Seminarski rad iz predmeta

Računarska inteligencija

Najbliži string

(eng. Closest String)

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Sadržaj

Uvodni deo

Opis problema

Problem najbližeg stringa se može definisati na sledeći način:

Dat je konačan skup stringova **S** = {s_1, s_2, …, s_N} formiranih nad konačnom azbukom **A** = {c_1, …, c_k}, od kojih je svaki dužine M. Treba pronaći string **t** koji predstavlja medijanu skupa **S**, dužine M koji minimizuje **d**, takav da je za svaki string $\mathbf{s_i}$ koji pripada **S**, važi $\mathbf{dist_H(t, s_i) \leq d}$. Rastojanje $\mathbf{dist_H(t, s_i)}$ predstavlja Hamingovo rastojanje između stringova **t** i $\mathbf{s_i}$. Hamingovo rastojanje stringova a i b jednake dužine, predstavlja broj različitih karaktera na istim pozicijama u stringovima. Ovaj problem spada u NP-teške probleme.

Iako postoje dobre aproksimacije algoritma za rešavanje ovog problema, kao i egzaktni algoritmi za fiksirano **d**, ne postoje pokušaji da se problem reši egzaktno za opšti slučaj.

Primer problema:

Neka je S = {‘ATTT’, ‘AGGG’, ‘ACCC’}. Jedno od rešenja je ‘ACGT’ zbog toga što je rastojanje od tog stringa do svih ostalih jednako, kao i takvo da je najmanje moguće najveće rešenje.

Primena

Rešenja ovog problema pronalaze primenu u poljima kao što su biološka izračunavanja (eng. *Computational Biology*), molekularna biologija (eng. *Molecular biology*), na primer za dizajniranje novih genetskih lekova koji imaju strukturu sličnu datom skupu postojećih sekvenci RNK, teoriji kodiranja (eng. *Coding theory*), na primer u određivanju najboljeg načina enkriptovanja skupa poruka.

Prethodni radovi

- Razvoj primene bioloških izračunavanja zahtevao je proučavanje optimizacionih problema nad sekvencama karaktera. Neka početna istraživanja su koristila statističke metode [1]
- Ming Li je prvi otkrio kombinatornu prirodu ovog problema i dokazao da je NP-težak. Takođe je opisao neke primene u molekularnoj biologiji [2]
- U [3] Gram je pokazao da se za fiksiranu vrednost **d** ovaj problem može rešiti u polinomijalnom vremenu.

Opis rešenja

Opis klase

Napravili smo klasu ‘ClosestString’ koja rešava problem korišćenjem genetskog algoritma. Atributi su parametri opšteg genetskog algoritma, poput veličine populacije, broja iteracija, verovatnoće mutacije, veličina turnira i drugih.

```
// members
std::vector<std::string> _setOfStrings;
std::vector<char> _allowedGeneValues;
size_t _length;
unsigned _numOfIterations;
unsigned _generationSize;
double _mutationRate;
unsigned _reproductionSize;
unsigned _tournamentK;
double _crossoverProb;
Chromosome _best;
```

Klasa sadrži metode za rad sa genetskim algoritmom.

```
public:
   //First, temporary constructor, without parameters
   ClosestString(const std::vector<std::string> &setOfStrings, const std::vector<char> &allowedGeneValues);

   //Main constructor, with all parameters for genetic algorithm
   ClosestString(const std::vector<std::string> &setOfStrings, const std::vector<char> &allowedGeneValues,
             unsigned numOfIterations, unsigned generationSize, double mutationRate,
             unsigned tournamentK, double crossoverProb);

   //Main function, all begin here
   void optimize();

private:
   //Create random population, from allowed gene values
   std::vector<Chromosome> initialPopulation();
   //tournament selection, with parametar K, which goes from GenerationSize/5 to GenerationSize
   std::vector<Chromosome> selection(const std::vector<Chromosome> &population);
   //Use selected chromosomes, do uniform crossover on 2 parents to get 2 children,
   //some of children are mutated and add to vector
   std::vector<Chromosome> createGeneration(const std::vector<Chromosome> &forReproduction);
   //Uniform crossover
   std::pair<Chromosome, Chromosome> crossover(const Chromosome &parent1, const Chromosome &parent2);
   //Mutation on random bit of chromosome value, with probability MutationRate
   void mutation(Chromosome &chromo);
   //From all chromosomes that are forwarded as parameter, pick and return the one with best fitness
   Chromosome pickOneTournament(const std::vector<Chromosome> & pop);
   //Calculate fitness for the forwarded string
   int fitness(const std::string & current);
   //Stop conditions for whole program
   bool stopConditions(size_t i, const std::vector<Chromosome> &chromosomes);
```

