Intr_{i+2}\rangle, p\}$$

During the automatic formation of the dictionary, it is offered to set a rule priority, which would correspond to the quantity of znams in the rule. The reason for this rule is that it is required to use the longest rules first. In the course of the research, an expert can edit values of priorities, changing them to what he considers to be more correct.

Formation of a dictionary based on a dvoznamennik. In the second case, a dictionary is based on a dvoznamennik, which represents a case of parallel chants (written down in two notations). It provides a chance to create N-gram model of the translation. As a result of the dvoyeznamennik analysis, the dictionary becomes similar to the one, which was built on the basis of popevkas, but in this case the dictionary will consist of n-grams (n=1,2,3,4). Probability of such rules can be calculated as a product probability of the included n-grams.

The dimension of n-grams, which equals three, is chosen within the basic functionality of the developed tools. Each trigram corresponds to a set of notes and has a probability of trigram translation by these notes (Figure 6).

Trigrams			Translation			Probability
						0,017327
						0,318182
						0,014851
						0,272727
						0,073529
						0,3125

Fig. 6. Fragment of n-gram model.

The probability of each rule is calculated according to the formation rules of the model translation in statistical machine translation: we calculate the probability of P (n|z) for each pair <n, z>, where z – sequence of znams, and n –translation of this sequence. This probability can be made according to the following formula:

$P(n|z) = \frac{C(n,z)}{C(z)}$ (2), where *C(n,z)* – number of times when the sequence of znams of z is translated by n notes.

The set of trigrams in this case can be presented as follows:

$$TrZ(r) = \varphi_5(RZ,\ r) = \{\langle z_i, z_{i+1}, z_{i+2}\rangle\}, \text{ where } z \in RZ(r)$$

Combined method. This method combines the dictionary, built on the basis of popevka studies, with the dictionary, received by means of statistical machine translation. Users need to set rules priorities so that rules set by the expert would be applied in the first place, followed by rules from popevka, and the rules received from the statistical n-grams translation at the end.

Drawing up of a general SL dictionary can be presented as φ_6 procedure , combining other sl_i dictionaries:

$$SL = \varphi_6(\bigcup_{i=1}^{s} sl_i)$$

Within the research of the manuscript, experts can construct frequent dvoyeznamennik and carry out the analysis of all rules, which include a certain znam. As a result of the research, experts can reveal some patterns and set up new rules, edit or exclude the old ones. Editing is understood as a change of probability or a priority of the rule, as well as a change of the znams and notes included in the rule [19].

6 Transformation (decoding) of the manuscript by means of the dictionary

At this stage of the technique, a manuscript is decoded by means of the dictionary, which was built at the previous stage.

Choosing suitable rules for a trigram:

$$\forall TrZ_i \in TrZ:\ PrTrz = \varphi_7(TrZ, S) = \{Pr_1, Pr_2, \dots, Pr_p\},$$

where p – number of the rules suitable for the translation.

Choosing the best rule from a set of the rules applicable for translation:

$$BestPrTrz(PrTrz) = \varphi_8(PrTrz) = \{\langle z'_i, z'_{i+1}, z'_{i+2}\rangle, \langle n_i, n_{i+1}, n_{i+2}\rangle, p\}$$

The translated manuscript remains in the database or in the file in the .xml format. The set of znams of the initial manuscript will be transformed to a set of notes with the use of the dictionary (one dictionary or a set of dictionaries).

$$Ns = \varphi_9(BestPrTrz, Rz_i) = \{\langle n_1, \dots, n_n\rangle\},$$

Where n – quantity of notes by which znams are transferred to manuscripts.

$$Zv = \varphi_{10}(Ns) = \{< V, D >\} = \{< v_1, \dots, v_n >, < d_1, \dots, d_n >\},$$

where V – pitch, D – duration.

