4. RESULTS AND COMPARASIONS

4.1 Introduction

The previous chapter describes the methodology of the proposed algorithm. In this chapter we discuss the results obtained by the proposed algorithms. We evaluate and compare the results against six popular algorithms known as ZS Algorithm [Zhang & Suen, 1984], LW Algorithm [Lu & Wang, 1986], WHF algorithm [Wang, Hui & Fleming, 1986], KWK Algorithm [Kwon, Woong & Kaang, 2001], AW Algorithm [Ahmad & Ward, 2002] and KNP Algorithm [Kardos, Nemeth & Palgyi, 2009]. An important measurement is the thinning ratio which is calculated based on the number of skeletal points and object points. Based on the number of skeletal points (discussed in sec. 1.4), one cannot derive conclusions about whether the skeleton suffers with excessive erosions, and whether the skeleton contains redundant points or disconnections. If the obtained skeleton is one pixel wide connected component, then less number of skeletal points indicates a better result. This is not always true because excessive erosions and disconnections which are undesirable, results in less number of skeletal points. Thus judging the quality of the skeleton is subjective rather than objective. But for comparison purpose one needs to evaluate the algorithm performance objectively. Thus the criteria used in evaluating the skeleton quality are thinness measurement, connectivity measurement and sensitivity measurement along with thinning ratio. Apart from this, the
proposed algorithm’s performance in terms of real execution time is evaluated against the above mentioned benchmark algorithms. The following sub-sections explain how one can measure the skeleton quality and algorithm performance.

4.2 Result analysis

The proposed thinning algorithm is tested on variety of digital image patterns consisting of curves, junctions, arcs, loops and lines which are of interest in many recognition applications. The set of images considered for testing involves patterns from alphabets of various international languages like Chinese, Arabic as well as Indic languages like English, Hindi, Telugu, Malayalam, and Bengali. We also tested it on the objects like animals and birds along with finger print images. The same images with different sizes and orientations are also considered.

The algorithm produces promising results with both foreground and background one pixel wide connected skeletons along with the medial axis. But for few patterns, the parts of the skeleton with negligible length are distorted slightly.
The skeleton of the capital English alphabet is superimposed on the input image of size 557x446 as shown in the above figure 4.1. The skeletal points obtained are 3262 against the 41910 object points which results in 92.22% thinning ratio. Thinness of the obtained skeleton is 0.999995 which is almost equal to 1 (indicates one pixel thick). The skeleton is well connected and the algorithm takes relatively less time to obtain the result.
Figure 4.2(a) is an input image of size 531x130, which consists of Telugu text and its output skeleton is shown in figure 4.2(b). The thinning ratio of the obtained skeleton is 58.665 (Skeletal points: 2895, Object points: 7001). The resultant skeleton produced in 124 ms with thinness measurement of 0.99993. The connectivity and sensitivity values are also less than that of the algorithms considered for comparison.
The thinned skeleton superimposed on the input image of small English alphabet of size 374x447 is shown in the figure 4.3. The skeleton is obtained in 161 ms with a thinness measurement of 0.99996. The 24515 object points are reduced to 3582 skeletal points resulting in a thinning ratio of 85.39%.

Figure 4.3 Small English alphabet
Figure 4.4 Handwritten English text

Figure 4.5 Handwritten Telugu text
The proposed algorithm tested with handwritten characters of English and Telugu texts and the skeletons obtained along with the input images are as shown in figures 4.4 and 4.5 respectively. The 386x97 size English handwritten text image results in a thinning ratio of 67.82 with 1172 skeletal points against 3642 object points. The Telugu handwritten text image is thinned to 1553 skeletal points whose input image is of size 402x137 with a total of 4655 object points. The thinning ratio for Telugu text is 66.60. The actual execution times for English and Telugu texts are 125 ms and 140 ms respectively.

Results obtained for both printed and handwritten text images of sizes 199x52 and 374x113 by the proposed algorithm are shown in figures 4.6 and 4.7 respectively. The number of skeletal points, object points, thinness, and thinning ratio along with the time taken to produce the output skeletons for theses figures are summarized in the following table 4.1.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Printed Text</th>
<th>Handwritten Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object Points</td>
<td>1911</td>
<td>4939</td>
</tr>
<tr>
<td>Skeletal points</td>
<td>892</td>
<td>1640</td>
</tr>
<tr>
<td>Thinning Ratio</td>
<td>53.32</td>
<td>66.79</td>
</tr>
<tr>
<td>Thinness</td>
<td>0.99968</td>
<td>0.99991</td>
</tr>
<tr>
<td>Execution Time</td>
<td>172 ms</td>
<td>109 ms</td>
</tr>
</tbody>
</table>

Table 4.1 Evaluation results for Hindi printed and Handwritten Text shown in figures 4.6(a) and 4.7(a)
The proposed algorithm applied on both printed and hand-written characters of almost all Indic languages and observed that the skeletons obtained are quite acceptable. The following figures 4.8 through 4.10 shows the skeletons obtained for Tamil Text, Malayalam vowels and Bengali
characters respectively. All the resultant skeletons are well connected and thinness measurement is more than 0.99995.