Opšti rad algoritma

Komponente genetskog algoritma

Karakteristika	Implementacija
Reprezentacija	String (niska karaktera)
Ukrštanje	Ravnomerno ukrštanje
Mutacija	Zamena nasumičnog karaktera nasumičnim karakterom
Selekcija roditelja	Fitnes-srazmerna (turnirska)
Selekcija preživelih	Smena generacija

Opšti genetski algoritam

```
void ClosestString::optimize() {
   std::vector<Chromosome> chromosomes = initialPopulation();

   size_t currIteration = 0;
   while (stopConditions(currIteration, chromosomes)) {
      std::vector<Chromosome> forReproduction = selection(chromosomes);
      chromosomes = createGeneration(forReproduction);

      // Chromosome with smallest fit in population
      _best = *(std::min_element(std::cbegin(chromosomes), std::cend(chromosomes), compare));
      currIteration++;
   }
}

bool compare(Chromosome c1, Chromosome c2){
   return c1.fit < c2.fit;
}
```

Inicijalizacija početne populacije

```
std::vector<Chromosome> ClosestString::initialPopulation(){

   srand(unsigned(time(nullptr)));

   std::vector<Chromosome> initPopulation;
   for (unsigned i = 0; i < _generationSize; ++i){
      std::vector<char> geneticCode;
      //make one string as vector<char> from allowed charachers
      for (size_t j = 0; j < _length; j++){
         size_t pos = unsigned(rand()) % _allowedGeneValues.size();
         geneticCode.push_back(_allowedGeneValues[pos]);
      }
      //make string from vector<char>
      std::string current = std::string(std::cbegin(geneticCode), std::cend(geneticCode));
      initPopulation.push_back(Chromosome{current, fitness(current)});
   }
   return initPopulation;
}
```

Selekcija roditelja

```
std::vector<Chromosome> ClosestString::selection(const std::vector<Chromosome> &population) {
    std::vector<Chromosome> forReproduction;

    for(size_t i = 0, n = population.size(); i < n; ++i){
        forReproduction.push_back(pickOneTournament(population));
    }
    return forReproduction;
}

Chromosome ClosestString::pickOneTournament(const std::vector<Chromosome> &pop) {
    Chromosome bestC{"", INT_MAX};
    for(size_t i = 0; i < _tournamentK; ++i){
        size_t pos = unsigned(rand()) % pop.size();
        if(pop[pos].fit < bestC.fit){
            bestC = pop[pos];
        }
    }
    return bestC;
}
```

Ukrštanje

```
std::pair<Chromosome, Chromosome> ClosestString::crossover(const Chromosome &parent1,
                                                           const Chromosome &parent2) {
    size_t n = parent1.value.size();
    std::string child1, child2;
    child1.resize(n);
    child2.resize(n);

    for (size_t i = 0; i < n; ++i) {
        double tmp = double((double(rand()) / RAND_MAX));
        if (tmp < _crossoverProb) {
            child1.at(i) = parent1.value.at(i);
            child2.at(i) = parent2.value.at(i);
        } else {
            child2.at(i) = parent1.value.at(i);
            child1.at(i) = parent2.value.at(i);
        }
    }
    return {Chromosome{child1, fitness(child1)}, Chromosome{child2, fitness(child2)}};
}
```

Mutacija

```
void ClosestString::mutation(Chromosome &chromo) {

    double mutationImpossible = (double(rand()) / RAND_MAX);
    if (mutationImpossible < _mutationRate) {
        //select position in string that will be changed
        size_t index = unsigned(rand()) % chromo.value.size();
        //select which charachter will be set on selected position in chromosome value
        size_t pos = unsigned(rand()) % _allowedGeneValues.size();

        chromo.value.at(index) = _allowedGeneValues.at(pos);
        chromo.fit = fitness(chromo.value);
    }
}
```

Generisanje nove generacije

```
std::vector<Chromosome> ClosestString::createGeneration(const std::vector<Chromosome> &forReproduction) {

    std::vector<Chromosome> newGeneration;
    for (size_t i = 0; i < _generationSize; i+=2) {
        size_t index1 = unsigned(rand()) % forReproduction.size();
        size_t index2 = unsigned(rand()) % forReproduction.size();

        std::pair<Chromosome, Chromosome> children =
                crossover(forReproduction[index1], forReproduction[index2]);

        mutation(children.first);
        mutation(children.second);

        newGeneration.push_back(children.first);
        newGeneration.push_back(children.second);
    }

    return newGeneration;
}
```