Structure of these chants in the database was influenced by the structure of the singing manuscripts in the first place. Besides the znam (presented by a letter and a tracing style), it is necessary to preserve a syllable, which came across this znam, a pometa, a page of the manuscript, peculiarity of the page arrangement (the first and the last symbol on the line, on the page), etc.

```
▼<ROWDATA>
   <ROW Znam="а" Slog="ко" Stil=" обычный" VPom="м" DPom=""/>
   <ROW Znam="Ар" Slog="кэч" Stil=" обычный Italic" VPom="в" DPom=""/>
   <ROW Znam="а" Slog="но" Stil=" Bold" VPom="п" DPom=""/>
   <ROW Znam="а" Slog="му" Stil=" Bold" VPom="п" DPom=""/>
   <ROW Znam="а" Slog="т" Stil=" Bold" VPom="п" DPom=""/>
   <ROW Znam="а" Slog="от" Stil=" Bold" VPom="п" DPom=""/>
   <ROW Znam="а" Slog="шу" Stil=" Bold" VPom="п" DPom=""/>
   <ROW Znam="а" Slog="ся" Stil=" Italic" VPom="п" DPom=""/>
```

Fig. 7. An example of chants in XML format.

Znamenny Chants translation rules retain a znam code, notes, duration and priority. The algorithm of decoding of the Znamenny Chants is shown in Figure 8.

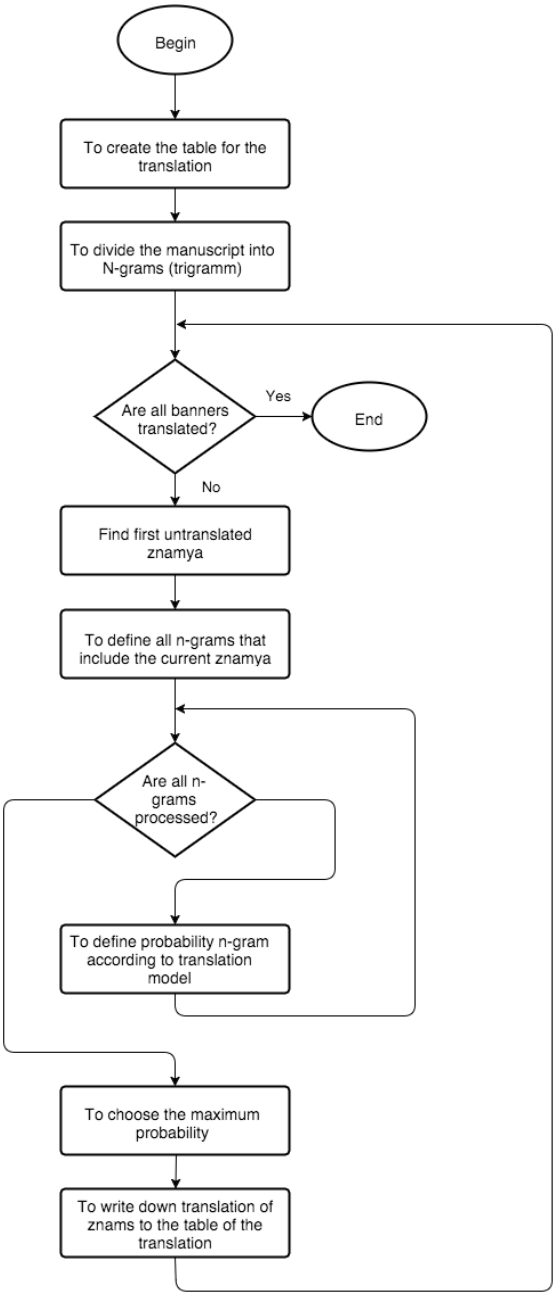

Fig. 8. Algorithm of the Znamenny Chants decoding.

7 Preparation of the research results for electronic representation

At this stage of the present technique, it is possible to play the received chant, which allows analyzing music «by ear», comparing multiple versions of the translation and choosing the best one.

Software components have been realized for automatization of the concluding parts of the technique. These components are functionally combined with the help of «Semio_muz» music player.

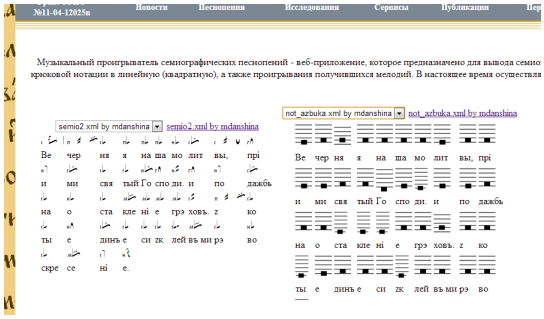

Fig. 9. Example of the translation by a musical editor.

