Variation of Boyer-Moore String Matching Algorithm: A Comparative Analysis

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Abstract- **String matching plays an important role in field of Computer Science and there are many algorithm of String matching, the important aspect is that which algorithm is to be used in which condition. BM(Boyer-Moore) algorithm is standard benchmark of string matching algorithm so here we explain the BM(Boyer-Moore) algorithm and then explain its improvement as BMH (Boyer-Moore-Horspool), BMHS (Boyer-Moore-Horspool-Sundays), BMHS2 (Boyer-Moore-Horspool-Sundays 2), improved BMHS(improved Boyer-Moore-Horspool-Sundays) ,BMI (Boyer-Moore improvement) and CBM (composite Boyer-Moore).And also analyze and compare them using a example and find which one is better in which conditions.**

Keywords-String Matching: BM; BMH; BMHS; BMHS2; improved BMHS; BMI; CBM

I. INTRODUCTION

In computer science, the Boyer-Moore string search algorithm is a particularly efficient string searching algorithm, and it has been the standard benchmark for the practical string search literature.

It was developed by Bob Boyer and J Strother Moore in 1977. The algorithm preprocesses the pattern string that is being searched in text string. [5]

Before BM algorithm was proposed, the direction of character comparison was consistent to the moving direction of the pattern i.e. both are from left to the right. But in BM the direction of character comparison is different from the moving direction of the pattern i.e. from right to left in pattern.[4]

After BM algorithm was proposed there were some algorithms are proposed to improve it. In 1980, Horspool simplified BM algorithm and proposed BMH algorithm Although it only used the information of the table Right, BMH algorithm acquired no bad efficiency. In 1990 Sunday proposed BMHS algorithm that improved the BMH algorithm.[6]

In 2010, Lin quan Xie, Xiao ming liu proposed BMHS2, which is strictly based on the analysis of BMHS algorithm to improve is in the match fails, the text string matches last bit characters to participate in the next match, a character string in the case appear to increase the last bit character and appear in the character string matching the first characters of a position if there is consideration.[3]

In 2010 BMI algorithm is proposed by Jingbo Yuan, Jisen Zheng, Shunli Ding which is improvement of BM algorithm. The BMI algorithm combines with the good-suffix function and the advantages of BMH and BMHS.At the same time the BMI algorithm also takes into account the singleness and combination features of the Next-Character and the Last- Character. [8, 9]

There are two important factors which influence the efficiency and speed of pattern matching and they are the cost to find the mismatching character in the text string and the shift distance to right.On basis of the two factors, an improved algorithm called Improved BMHS algorithm which is given by Yuting Han, Guoai Xu in 2010. [7]

Another improved algorithm called composite Boyer-Moore was proposed in 2010 by Zhengda Xiong. The key issue of the composite Boyer-Moore algorithm is how to utilize the history comparison information achieved at previous iteration. So a new concept of two-dimensional table Jump[*m*][*m*] is introduced.[4]

II. BM ALGORITHM

The BM algorithm scans the characters of the pattern from right to left beginning with the rightmost one and performs the comparisons from right to left. In case of a mismatch (or a complete match of the whole pattern) it uses two pre-computed functions to shift the window to the right. These two shift functions are called the good-suffix shift (also called matching shift and the bad-character shift (also called the occurrence shift).

Assume that a mismatch occurs between the character $P[i] = b$ of the pattern and the character $T[i+j] = a$ of the text during an attempt at position j. Then, $P[i+1 .. m-1] = T[i+j+1 .. j+m-1] = u$ and $P[i] \neq T[i+j]$.The good-suffix shift consists in aligning the segment $T[i+j+1 .. j+m-1] = P[i+1 .. m-1]$ with its rightmost occurrence in P that is preceded by a character different from $P[i]$.

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BM algorithm will carry through shift computing as follow.

(1) good-suffix function

The algorithm looks up string *u* leader character is not *b* in *P* from right to left. If there exist such segment, shift right *P* to get a new attempt window. If there exists no such segment, the shift consists in aligning the longest suffix *v* of *T[i+j+1 .. j+m- 1]* with a matching prefix of *P*.

(2) bad-char function

The bad-character shift consists in aligning the text character *T [i+j]* with its rightmost occurrence in *P [0 ... m-2*].