Funkcija prilagođenosti

```
int hamingDistance(const std::string & s1, const std::string & s2){
    return std::inner_product(std::cbegin(s1), std::cend(s1), std::cbegin(s2), 0,
                              [] (int left, int right) {return left + right;},
                              [] (char c1, char c2) {return c1 != c2 ? 1 : 0;});
}

int ClosestString::fitness(const std::string &current) {
    //Getting position in setOfStrings vector,
    //that belongs to string which is furthest from Current chromosome value from population
    auto i = std::max_element(std::cbegin(_setOfStrings), std::cend(_setOfStrings),
                             [current](std::string s1, std::string s2){
                                             return hamingDistance(s1, current) < hamingDistance(s2, current);});
    //Calculate their distance
    return hamingDistance(*i, current);
}
```

Kriterijumi zaustavljanja

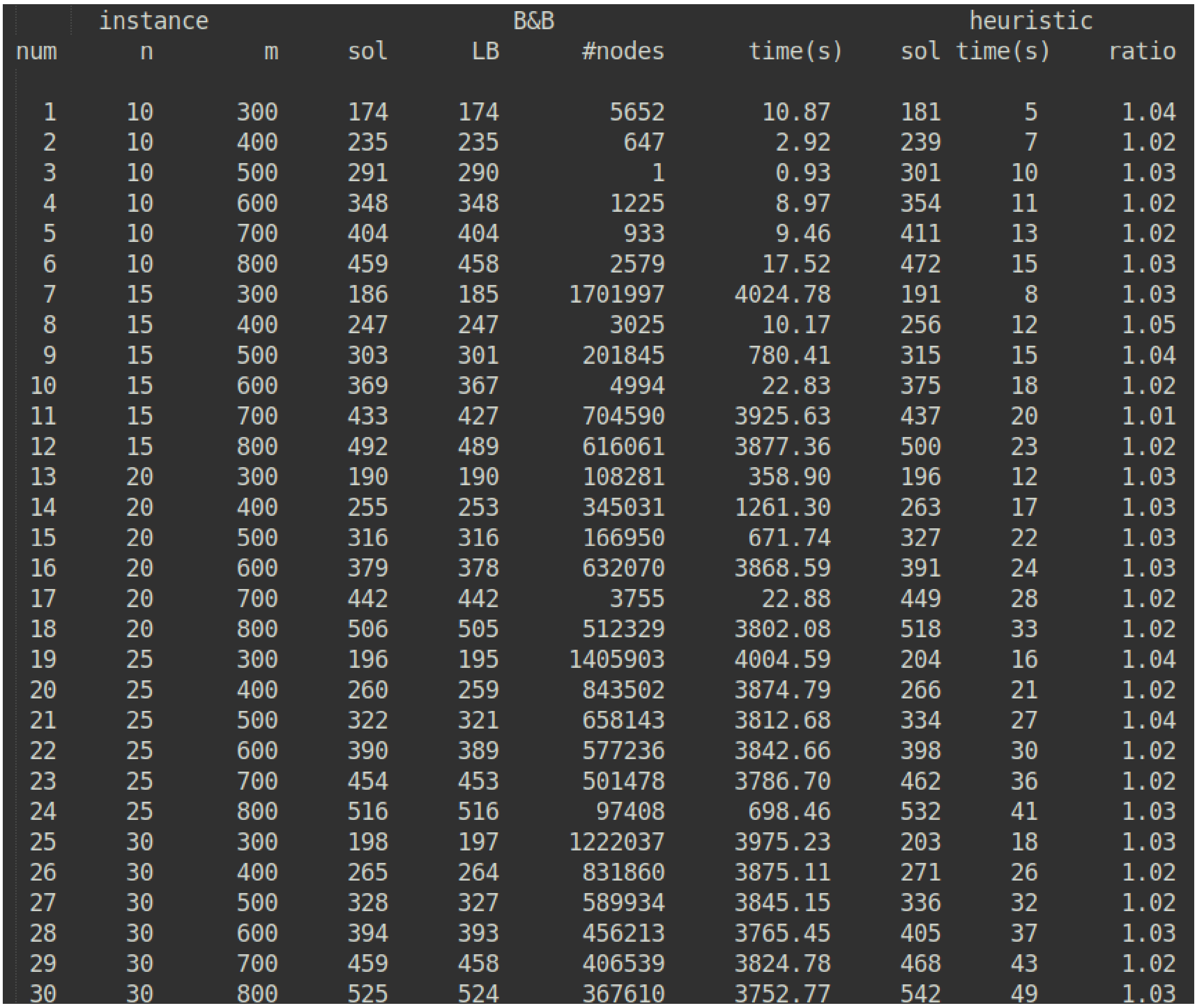
```
bool ClosestString::stopConditions(size_t currIteration, const std::vector<Chromosome> &) {
    if (currIteration >= _numOfIterations)
        return false;

    if (_best.fit == 0)
        return false;
}
```