Development of ASNI KS. The Automated system of the scientific researches "Computer semiography" was developed to realize the technique stages. Figure 10 illustrates the block diagram of ASNI. The main modules are: chants inputting, Znamenny Chants decoding, Znammeny Chants researching, and module of chants playing. At the first stage, all chants are entered into the database, after that they are read out by modules of decoding, playing and researching. Translation rules are stored in the database. In the final part of the research, experts can add, edit or delete any rules from the database. Dictionaries and chants, obtained in the process of decoding, are stored in the database.

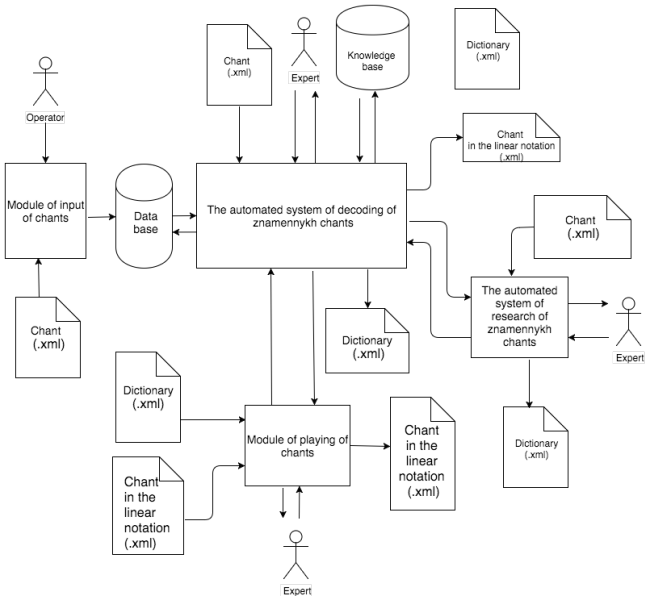

Fig.10. Block diagram of decoding.

8 Evaluation

First of all the developed technique is unique and allows experts to completely avoid manual translation of Znamenny chants. Expert rules from the final translation dictionary are used in combined method of translation.

Comparison of methods:

Method	Translation time per page	Time percent (to manual method)	Capacity factor	Average % of not translated signs
Manual translation	90 min.	100 %	1	25 %
Translation by alphabet	60 min.	66 %	1,5	15 %
Translation by combined method	20 min.	22 %	4,5	2 %

Secondly, the final dictionary is continuously expanded by trigrams from dvoyeznamennik. This way the researchers have an opportunity to get one of the possible translations of the unknown part of the manuscript. The experts can also perform musical analysis and create new rules or correct the existing ones.

We can use methods of hybrid machine translation systems [21] for a quality assessment of our machine translation methods:

1) BLEU score
2) TER (Translation-Error rate)

Thus, it is necessary to develop a specialquality assessment technique for the developed method. We are going to research methods for an assessment of machine translation and create a new method suitable for our system.

Unfortunately, at this moment the database of the Znamenny chants is not as big as we would like. Therefore many metrics are equal to zero due to the lack of some parameters. But some other methods provide good results. The initial manuscript divided in two parts (1/3 and 2/3). The system uses 2/3 of the manuscript for learning and 1/3 for checking. As it is one and same manuscript, the dictionary contains the majority of the discovered trigrams and the translation assessment indicators are very high. This results will be different for other manuscripts.

Also the majority of these metrics are based on comparison of translated texts with the reference (human) translation. We can get such reference translation only from dvoyeznamennik and we use the same manuscript for the training of the dictionary.

9 Work results.

The developed methodology is of great value for researchers, as due to a huge number of sources (manuscripts, and theoretical manuals), it is rather difficult to systematize and work them out carefully. It is caused, as a rule, by the fact that it is necessary to analyze and carry out quantitative estimates of some indicators manually. Information technology is not involved in this case effectively. The developed set of services is intended to simplify the most time-consuming operations, which researchers-medievalists face. As a result, researchers spend less time on checking and calculating any data.

The offered decoding methodology of the Znamenny Chants allows producing three main components required for the Znamenny Chants decoding: a dictionary with the transfer rules from znams to notes, a version of the translated manuscript into the linear notation, language model and model of Znamenny Chants translation. Transfer of chants into electronic format makes them more available.

This work has developed software, which allows inputting Znamenny Chants into the database, edit them, and look through them. We have realized the language construction and translation modules that allow transferring Znamenny Chants into a linear notation. The program is also able to build dvoeznamenny frequency dictionaries and indexes of znams.

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