If *T[i+j]* does not occur in the pattern *P*, no occurrence of *P* in *T* can include *T[i+j]*, and the left end of the window is aligned with the character immediately after *T[i+j]*, namely *T[i+j+1]*

BM algorithm uses good-suffix function and bad-char function to calculate the new comparing position, shifting rightward *P* by taking maximum of these two values. [1]

Practice shows that BM Algorithm is fast in the case of larger alphabet. In preprocessing phase, time and space complexity is *O (m+* ů*)*, where ů is the size of the finite character set relevant with pattern and text. In searching phase time complexity is in *O (mn)*. There are *3n* text character comparisons in the worst case when searching for a non periodic pattern. Under best performance time complexity is *O (n/m)*. Under the worst time complexity is *O (mn)*. [1]

Advantages

- The both good-suffix and bad-char combined provides a good shift value as maximum of two is taken as shift value.

Disadvantages

- The preprocessing of good-suffix is complex to implement and understand.
- Bad-char of mismatch character may give small shift, if mismatch after many matches.

***Example*:** We have a text string ñ*STRINGMATCHINGISTOFINDTHEPATTERN*ò. And a pattern ñ*PATTERN*ò which is to find in a text string, so we apply all above algorithm as discussed below to solve this example. Example of BM is *shown in Table 1.*

TABLE 1.BM Example (5 Shift and 13 Comparisons)

	S	T	R	I	N	G	M	A	T	C	H	I	N	G	I	S	T	O	F	I	N	D	T	H	E	P	A	T	T	E	R	N
1	P	A	T	T	E	R	N																									
2								P	A	T	T	E	R	N																		
3															P	A	T	T	E	R	N											
4																						P	A	T	T	E	R	N				
5																									P	A	T	T	E	R	N	
6																										P	A	T	T	E	R	N

III. IMPROVEMENT OF BM ALGORITHM

A. *BMH Algorithm*

The preprocessing of good suffix is hard to be understood and implemented; BMH algorithm only uses the bad characters shift. In BMH algorithm, no matter the location of mismatching, the distance of shift to right is determined by the character in the text string which is aligned to the last one of pattern string.[7]

In preprocessing phase, time complexity is*O*(*m+ s*). In searching phase, time complexity is *O*(*mn*). In the best performance, time complexity is *O*(*n /m*). Practical applications show that BMH algorithm is much more efficient than BM algorithm. [2] [10]

Example: shown in Table 2.

Advantages

- The concept of Good-suffix is removed so easy to implement.
- In case of mismatch ,the shift value is determined by the bad char value of last character instead of character that caused mismatch so more jump is archived using bad char than in BM.

Disadvantages

- The removal of good-suffix sometime may not give shift as much as in BM.

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TABLE 2.BMH Example (5 Shift and 13 Comparisons)

	S	T	R	I	N	G	M	A	T	C	H	I	N	G	I	S	T	O	F	I	N	D	T	H	E	P	A	T	T	E	R	N
1	P	A	T	T	E	R	N																										
2								P	A	T	T	E	R	N																			
3															P	A	T	T	E	R	N											
4																						P	A	T	T	E	R	N				
5																									P	A	T	T	E	R	N	
6																										P	A	T	T	E	R	N

B. BMHS Algorithm

The core idea is in the calculation of Bad char function; consider the situation of the next character, namely the use of the next character T[m] to determine the right offset. If the character does not appear in the matching string is skip that step by pattern length + 1; otherwise, the mobile step= match strings in the far right of the character to the end of the range+1.In the matching process, the mode string must not be asked to compare, it does not match is found, the algorithm can skip as many characters to match the next step to improve the matching efficiency. [3]

BMHS algorithm worst case time complexity is O (mn), the best case time complexity is O (n/m+1). For a short pattern string matching problem, the algorithm is faster. [3]

Example: shown in Table 3

Advantages

- In BMH the maximum shift achieved is equal to pattern length but in BMHS the maximum shift that can be achieved is equal to one more than pattern length.

Disadvantages

- Suppose last character is not in pattern but next-to-last character is in pattern so In state of mismatch less shift is achieved as compared to BMH.

