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A Shortest Path Approach for Staff Line Detection

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Abstract

Many music works produced in the past still exist only as original manuscripts or as photocopies. Preserving them entails their digitalization and consequent accessibility in a digital format easy-to-manage. The manual process to carry out this task is very time consuming and error prone. Optical music recognition (OMR) is a form of structured document image analysis where music symbols are isolated and identified so that the music can be conveniently processed. While OMR systems perform well on printed scores, current methods for reading handwritten musical scores by computers remain far from ideal. One of the fundamental stages of this process is the staff line detection. In this paper a new method for the automatic detection of music staff lines based on a shortest path approach is presented. Lines with some curvature, discontinuities, and inclination are robustly detected. The proposed algorithm behaves favourably when compared experimentally with well-established algorithms.

1. Introduction

The impact of music in our lives can hardly be overestimated. Music is a pivotal part of our cultural heritage and its preservation, in all of its forms, must be pursued. Frequently, the preservation of many music works entails the digitalization of these works and consequent accessibility in a format that encourages browsing, analysis and retrieval. In fact, many music works produced during the last centuries still exist only as original manuscripts or as photocopies. The digitalization of these works is therefore a highly desirable goal. Unfortunately, the ambitious goal of providing generalized access to handwritten scores that

were never published has been severely hampered by the actual state-of-the-art of handwritten music recognition. The manual process required to recognize handwritten musical symbols in scores and to put them in relationship with the spine structure is very time consuming.

Despite the fact that OMR systems dealing with machine printed scores exhibit good performance, handwritten music recognition introduces several additional difficulties. Outstanding problems include notation varying from writer to writer, and possibly varying in the same score: symbols and staff lines written with different sizes, shapes or intensity. Despite the continued research on OMR, with the availability of several commercial OMR systems, we are still lacking a satisfactory performance in terms of precision and reliability. Most of the existing work provides a real efficiency only when quite regular, printed music sheets are processed. This condition is exacerbated with handwritten music scores. This justifies the research around the definition of reliable OMR algorithms.

Staff line detection is one of the fundamental stages of the OMR process, with subsequent processes relying heavily on its performance. The reasons for detecting and removing the staff lines lie on the need to isolate the musical symbols for a more efficient and correct detection of each symbol presented on the score.

The detection of staves is complicated by a variety of reasons. The handwritten staff lines are rarely straight and horizontal, and are not parallel to each other. For example, some staves may be tilted one way or another on the same page or they may be curved. This is especially true for handwritten scores. Since these scores tend to be rather irregular and determined by a person's own writing style, the staff lines might be twisted, being curved and not really horizontal at all. It depends on how regular the author writes the symbols in his scores. There might also be big-

ger or smaller gaps along a staff line. And if we consider that most of these works are old, the quality of the paper in which it is written might have degraded throughout the years, making it a lot harder to correctly identify its contents.

In this paper a method for the automatic detection of staff lines based on a shortest path approach is presented. The proposed paradigm uses the image as a graph, where the staff lines result as the shortest path between the two margins of the image.

This introduction is concluded with a brief review of the work done in this area. In section 2 the proposed algorithm is described. In section 3, the proposed algorithm is experimentally evaluated using real music scores. Finally, conclusions are drawn and future work is outlined in section 4.

1.1. Related Works

Different methods for staff line detection have been researched. The simplest approach consists on finding local maxima in the horizontal projection of the black pixels of the image [2]. These local maxima represent line positions. This method assumes straight and horizontal lines. Several horizontal projections can be made with different image rotation angles, keeping the image in which the local maxima are bigger. This eliminates the assumption that the lines are always horizontal. An alternative strategy for identifying staff lines is to use vertical scan lines [3, 7, 8, 13]. More recent works present a more or less sophisticated use of a combination of projection techniques to improve on the basic approach [1].

Fujinaga [5] incorporates a set of image processing techniques in the algorithm, including run-length coding (RLC), connected-component analysis, and projections. After applying the RLC to find the thickness of staff lines and the space between the staff lines, any vertical black runs that are more than twice the staff line height are removed from the original. Then, the connected components are scanned in order to eliminate any component whose width is less than the staffspace height. After a global deskewing, taller components, such as slurs and dynamic wedges are removed.

Other techniques for finding stave lines include the application of mathematical morphology algorithms [11, 15, 6], rule-based classification of thin horizontal line segments [10], and line tracing [12, 14].