![Original Image](image1.png) ![Thinned Image](image2.png)

Figure 4.8 Printed Tamil text

![Input Image](image3.png) ![Thinned Image](image4.png)

(a) Input Image

![Thinned Image](image5.png)

(b) Thinned Image

Figure 4.9 Malayalam Vowels
The proposed algorithm tested on numerical digits from 0 to 9 and the obtained skeletons are one pixel thick and also preserved the topological and geometrical properties. This is illustrated in the following figure 4.11. To illustrate that the proposed algorithm results in connected one pixel wide skeletons, we converted the skeleton superimposed on the input image of binary digit 4 into 1s (representing skeletal points) and 0s (object points) as shown in figure 4.12.
Figure 4.11 Numeral digits

Figure 4.12 Binary digit ‘4’ (superimposed)
The figure print shown in figure 4.13(a) is thinned by the proposed thinning algorithm and the traditional (morphological) thinning operator to verify consistency and stability of the thinning algorithm. Thinning result obtained by the proposed algorithm shown in figure 4.13(b) is preserving all ridges and furrows in the thinned patterns; whereas the results obtained by the traditional thinning operator is not preserving all ridges and furrows as shown in figure 4.13(c). As a result, the performance of the fingerprint recognition will be low for the images thinned by Morphological operator. As we all know the ridges and furrows play an important role in the fingerprint recognition, which are preserved by the proposed approach shown in figure 4.13(b) as a result the performance of the recognition will be more.
(b) Result by proposed approach

(c) Result by morphological operator

Figure 4.13 Results comparison for fingerprint image
It is evident in the figure 4.13 that the proposed algorithm gives better thinning performance for thinning finger prints when compared with morphological operator. Important cues where the proposed algorithm successfully captures are marked with circles.

![Rabbit Image thinned and superimposed](image)

Figure 4.14 Rabbit Image thinned and superimposed

This proposed algorithm is not only limited to thin the digital patterns of characters of various languages, but also equally thins shapes of different objects in the real world. This is illustrated in the figure 4.14. By observing the skeletons, one can easily derive that the results are one pixel wide and doesn’t result in any excessive erosions.

### 4.3 Evaluating Skeleton Quality of Proposed Algorithm

The following sub-sections explain how one can judge the quality of the skeletons obtained by the thinning algorithms by computing the thinning ratio, thinness, connectivity and sensitivity measurements.
Figure 4.15 Thinning results for duck image
The figure 4.15 shows the skeleton superimposed on the input image by various algorithms. Various comparisons are depicted in figure 4.18 to 4.22. Except AW, KNP and Proposed algorithms, all other (ZS, LW, WHF and KWK) algorithms are not preserving topology where in the two legs are joined as shown in figure 4.15. AW algorithm erases one finger of the right leg of the duck which is undesirable. The KNP algorithm produces the fingers correctly however the second line of the tail of the duck is missing. Another problem with the KNP is as the size of the image is reduced shown in figure 4.16 and it also erased the 2nd finger of the duck. This is illustrated in figure 4.17(b).

Figure 4.16 Thinning results for duck image of size 213x183 (12,900)
However the proposed algorithm produced the same skeleton irrespective of the size of the duck image as shown in figures 4.17(a) and 4.17(c). Thus the skeletal points produced by the proposed algorithm are
much higher than that of all other algorithms. This is due to preserving the
topological properties and minimizing the excessive erosions. The execution
time of the algorithm is much lesser than that of all other algorithms.

The thinning ratio, thinness, connectivity, sensitivity and execution
time are evaluated for the skeletons obtained by the proposed and
benchmark algorithms for duck image shown in figure 4.15. These are
discussed in the following sub-sections 4.3.1 through 4.4.2. The
corresponding comparison charts are depicted in figures 4.18 – 4.22.