TABLE 3.BMHS Example (4 Shift and 13 Comparisons)

	S	T	R	I	N	G	M	A	T	C	H	I	N	G	I	S	T	O	F	I	N	D	T	H	E	P	A	T	T	E	R	N
1	P	A	T	T	E	R	N																										
2							P	A	T	T	E	R	N																				
3															P	A	T	T	E	R	N											
4																							P	A	T	T	E	R	N			
5																										P	A	T	T	E	R	N

C. BMHS2 Algorithm

The idea of algorithm is when mismatch occur at any position then the Right Shift value is determined by Next-to-Last character and Last character of Text corresponding to Pattern that is T[i+m] and T[i+m-1] where m is length of Pattern.

Now matching start from Last character of Pattern, if mismatch at any position than consider Next-to-Last character (T[i+m]) of Text and find its position in pattern

(1) If not in pattern than right shift by m+1.
(2) If occur at first position than right shift by m.
(3) If occur other than first position than shift calculated is X than
   - Consider Last character of Text corresponding to pattern and calculate shift, if shift calculated by this is X than shift by X.
   - Otherwise shift by m+1.

BMHS2 algorithm worst case time complexity is O(mn), the best case time complexity is O(n),where n is length of text and the maximum moving distance of m+1. [3]

Example: shown in Table 4

Advantages

- This algorithm considers last character and next-to-last character both so it combined advantages of both BMH and BMHS.

Disadvantages

- Searching overhead increases as we have to take care of two characters for calculation of shift.

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TABLE 4.BMHS2 Example (4 Shift and 11 Comparisons)

	S	T	R	I	N	G	M	A	T	C	H	I	N	G	I	S	T	O	F	I	N	D	T	H	E	P	A	T	T	E	R	N
1	P	A	T	T	E	R	N																										
2									P	A	T	T	E	R	N																		
3																	P	A	T	T	E	R	N									
4																									P	A	T	T	E	R	N	
5																										P	A	T	T	E	R	N

D. Improved BMHS Algorithm

The improved algorithm uses the comparative order from right to left. Supposing that the pattern string P0P1é P_{M-1} aligns with the part of the text string T_{k-m+1} é T_{k-1} T_k.

The preprocessing phase is as follows: construct the array *Skip*[*x*] according to the bad-character rules, in the conditions of $x \in \times$. In addition, improved algorithm needs to construct *Num*[*y*] which records the times of each character appearing in the pattern string.

The searching phase is as follows: compare the character *Pm-1* with *T* k.

When mismatch occurs between P_{m-1} and T_k, calculate Skip $[T_{k+1}]$ and *Skip* $[T_{k+2}]$. If *Skip* $[T_{k+1}]$ is equal with one, the pattern string will shift one point to right. Otherwise, the movement will be determined by the larger one between Skip $[T_{k+1}]$ and *Skip* $[T_{k+2}]$.

When P_{m-1} and T_k match successfully, compare the character P_{m-2} with character T_{k-1}. If the match is successful, continue to comparing P_{m-3} and T_{k-2}, P_{m-4} and T_{k-3}, and so on, until the text string is matched completely. If mismatch occurs at P_{m-4} Í T_{k-3}, calculate Skip $[T_{k+1}]$ and *Skip* $[T_{k+2}]$. If *Skip* $[T_{k+1}]$ is equal with one, check Num $[P_{m-3}]$ whether it is equal with one, if *Num* $[P_{m-3}]$ is equal with one, change *Skip* $[T_{k+1}]$ to m+1. Then compare between *Skip* $[T_{k+1}]$ and *Skip* $[T_{k+2}]$, select the larger one as the movement of the Pattern shift. [2]

In preprocessing phase, time complexity is *O* (*m*+ *s*). In searching phase, if the successful match takes place in *Ti,* it is compared (i-1)*m times before successful matching, and m times during article i time of comparison. So it is compared i*m times.

The time complexity is *O* (*mn*). In the best case, if successful match takes place in *Ti,* it is compared *i* /(*m*+2) times before successful matching, and m times during article i time of comparison. So it is compared m+*i* / (*m*+2) times. The best time complexity is *O* (*n* /*m*+2). [2]
Example: shown in Table 5

Advantages

- Maximum shift that can be achieved using this algorithm is pattern length + 2.