In spite of the variety of methods available, they all suffer from some limitations. In particular, lines with some curvature or discontinuities are inadequately resolved. The dash detector [9] is one of few works that try to handle discontinuities. The dash detector is an algorithm that searches the image, pixel by pixel, finding black pixel regions that it classifies as stains or dashes. Then, it tries to unite the dashes to construct lines.

2. A Shortest Path Approach for Staff Line Detection

A staff line can be considered as a path from the left side of the music score to the right side. As staff lines are almost the only extensive black objects on the music score, the path we are looking for is the shortest path between the two margins **if** paths (almost) entirely through black pixels are favoured.

In the work to be detailed, the image grid is considered as a graph with pixels as nodes and edges connecting neighbouring pixels. Therefore, some graph concepts are in order.

2.1. Definitions and Notation

A *graph* $G = (V, A)$ is composed of two sets V and A . V is the set of nodes, and A the set of arcs (p, q) , $p, q \in V$. The graph is *weighted* if a weight $w(p, q)$ is associated to each arc, and it is called a *digraph* if the arcs are directed, i.e., $(p, q) \neq (q, p)$. A path from p_1 to p_n is a list of unique nodes p_1, p_2, \dots, p_n , $(p_i, p_{i+1}) \in A$. The *path cost* is the sum of each arc weight in the path.

In graph theory, the shortest-path problem seeks the shortest path connecting two nodes; efficient algorithms are available to solve this problem, such as the well-known Dijkstra algorithm [4].

2.2. General Framework Description

As mentioned before, a staff line corresponds to a path from (almost) the left margin of the image to (almost) the right side of the image, (almost) always through black pixels.

Starting by modelling the edge image as a graph, match a node to each pixel. Connect two nodes with an arc on the graph iff the corresponding pixels are neighbours (8-connected neighbourhoods) on the image. The weight of each arc is a function of pixels values and pixels relative positions (see Figure 1):

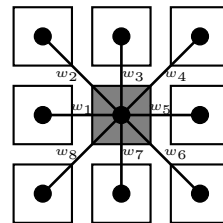


Figure 1. Arc weight between two pixels.

$$w_i = \begin{cases} f(p, q_i) & \text{if } q_i \in \text{4-connected neighbourhood of } p \\ h(p, q_i) & \text{if } q_i \notin \text{4-connected neighbourhood of } p \end{cases}$$

In this work we set $h(\cdot, \cdot) = \sqrt{2}f(\cdot, \cdot)$.

The objective is then to design the weights w_i such that the weights are low for the pixels of interest (black) and high otherwise (this will lead to small weighted distances from left to right for paths through staff lines and large for the rest). Therefore this setting will favour paths through black pixels, as required. We set

$$f(p, q) = \begin{cases} c_1 & \text{if } p \text{ or } q \text{ are black pixels} \\ c_2 & \text{otherwise} \end{cases}$$

with $c_2 > c_1$. In this work c_1 and c_2 were experimentally determined as 2 and 6, respectively. Note that c_1 must be set greater than zero in order to also favour the smallest path, when more than one exists through black pixels only. Finally, the solution to the shortest path problem will yield the intended staff line.

2.3. Illustrative Examples

In order to get a better intuition of the general result, it is instructive to first explore some basic examples. Consider a music score with a single staff line as represented in Figure 2(a). In Figure 2(b) the shortest paths between starting

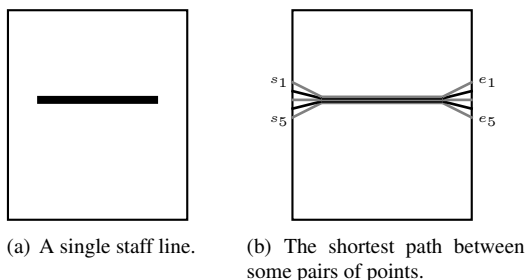


Figure 2. A first exemplificative example.

points s_i on the left margin and ending points e_i on the right margin, at the same row, are traced. All paths get attracted by the staff line. A similar condition is verified when we have more than one staff line (see Figure 3). Now paths get attracted to the nearest staff line. Half of the paths in-between two consecutive staff lines goes along the top staff line; the other half follows the bottom staff line.

The last example, in Figure 4, shows that music symbols placed on top of staff lines do not interfere with the detection of the staff lines. Moreover, the example also makes

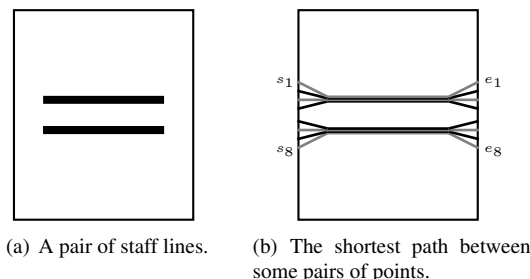


Figure 3. A second exemplificative example.