4.3.1 Thinning Ratio

Thinning ratio specifies the degree to which the input image is
thinned. Larger thinning ratio indicates high degree of thinning. It can be
measured based on the following formula referred from [Luping, Zhang,
Liffeng and Xiaorong, 2007].

\[
\text{Thinning Ratio (TR)} = (1 - \frac{T_1}{T_0}) \times 100 \%
\]

Where, \(T_1\) = the number of pixels in the thinned image.

\(T_0\) = the number of pixels in the original image.

The comparisons of the thinning ratios of various algorithms are
shown in figure 4.18. The thinning ratios of most of the thinning algorithms
shown above are better than the proposed algorithm. This is due to the fact
that, all other thinning algorithms are not topology preserving and thus results in less number of pixels which is undesirable.

![Thinning Ratio Chart](image)

**Figure 4.18** Comparison chart of thinning ratio

### 4.3.2 Thinness

Another way of measuring thinness is based on triangles counts in the 8-neighborhood of the candidate pixel as referred in [Ng, Zhou and Quek, 1994]. If the skeleton is not one pixel wide, there exists a triangle composed of the three black pixels. Thus the thinness is measured as

\[
TM = 1 - \frac{\sum_{i=0}^{\text{size}} TC(p_i)}{4 \times [\max(\text{width, height}) - 1]^2}
\]

Where \( TC(p_i) = (P_i \times P_8 \times P_1) + (P_i \times P_1 \times P_2) + (P_i \times P_2 \times P_3) + (P_i \times P_3 \times P_4) \)

- \( \text{size} = \text{width} \times \text{height} \)
- + and \( \times \) are arithmetic addition and multiplication
If the thinness is nearly equal to 1, it indicates a better skeleton. The thinness of the proposed algorithm is compared with other thinning algorithms and it is found that the thinness is better than the other thinning algorithms as shown in figure 4.19.

![Comparison chart of thinness](image)

**Figure 4.19 Comparison chart of thinness**

### 4.3.3 Connectivity

The endpoints and discrete points are fixed and should be the same for the original input image and the skeleton obtained. If either the endpoints and/or the discrete points are more for the obtained skeleton, compared to its input image indicates more disconnections. Thus as referred in [Ng, Zhou and Quek, 1994], the connectivity is measured by using the following formula:
\[ CM = \sum_{i=0}^{size} s(p_i) \]

\[ S(P_i) = \begin{cases} 1 & \text{if } BP < 2 \\ 0 & \text{otherwise} \end{cases} \]

Lesser connectivity value indicates better skeleton. The connectivity of the proposed algorithm is lesser than that of all other algorithms except LW (which is not preserving the topology) as shown in figure 4.20.

![Connectivity Chart](image)

Figure 4.20 Comparison chart of connectivity

### 4.3.4 Sensitivity

Images usually contain noise as perturbations in the outline of the object. It is hard to differentiate these noisy pixels with actual pixels of the image. These small noise dots cause deformation, offshoots, and tabs. This can be measured by counting the number of cross points. Fewer cross
points indicates higher noise sensitivity. Sensitivity of the resultant skeleton measured as referred in [Ng, Zhou and Quek, 1994].

\[ S(M) = \sum_{i=0}^{\text{size}} S(P_i) \]

\[ S(P_i) = \begin{cases} 
1 & \text{if } |AP| > 2 \\ 
0 & \text{otherwise} 
\end{cases} \]

Smaller sensitivity values indicate better skeletons. The sensitivity of the thinning algorithm compared with benchmark algorithms is shown in figure 4.21. The smaller sensitivity values indicate better skeletons.

![Sensitivity](image)

Figure 4.21 Comparison chart of sensitivity

### 4.4 Evaluating time complexity of proposed algorithm

The time complexity of an algorithm quantifies the amount of time taken by an algorithm to thin the input image. Thinning time can be
computed either asymptotically or by recording the time by really executing the program on a computer.

4.4.1 Asymptotic time

The proposed algorithm processes the pixels layer by layer until the desired skeleton produced and cannot be thinned further. Thus the asymptotic time complexity of the proposed algorithm is $O(MN)$, where $MxN$ is the size of the input image.