Disadvantages

- Calculation of shift using Next-to-Last and Next-to-Next-to-Last character increase searching over head and for that preprocessing of Num[ ] is done which increases preprocessing overhead.

TABLE 5.Improved BMHS Example (4 Shift and 12 Comparisons)

	S	T	R	I	N	G	M	A	T	C	H	I	N	G	I	S	T	O	F	I	N	D	T	H	E	P	A	T	T	E	R	N
1	P	A	T	T	E	R	N																										
2							P	A	T	T	E	R	N																				
3																P	A	T	T	E	R	N										
4																									P	A	T	T	E	R	N	
5																										P	A	T	T	E	R	N

E. BMI Algorithm

The BMI algorithm combines with the good-suffix function and the advantages of BMH and BMHS [8][9]. At the same time the BMI algorithm also takes into account the singleness and combination features of the *Next-Character* and the *Last- Character.*

The basic idea behind the algorithm is to achieve the maximum shift distance in the event of a mismatch. Assume that now *P [0]…P[m-1]* correspond to *T[i]…T[i+m-1]* during the attempt. If a mismatch occurs, the shift right position will be calculated with function *Onechar(x)* and *TwoChar(x)* as following formula (1) and (2).[1]

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$$\text{OneChar(X)} = \begin{cases} -1 & \text{Character } x \text{ not in pattern} \\ j & \text{the rightmost position of character } x \text{ in pattern} \end{cases} \quad (1)$$

$$\text{TwoChar(X)} = \begin{cases} -1 & \text{two characters } T[j+m-1]x \text{ not in pattern} \\ j & \text{the rightmost position of characters } T[j+m-1]x \text{ in pattern} \end{cases} \quad (2)$$

Define: The *Last-Character* refers to the rightmost character of each attempting window in text *T*. The *Next-Character* refers to the first character on right side of attempting window in text *T*.

Now if m comparisons have completed and $T_iT_{i+1}...T_{i+m-1}=P_1P_2...P_{m-1}$, the matching is successful. If $(P_j=a) \neq (T_{i+j}=b)$ in *(m-j)*-th comparison, the BMI algorithm calculates the jump shift as below methods. Denote $T_{i+j+1}T_{i+j+2}...T_{i+m-1}=P_{j+1}P_{j+2}...P_{m-1}=u$ *and* $T_{i+j}\neq P_j$.

(1)Calculate the jump shift using the *Last-Character d* in pattern and *OneChar* function. The algorithm looks up the position of the first occurrence of the *Last-Character d* from right to left in $P_0P_1...P_{m-2}$. If found the position, the pattern *P* right shifts to align with character *d*. If not found the position, the pattern *P* right shifts to align with right side of character d. Then the algorithm begins to compare in new attempt window.

(2)Calculate the jump shift using the *Next-Character c* and *OneChar* function. The algorithm look up the position of the first occurrence of *Next-Character c* from right to left in *P0P1…Pm-1*. If found the position, the pattern *P* right shifts to align with character *c*. If not found the position, the pattern *P* right shifts to align with right side of character *c*. Then the algorithm begins to compare in new attempt window.

(3)Calculate the jump shift using the Last-Character d, the Next-Character c and TwoChar function. Denote X as the combination of character b and c, that is, X=bc. The algorithm look up the position of the first occurrence of X from right to left in P0P1é Pm-1. If found the position, the pattern P right shifts to align with character b. If not found the position, the pattern P right shifts to align with right side of character *b*. Then the algorithm begins to compare in new attempt window.

In the case of mismatch, the BMI algorithm combines three different shift functions to optimize the number of characters that can be skipped during the skip process.

If the *Last-Character d* is matching with the rightmost character of Pattern, the algorithm calculates the jump shift using above three methods and takes the maximum value of its results as final jump shift. If failed, the algorithm calculates the jump shift using above method (1) and method (2) and takes the maximum value as final jump shift. [1]

Under best performance the time complexity of BM and BMH algorithm all are *O(n/m)*, the time complexity of BMHS and BMI algorithm all are *O(n/m+1)*, but the average time complexity of BMI algorithm is better. [1]

Example: shown in Table 6

Advantages

- BMI uses last character, Next-to-Last character and combination of these two characters for calculation of shift means BMI Takes advantages of BMH, BMHS and good-suffix feature of BM for combination of last character and Next-to-Last character.