Rezultati

Upoređivanje sa drugim rešenjima iz literature

Upoređivanje 1

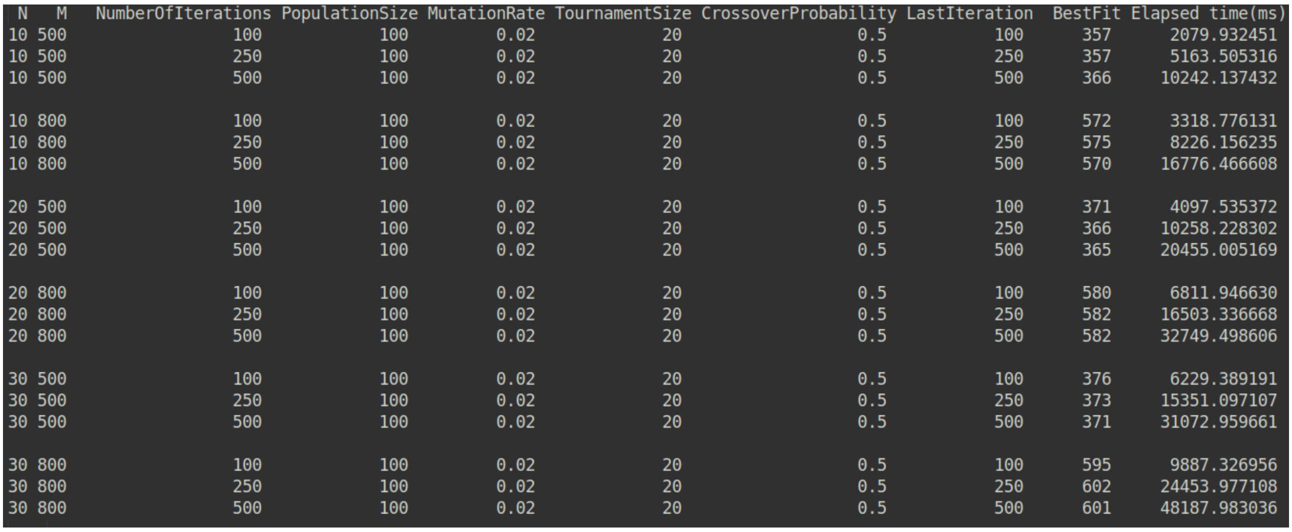
Testovi rešenja koji su dobijeni u [6]. Dobijeni su primenom B&B algoritma [7], kao i B&B algoritma poboljšanog heuristikom [8]. Dati rezultati su izvršeni na sistemu sa specifikacijama: Pentium 4 CPU, 2.8 GHz i 512MB RAM na WindowsXP.



	instance			B&B			heuristic		
num	n	m	sol	LB	#nodes	time(s)	sol	time(s)	ratio
1	10	300	174	174	5652	10.87	181	5	1.04
2	10	400	235	235	647	2.92	239	7	1.02
3	10	500	291	290	1	0.93	301	10	1.03
4	10	600	348	348	1225	8.97	354	11	1.02
5	10	700	404	404	933	9.46	411	13	1.02
6	10	800	459	458	2579	17.52	472	15	1.03
7	15	300	186	185	1701997	4024.78	191	8	1.03
8	15	400	247	247	3025	10.17	256	12	1.05
9	15	500	303	301	201845	780.41	315	15	1.04
10	15	600	369	367	4994	22.83	375	18	1.02
11	15	700	433	427	704590	3925.63	437	20	1.01
12	15	800	492	489	616061	3877.36	500	23	1.02
13	20	300	190	190	108281	358.90	196	12	1.03
14	20	400	255	253	345031	1261.30	263	17	1.03
15	20	500	316	316	166950	671.74	327	22	1.03
16	20	600	379	378	632070	3868.59	391	24	1.03
17	20	700	442	442	3755	22.88	449	28	1.02
18	20	800	506	505	512329	3802.08	518	33	1.02
19	25	300	196	195	1405903	4004.59	204	16	1.04
20	25	400	260	259	843502	3874.79	266	21	1.02
21	25	500	322	321	658143	3812.68	334	27	1.04
22	25	600	390	389	577236	3842.66	398	30	1.02
23	25	700	454	453	501478	3786.70	462	36	1.02
24	25	800	516	516	97408	698.46	532	41	1.03
25	30	300	198	197	1222037	3975.23	203	18	1.03
26	30	400	265	264	831860	3875.11	271	26	1.02
27	30	500	328	327	589934	3845.15	336	32	1.02
28	30	600	394	393	456213	3765.45	405	37	1.03
29	30	700	459	458	406539	3824.78	468	43	1.02
30	30	800	525	524	367610	3752.77	542	49	1.03