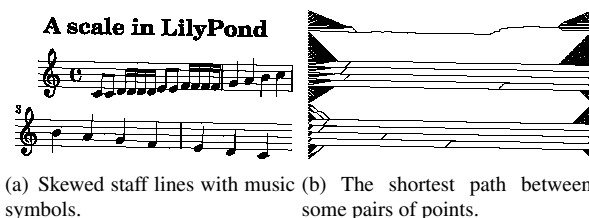


Figure 4. A third exemplificative example.

clear that slight skewed scores do not pose any problem to the proposed approach.

Nonetheless, some issues are visible and need to be conveniently addressed. Due to the skew of the staff lines, some of the shortest paths jump between consecutive staff lines. The text on the top of the score also constitutes a false low weight path between the two margins, inducing some paths to go through it. Finally, even when a staff line is correctly followed by the path, the initial and the final parts of the path should be ignored.

2.4. Proposed Algorithm

To detect the staff lines, the proposed overall algorithm starts by estimating the staffspace height. This length will be used as a reference length for the subsequent operations. Robust estimators of the staffspace height are already in common use. The technique starts by computing the vertical run-lengths representation of the image. If a bit-mapped page of music is converted to vertical run-lengths coding, the most common black-runs represents the staff line height and the most common white-runs represents the staffspace height [5].

After the estimation of the staffspace height, the proposed approach applies the main step of the framework: for each row of the image, the shortest path between the leftmost pixel and the rightmost pixel is found, using the Dijkstra algorithm [4]. Instead of considering the whole image when computing the shortest path,

only a strip centred on the row of interest is used—see Figure 5. This allows to constrain the complexity of the algorithm. On the experiments we have set $\text{STRIP_HEIGHT} = \text{STAFFSPACE_HEIGHT}$.

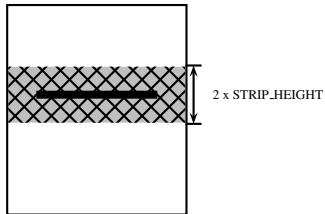


Figure 5. Vertical strip around the row of interest.

Now, because the search for the shortest path is constrained to stay in a vertical strip (or because the nearest staff line is far enough from the current row), the shortest path may not follow a staff line. Therefore, the main step is followed by a sequence of (arguably) sensible rules, aimed at discarding false staff lines. First, all paths without a percentage of black pixels above a threshold BLACK_PERC are discarded (a threshold of $\text{BLACK_PERC} = 0.75$ was used on the experiments).

Next, each retained path is trimmed at the beginning and at the end. As visible in the previous examples (refer to Figure 4), before meeting with a staff line, a path travels through a sequence of white pixels. Likewise, after the end of the staff line, the path goes again through a sequence of white pixels until it meets the right margin of the image. In order to ignore all these white pixels, the initial pixels of the path are discarded until a run of at least BLACK_RUN black pixels are found in the path. In the same way, all pixels of the path after the last occurrence of a run of at least BLACK_RUN black pixels are discarded. A threshold of $\text{BLACK_RUN} = 2 \times \text{STAFFSPACE_HEIGHT}$ was used on the experiments.

Finally, the proposed overall algorithm ends with the validation of the preserved paths. Because the staff lines are expected to be straight lines, the linear correlation coefficient of the x and y components of the pixels of the path is used to reject paths that do not meet the linearity criterion, with a correlation coefficient below a threshold CORR_COEF . The threshold used here is conservative, since for manuscript lines the (perfect) linearity is not guaranteed. This precaution is needed because staves on a page are often distorted in different ways.

2.4.1 Summation

The shortest path approach has some advantages over standard algorithms presented in the literature for the detection of staff lines:

- While almost all current approaches provide only isolated pieces of a staff line, the approach proposed here outputs a complete line, with starting and ending points.
- The staff lines are rarely straight and horizontal, and are not parallel to each other. For example, some staves may be tilted one way or another on the same page or they may be curved. While current approaches apply a chain of heuristics to correct these undesired imperfections, the shortest path algorithm is naturally robust to these challenging conditions.
- The proposed approach is robust to broken staff lines (due to low-quality digitalization or low-quality originals) or staff lines as thin as one pixel. Missing pieces are automatically 'completed' by the algorithm.