Disadvantages

- In calculation of shift using three different methods and taking maximum of these increases overhead in searching.

TABLE 6.BMI Example (4 Shift and 11 Comparisons)

	S	T	R	I	N	G	M	A	T	C	H	I	N	G	I	S	T	O	F	I	N	D	T	H	E	P	A	T	T	E	R	N
1	P	A	T	T	E	R	N																									
2								P	A	T	T	E	R	N																		
3																P	A	T	T	E	R	N										
4																							P	A	T	T	E	R	N			
5																										P	A	T	T	E	R	N

F. CBM Algorithm

The key issue of the CBM algorithm is how to utilize the history comparison information achieved at previous iteration. So we construct a two-dimensional table Jump[*m*][*m*]. Jump[*i*][*j*] denotes the shift distance of pattern P, when the mismatch at previous iteration appears at p[*i*], and the mismatch at current iteration appears at p[*j*]. This table is only related to pattern P. Once Jump[*m*][*m*] is constructed, it can be utilized for searching P in different texts.

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The comparison principle of algorithm CBM is shown in Figure 1. Suppose P is at place P_0 at previous iteration, and the mismatch appears at index *i* of P_0; and suppose P is at place P_1 at current iteration, the mismatch appears at index *j* of P_1; then P_2, P's new position, must meet following conditions: its substring at B matches with P_1's substring at B; its character at *b* does not match P_1's character at *j*; its substring at A matches P_0's substring at A; and its character at *a* does not matches with P_1's character at *i*. Above four matching conditions make a large shift distance Jump[*i*][*j*] for pattern P.[4]

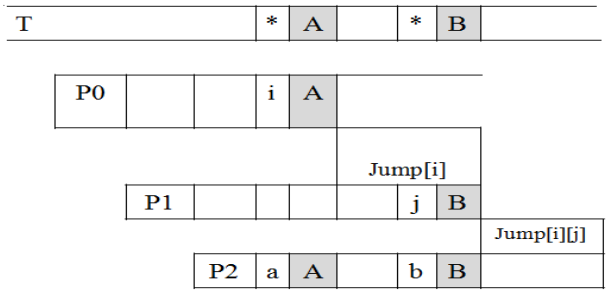

Figure1.Working principle of CBM

In the procedure, the initial values of Jump[*i*][*j*] is set to Jump[*j*] for every *i*. Then the values increased gradually by test, until it satisfies above four matching conditions. After generating table Jump[m][m], the specific matching process is similar to the BM algorithm.

In the case of small alphabet and long pattern, values in Jump[m][m] that is close to the right column are usually larger than the corresponding values in Jump[m], and the matching efficiency are improved. Binary searching in Computer Science and DNA sequence tests in genetic engineering are such kind of applications. [4]

IV. COMPARISON AND ANALYSIS

BMH algorithm is more efficient when last character does not occur in pattern. BMHS is more effective than BMH when last character occur in pattern but next to last character does not occur in pattern. Improved BMHS algorithm is efficient when next to last character and next to next to last character does not occur in pattern. BMHS2 perform better when next to last character does not occur in pattern or occur at first position in pattern. BMI algorithm perform better when Next to Last character does not occur in pattern; Or when Last character does not occur in pattern; Or when combination of Last character with Next to Last character does not occur in pattern. CBM is effective in case of small alphabet and long pattern such as Binary Searching.

Analysis Based on Example:

- In our example BM and BMH performance was equal as SHIFT=5 and Comparison=13.
- In case of BMHS SHIFT decreases to 4 but Comparison remains to 13, so we can't say that BMHS always perform better than BMH, it totally depends on Input.
- Improved BMHS performance is better than BM, BMH and BMHS as SHIFT=4 and Comparison=12.
- Performance of BMI and BMHS2 is even better than Improved BMHS as SHIFT=4 and Comparison=11.
- In example performance of BMI and BMHS2 is equal but we also can't say that there performance remains always same, it is also depends on Input.