Slika 1: $\mathbf{A} = \{A, C, T, G\}$

Rezultati dobijeni primenom našeg rešenja

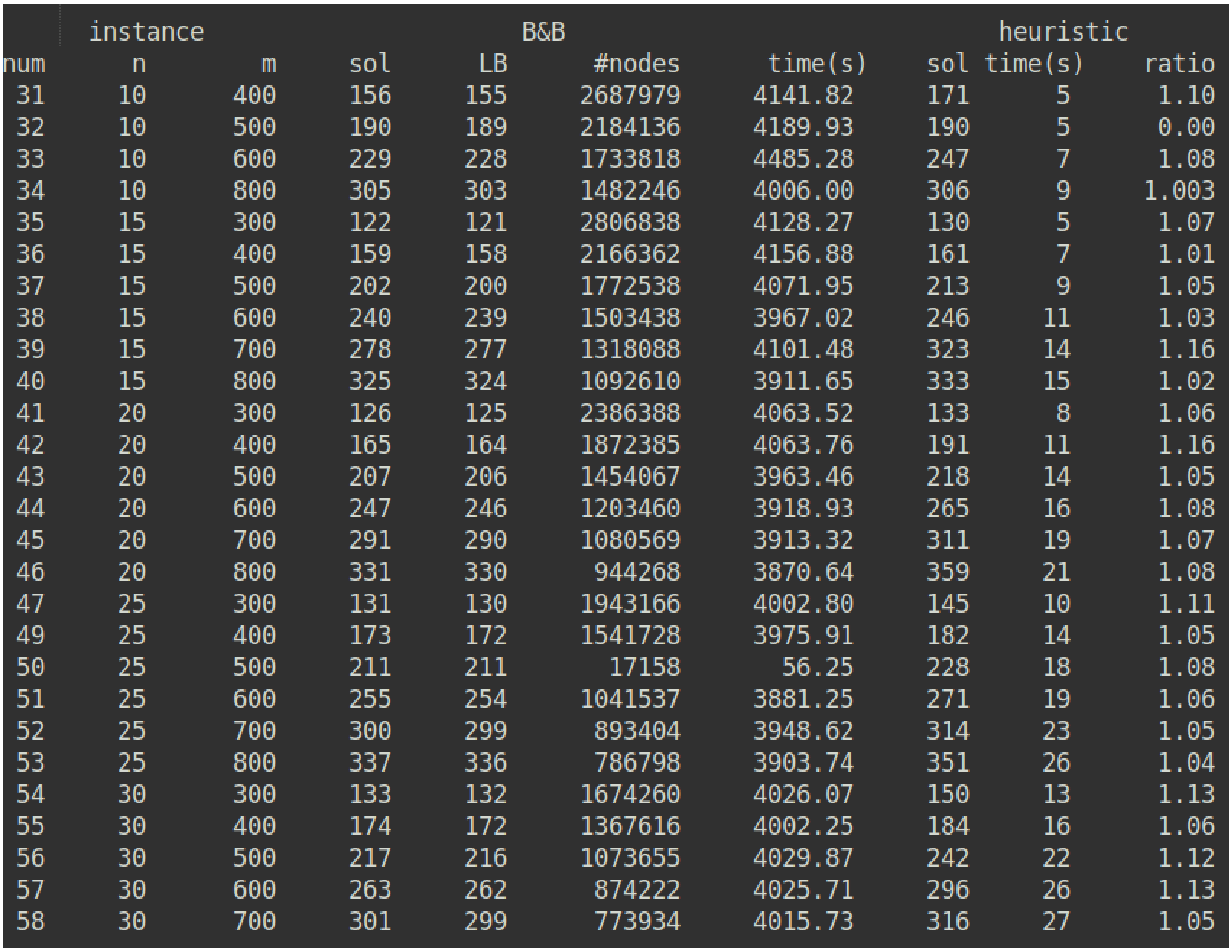


```
 N   M   NumberOfIterations PopulationSize MutationRate TournamentSize CrossoverProbability LastIteration  BestFit Elapsed time(ms)
10 500                  100            100         0.02             20                  0.5           100      357       2079.932451
10 500                  250            100         0.02             20                  0.5           250      357       5163.505316
10 500                  500            100         0.02             20                  0.5           500      366      10242.137432

10 800                  100            100         0.02             20                  0.5           100      572       3318.776131
10 800                  250            100         0.02             20                  0.5           250      575       8226.156235
10 800                  500            100         0.02             20                  0.5           500      570      16776.466608

20 500                  100            100         0.02             20                  0.5           100      371       4097.535372
20 500                  250            100         0.02             20                  0.5           250      366      10258.228302
20 500                  500            100         0.02             20                  0.5           500      365      20455.005169

20 800                  100            100         0.02             20                  0.5           100      580       6811.946630
20 800                  250            100         0.02             20                  0.5           250      582      16503.336668
20 800                  500            100         0.02             20                  0.5           500      582      32749.498606

30 500                  100            100         0.02             20                  0.5           100      376       6229.389191
30 500                  250            100         0.02             20                  0.5           250      373      15351.097107
30 500                  500            100         0.02             20                  0.5           500      371      31072.959661

30 800                  100            100         0.02             20                  0.5           100      595       9887.326956
30 800                  250            100         0.02             20                  0.5           250      602      24453.977108
30 800                  500            100         0.02             20                  0.5           500      601      48187.983036
```