4.4.2 Execution time

This is the actual time taken by executing the program on a computer. Here thinning times are recorded on a laptop with Intel core2 Duo (C2D) processor T6400 (@ 2.00GHz, 2.00 GHz), 4GB RAM loaded with 64-bit windows 7 operating system. Time is recorded initially before the thinning process starts and then after the thinning is completed. The difference between these two times is considered as execution time. This time depends on factors like current load at the time of execution and thus we consider executing the same program five times and the average time is considered as execution time. The execution time requirement is illustrated in figure 4.22.
4.5 Results comparison

The results obtained by the proposed thinning algorithm applied on different Indic languages and the handwritten digit 7 are evaluated against ZS, LW, WHF, KWK, AW and KNP algorithms in the following sub-sections 4.5.1 and 4.5.2. The evaluation done against six parameters out of which five parameters are thinning ratio, thinness, connectivity, sensitivity and the number of skeletal points obtained are related to judge the skeleton quality where as the execution time related to algorithm performance. Each of the evaluation criteria is compared among all the benchmark algorithms along with proposed algorithm independently and presented in the form of comparison charts.
4.5.1 Indic language characters

The figure 4.2 shows the skeletons obtained by the proposed as well as other benchmark algorithms for an input image which consists of words from different Indic languages. The comparison of the evaluation criteria are presented as graphs in the figure 4.24.

(a) Input Image

(b) ZS Algorithm

(c) LW Algorithm

(d) WHF Algorithm
Figure 4.23 Thinning results for the image consist of different indic language characters 594X113 (9183)
The input image is of size 594x113 with 9183 object points. The number of skeletal points obtained (3075) by proposed algorithm is same as that of KNP algorithm and better than that of all other algorithms. Thus the thinning ratio which depends on skeletal points count is same as that of KNP algorithm but is more than that of all other algorithms. The thinness of the skeleton produced by proposed algorithm (0.99998) is higher than all
others and thus indicates the thinner skeleton. Connectivity and sensitivity values are also lesser than that of all others. The most important property of the proposed algorithm is efficiency in terms of its execution time (78 ms). This execution time is much lower than the popular algorithms like KNP algorithm (94 ms), but higher than AW algorithm (62 ms). However, it is suffering with excessive erosion and connectivity like limitations. But the proposed algorithm produces better skeletons than AW algorithm.

4.5.2 Handwritten numeral digit

The handwritten image of digit 7 whose skeleton is superimposed on the original image is shown in figure 4.25 and the result comparisons are depicted in the table 4.2. The results show that the performance of the proposed algorithm is better than that of all other benchmark algorithms. But only KNP algorithm is almost nearest to the proposed algorithm. By considering collectively all the parameters, proposed algorithm is superior to all other algorithms.
Figure 4.25 Thinning results for the handwritten image digit 7
Proposed algorithm has been tested against different images with varying sizes and orientations. The set of images considered for testing are of different shapes varying from language characters, birds, animals to finger print images. For most of the images it produces better skeletons with lesser number of skeletal points. In all output images it is observed that the width of the skeleton is invariably one pixel. It preserves the topological and geometrical properties better than the popular algorithms like AW and KNP algorithms. The algorithm out performs all other algorithms for most of the image patterns. The proposed algorithm produces skeletons in less amount of time compared to all other algorithms in our experiments.

### Table 4.2 The result comparisons of figure 4.25

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ZS</th>
<th>LW</th>
<th>WHF</th>
<th>KWK</th>
<th>AW</th>
<th>KNP</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object Points</td>
<td>1490</td>
<td>1490</td>
<td>1490</td>
<td>1490</td>
<td>1490</td>
<td>1490</td>
<td>1490</td>
</tr>
<tr>
<td>Skeletal Points</td>
<td>191</td>
<td>204</td>
<td>199</td>
<td>188</td>
<td>193</td>
<td>187</td>
<td>188</td>
</tr>
<tr>
<td>Thinning Ratio</td>
<td>87.18</td>
<td>86.30</td>
<td>86.64</td>
<td>87.38</td>
<td>87.04</td>
<td>87.44</td>
<td>87.38</td>
</tr>
<tr>
<td>Thinness</td>
<td>0.9997</td>
<td>0.9995</td>
<td>0.9997</td>
<td>0.9998</td>
<td>0.9998</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Execution Time</td>
<td>0.015</td>
<td>0.02</td>
<td>0.16</td>
<td>0.14</td>
<td>0.04</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>Connectivity</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

### 4.6 Summary

Proposed algorithm has been tested against different images with varying sizes and orientations. The set of images considered for testing are of different shapes varying from language characters, birds, animals to finger print images. For most of the images it produces better skeletons with lesser number of skeletal points. In all output images it is observed that the width of the skeleton is invariably one pixel. It preserves the topological and geometrical properties better than the popular algorithms like AW and KNP algorithms. The algorithm out performs all other algorithms for most of the image patterns. The proposed algorithm produces skeletons in less amount of time compared to all other algorithms in our experiments.