For reference, the overall algorithm is summarized in Listing 1 with pseudo-code.

```
StaffLine_Detection(IMAGE, CORRCOEF)
{
    STAFFSPACE_HEIGHT = computeStaffSpaceHeight();
    BLACK_PERC = 0.75;
    BLACK_RUN = STAFFSPACE_HEIGHT;
    STRIP_HEIGHT = STAFFSPACE_HEIGHT;
    for (int row = 0; row < ImageHeight; row++)
    {
        Point2D start(0, row);
        Point2D end(ImageWidth-1, row);
        Path path = findShortestPath(start, end);
        if(blackPercentage(path) < BLACK_PERC)
            continue;
        path = trimPath(path);
        if(corrcoef(path) < CORRCOEF)
            continue;
        addPathToSetOfStaffLines(path);
    }
}
```

Listing 1: Shortest Path StaffLine Detection.

3. Results

We now present additional, complete, examples of the proposed framework for automatic staff lines detection. The code for all the examples in this paper has been written in C++¹. For comparison purposes, the method by Fujinaga [5] was also implemented. Three types of scores were used

¹The source code is available upon request to the authors.

in the experiments: machine printed scores—see Figure 6; handwritten music scores sitting on regular staff lines—see Figure 7 and Figure 8; and irregular handwritten scores—see Figure 9. Before applying the staff line detection algorithms, each image was binarized.

Analysing the results for Fujinaga’s method, we observe that some information is lost, information that could be important for the recognition tasks which follow. The places where musical symbols are present create gaps on the detected staff lines; in some places the gaps are larger than the space occupied by those symbols—see Figure 7(c). This is mainly due to the low quality of the lines. The shortest path approach is able to overcome these conditions because it follows a continuous path connecting both line ends. The robustness of the proposed approach to possible defects in staff lines (curvature, discontinuities) is apparent in the example of Figure 7(c).

Occasionally, the shortest path algorithm retains paths that do not go completely through a staff line. This problem is prone to happen when there’s a large beamed note density—see Figure 9(b)—making it go through the beams for this set of notes (e.g. quavers and semiquavers) or when the curvature of the lines is such that the path jumps between consecutive lines. This condition can be overcome by automatically learning the best threshold on the linearity test of the path for each image being processed, or by the incorporating additional rules to validate the path. Both approaches are currently being investigated. Nevertheless, considering handwritten scores, we can see that the proposed algorithm has good and promising results.

4. Conclusion

The first challenge faced by an OMR system is staff line detection. This first task dictates the possibility of success for the recognition of the music score. And when it comes to handwritten music scores, existing solutions are far from presenting satisfactory results.

In this paper, a new algorithm for the automatic detection of staff lines in music scores was proposed. The shortest path approach for staff line detection algorithm brings a new and promising approach to the staff line detection task. The technique is adaptable to a wide range of image conditions, thanks to its intrinsic robustness to (slightly) skewed images, discontinuities, and curved staff lines.

There are several directions of research to pursue with the framework introduced in this paper. We are currently investigating the computational feasibility of, instead of finding the shortest path between a starting point on the left margin and an ending point on the right margin *at the same row*, finding the shortest path between a starting point on the left margin and the *whole right margin*. That will allow coping with severely skewed scores. Another line of investigation

is the automatic learning of the parameters of the algorithm. Although most of the parameters values are scaled by the staff height space, the threshold for the test of linearity is still manually set. This improvement could make the algorithm work with a wide range of types of scores, without requiring any parameter tuning by the user. Finally, more than just having spatial continuity of the path—enforced by the shortest path algorithm—, we are also pursuing the continuity of the direction of the path. As staff lines do not suffer abrupt changes of direction, even when manually drawn, it seems sensible to impose this additional constraint.

Acknowledgments

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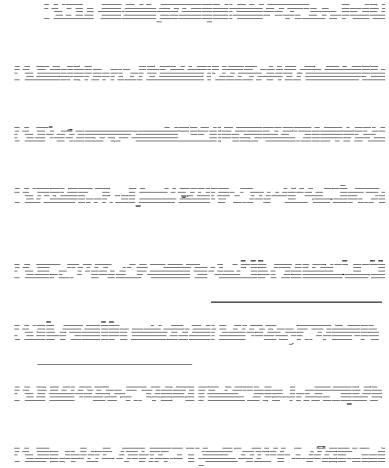
Allegretto



(a) Original score.



(b) Staff lines detected by our algorithm.