Slika 2: ***A*** *= {A, C, T, G}*

Upoređivanje 2

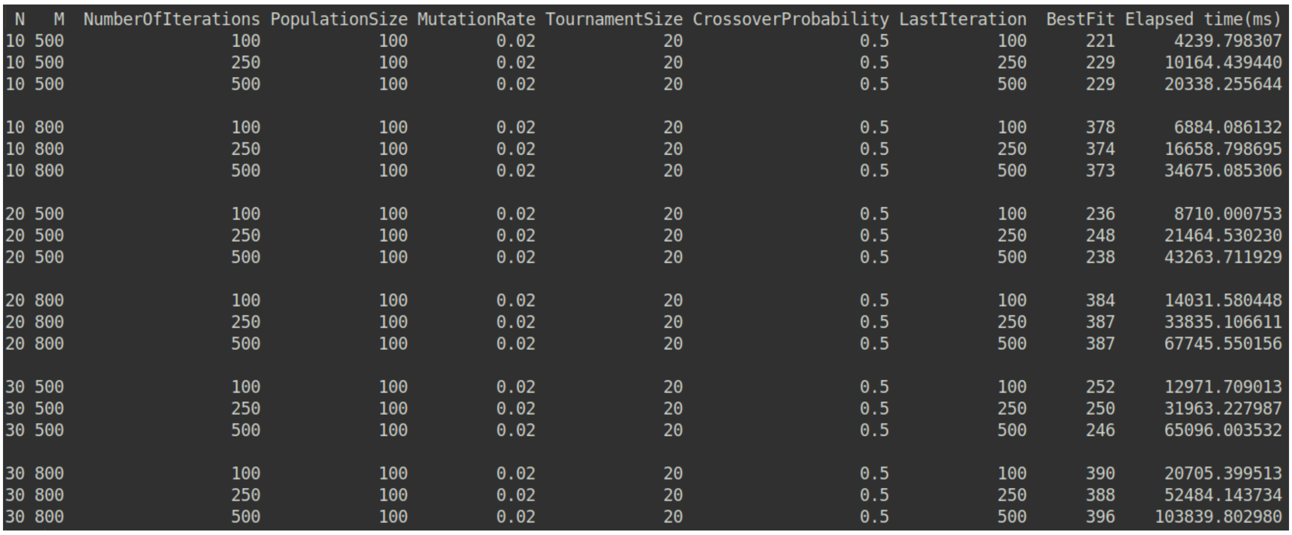
Rezultati rešenja iz [6] dobijeni primenom istog algoritma i heuristike kao u prvom upoređivanju. Specifikacije sistema su takođe iste.



	instance		B&B				heuristic		
num	n	m	sol	LB	#nodes	time(s)	sol	time(s)	ratio
31	10	400	156	155	2687979	4141.82	171	5	1.10
32	10	500	190	189	2184136	4189.93	190	5	0.00
33	10	600	229	228	1733818	4485.28	247	7	1.08
34	10	800	305	303	1482246	4006.00	306	9	1.003
35	15	300	122	121	2806838	4128.27	130	5	1.07
36	15	400	159	158	2166362	4156.88	161	7	1.01
37	15	500	202	200	1772538	4071.95	213	9	1.05
38	15	600	240	239	1503438	3967.02	246	11	1.03
39	15	700	278	277	1318088	4101.48	323	14	1.16
40	15	800	325	324	1092610	3911.65	333	15	1.02
41	20	300	126	125	2386388	4063.52	133	8	1.06
42	20	400	165	164	1872385	4063.76	191	11	1.16
43	20	500	207	206	1454067	3963.46	218	14	1.05
44	20	600	247	246	1203460	3918.93	265	16	1.08
45	20	700	291	290	1080569	3913.32	311	19	1.07
46	20	800	331	330	944268	3870.64	359	21	1.08
47	25	300	131	130	1943166	4002.80	145	10	1.11
49	25	400	173	172	1541728	3975.91	182	14	1.05
50	25	500	211	211	17158	56.25	228	18	1.08
51	25	600	255	254	1041537	3881.25	271	19	1.06
52	25	700	300	299	893404	3948.62	314	23	1.05
53	25	800	337	336	786798	3903.74	351	26	1.04
54	30	300	133	132	1674260	4026.07	150	13	1.13
55	30	400	174	172	1367616	4002.25	184	16	1.06
56	30	500	217	216	1073655	4029.87	242	22	1.12
57	30	600	263	262	874222	4025.71	296	26	1.13
58	30	700	301	299	773934	4015.73	316	27	1.05