Table 7.Comparison

Para.\Algo.	BM	BMH	BMHS	Improved BMHS	BMHS2	BMI
SHIFT	5	5	4	4	4	4
COMPARISION	13	13	13	12	11	11
BEST-CASE TIME COMPLEXITY	O(n/m)	O(n/m)	O(n/m+1)	O(n/m+2)	O(n/m+1)	O(n/m+1)
WORST-CASE TIME COMPLEXITY	O(mn)	O(mn)	O(mn)	O(mn)	O(mn)	O(mn)

Analysis Based on Experiment:
Experimental Environment
Processor: i7
RAM: 8 GB
OS: windows 7
Language: visual C++ runs on visual studios 2008

Experimental Data
Text File: of size 2, 68,196 KB in which large number of occurrence of pattern.
Pattern of length 15

Experiment

In the experiment we have search a pattern in text and calculated number of comparison which is how many times we compare pattern character with text character and search time is also calculated in milliseconds. The results as search time and number of comparison, corresponding to different algorithm are shown in table 8.

TABLE 8: Experimental Results

S.N.	Para\Algo	No. of Comparison	Search Time (millisec.)
1	BM	26112769	108
2	BMH	26220229	110
3	BMHS	26041122	120
4	Improved BMHS	20238289	104
5	BMI	20023363	92
6	BMHS2	19199507	73

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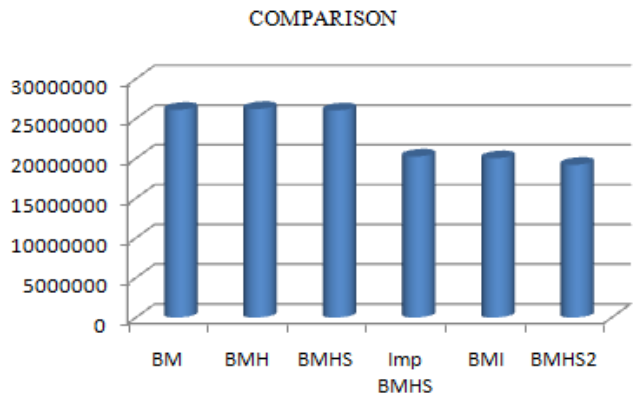
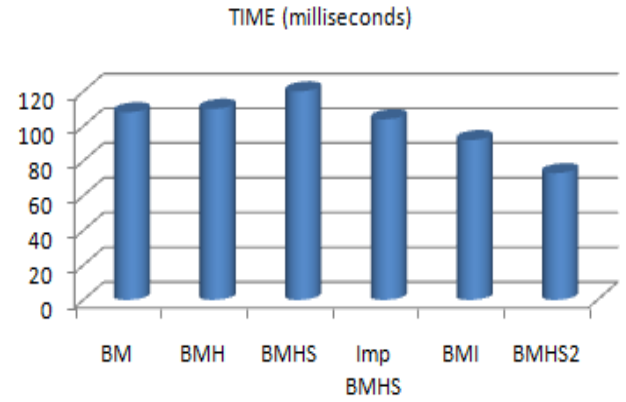
On the basis of experimental results we plot bar graphs for comparison and search time as shown in graph1 and graph2.



Graph1: Number of Comparison of Different Algorithm



Graph2: Searching Time of Different Algorithm

V. CONCLUSION

The comparison of BM and its relative algorithm is performed on the basis two factors; one is number of comparison performed and second is search time. In example and in experiment we present a comparison on the basis of number of comparison performed that performance of BM, BMH and BMHS are almost equal as number of comparison is almost same. Improved BMHS perform better than BMHS as number of comparison decreases.BMI and BMHS2 perform even better than Improved BMHS as number of Comparison decreases. In Experiment we also present a comparison on the basis of search time in which BM and BMH perform almost same but BMHS search time increases. Improved BMHS search time is less in comparison to BM, BMH and BMHS. In BMI searching is faster than above four and BMHS2 search time is even less than BMI. So finally we can say that BMHS2 is best of all six algorithms as search time and number of comparison both are less than in all other algorithm.

Composite Boyer-Moore algorithm is efficient in case of binary searching where small varieties of alphabet and long pattern.

The performance of algorithm depends on two factors, first on Input, number of inputs and type of inputs, Second is Methodology of algorithm, so there may be possible that some variation in performance occur as input changes.

VI. FUTURE WORK

The focus of future work is to improve existing algorithm and finding the efficient string searching algorithm so that searching speed can be increased and performance as well.

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