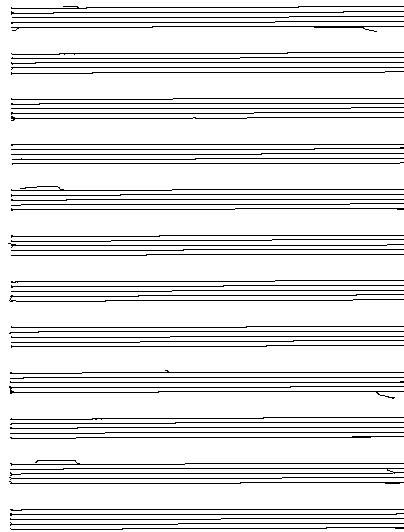


(c) Staff lines detected by Fujinaga's method [5].

Figure 6. Results for a machine-printed score.



(a) Original score.



(b) Staff lines detected by our algorithm.



(c) Staff lines detected by Fujinaga's method [5].

Figure 7. Results for a handwritten score.

[13] T. Reed. Optical music recognition. Master's thesis, Department of Computer Science, University of Calgary, Canada, 1995.

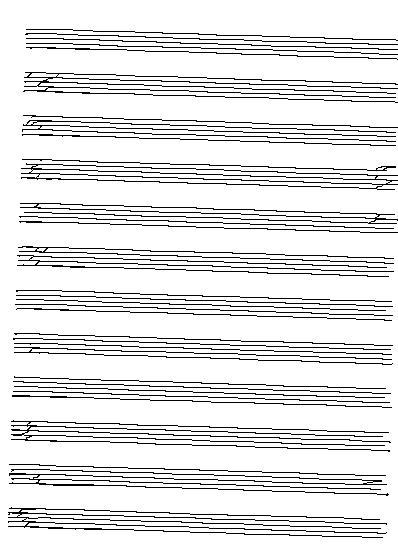
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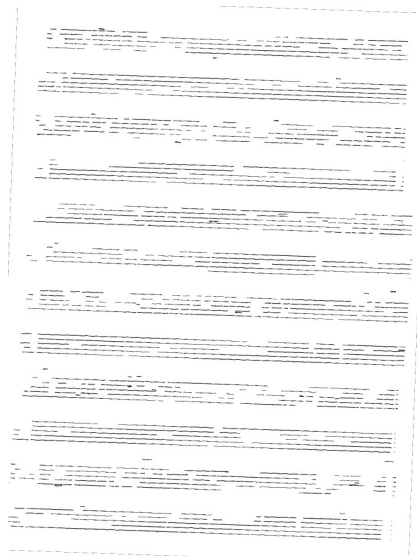
Swiss Federal Institute of Technology, 1992.



(a) Original skewed score.



(b) Staff lines detected by our algorithm.

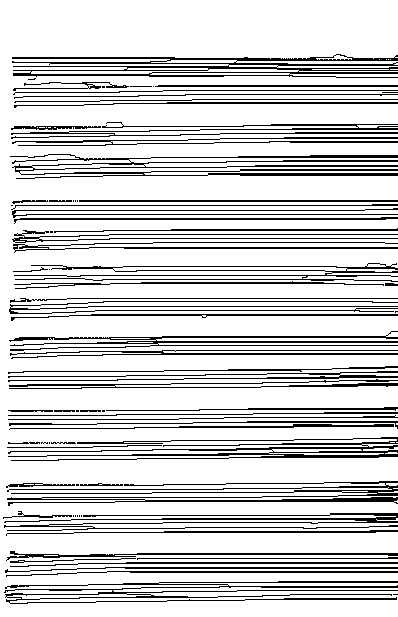


(c) Staff lines detected by Fujinaga's method [5].

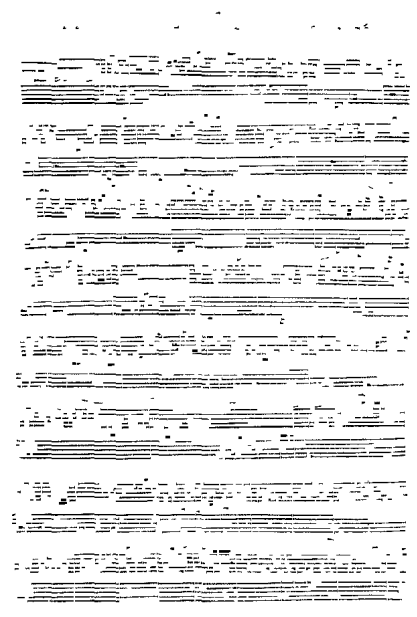
Figure 8. Results for a skewed handwritten score.



(a) Original score.



(b) Staff lines detected by our algorithm.



(c) Staff lines detected by Fujinaga's method [5].

Figure 9. Results for a handwritten score.