Slika 3: ***A*** *= {0, 1}*

Rezultati dobijeni primenom našeg rešenja



```
 N   M  NumberOfIterations PopulationSize MutationRate TournamentSize CrossoverProbability LastIteration  BestFit Elapsed time(ms)
10 500                100            100         0.02             20                  0.5           100      221       4239.798307
10 500                250            100         0.02             20                  0.5           250      229      10164.439440
10 500                500            100         0.02             20                  0.5           500      229      20338.255644

10 800                100            100         0.02             20                  0.5           100      378       6884.086132
10 800                250            100         0.02             20                  0.5           250      374      16658.798695
10 800                500            100         0.02             20                  0.5           500      373      34675.085306

20 500                100            100         0.02             20                  0.5           100      236       8710.000753
20 500                250            100         0.02             20                  0.5           250      248      21464.530230
20 500                500            100         0.02             20                  0.5           500      238      43263.711929

20 800                100            100         0.02             20                  0.5           100      384      14031.580448
20 800                250            100         0.02             20                  0.5           250      387      33835.106611
20 800                500            100         0.02             20                  0.5           500      387      67745.550156

30 500                100            100         0.02             20                  0.5           100      252      12971.709013
30 500                250            100         0.02             20                  0.5           250      250      31963.227987
30 500                500            100         0.02             20                  0.5           500      246      65096.003532

30 800                100            100         0.02             20                  0.5           100      390      20705.399513
30 800                250            100         0.02             20                  0.5           250      388      52484.143734
30 800                500            100         0.02             20                  0.5           500      396     103839.802980
```

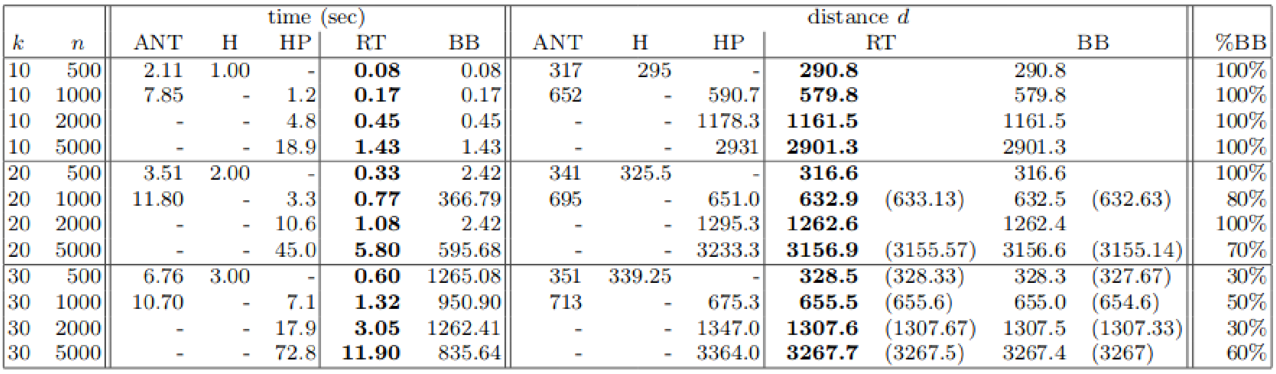
*Slika 4: **A** = {0, 1}*

Upoređivanje 3

Testovi rešenja koji su dobijeni u [9]. Dobijeni su primenom ANT algoritma [10], heuristikom [11], paralelizovana verzija heuristike [12], 'root' heuristika objašnjena u [13] i B&B [14].

Specifikacija sistema:

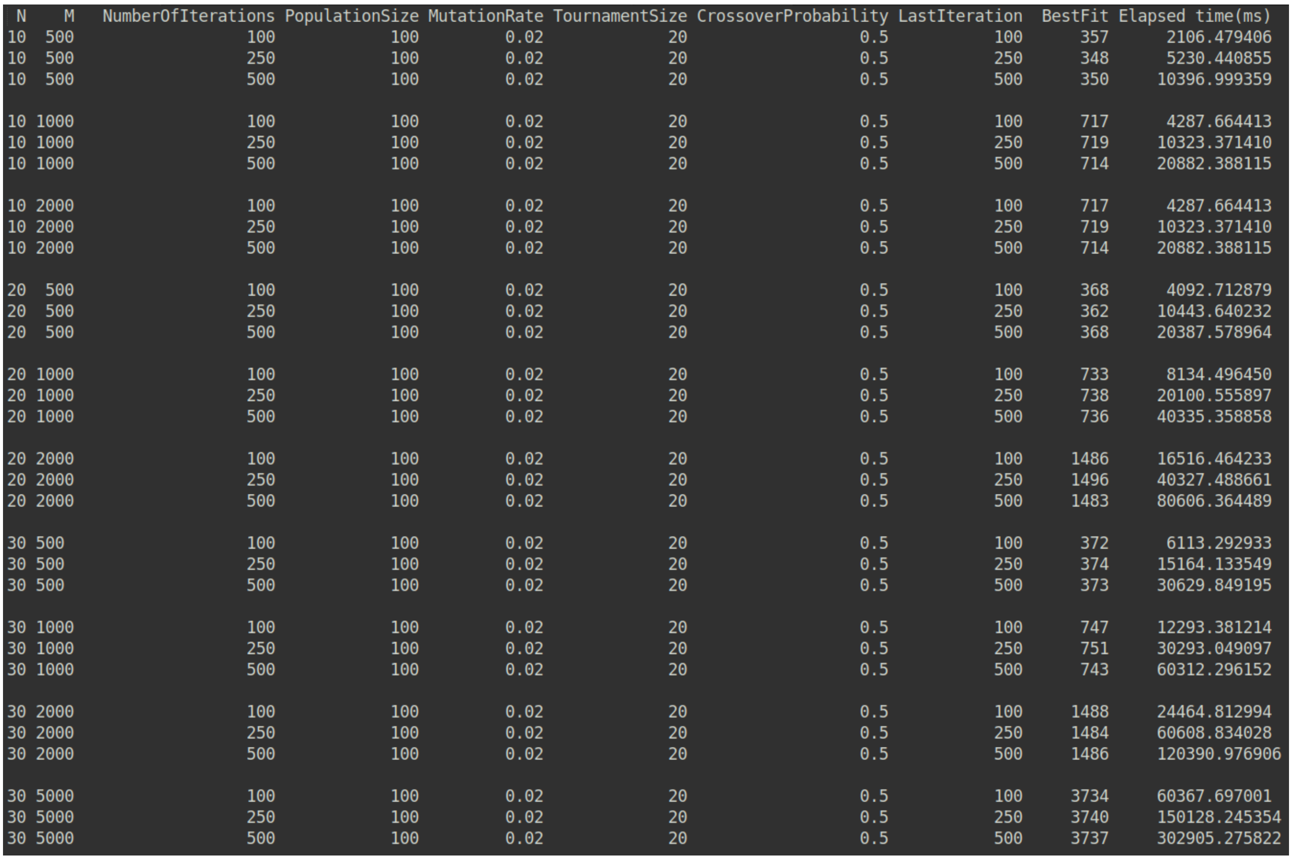
- ANT: CPU 1.8 GHz 1GB RAM
- H: CPU 2.8 GHz 512MB RAM
- HP: CPU Intel Xeon dual 2 x 1GB RAM



		time (sec)					distance d							
k	n	ANT	H	HP	RT	BB	ANT	H	HP	RT		BB		%BB
10	500	2.11	1.00	-	**0.08**	0.08	317	295	-	**290.8**		290.8		100%
10	1000	7.85	-	1.2	**0.17**	0.17	652	-	590.7	**579.8**		579.8		100%
10	2000	-	-	4.8	**0.45**	0.45	-	-	1178.3	**1161.5**		1161.5		100%
10	5000	-	-	18.9	**1.43**	1.43	-	-	2931	**2901.3**		2901.3		100%
20	500	3.51	2.00	-	**0.33**	2.42	341	325.5	-	**316.6**		316.6		100%
20	1000	11.80	-	3.3	**0.77**	366.79	695	-	651.0	**632.9**	(633.13)	632.5	(632.63)	80%
20	2000	-	-	10.6	**1.08**	2.42	-	-	1295.3	**1262.6**		1262.4		100%
20	5000	-	-	45.0	**5.80**	595.68	-	-	3233.3	**3156.9**	(3155.57)	3156.6	(3155.14)	70%
30	500	6.76	3.00	-	**0.60**	1265.08	351	339.25	-	**328.5**	(328.33)	328.3	(327.67)	30%
30	1000	10.70	-	7.1	**1.32**	950.90	713	-	675.3	**655.5**	(655.6)	655.0	(654.6)	50%
30	2000	-	-	17.9	**3.05**	1262.41	-	-	1347.0	**1307.6**	(1307.67)	1307.5	(1307.33)	30%
30	5000	-	-	72.8	**11.90**	835.64	-	-	3364.0	**3267.7**	(3267.5)	3267.4	(3267)	60%

*Slika 5: |**A**| = 4*

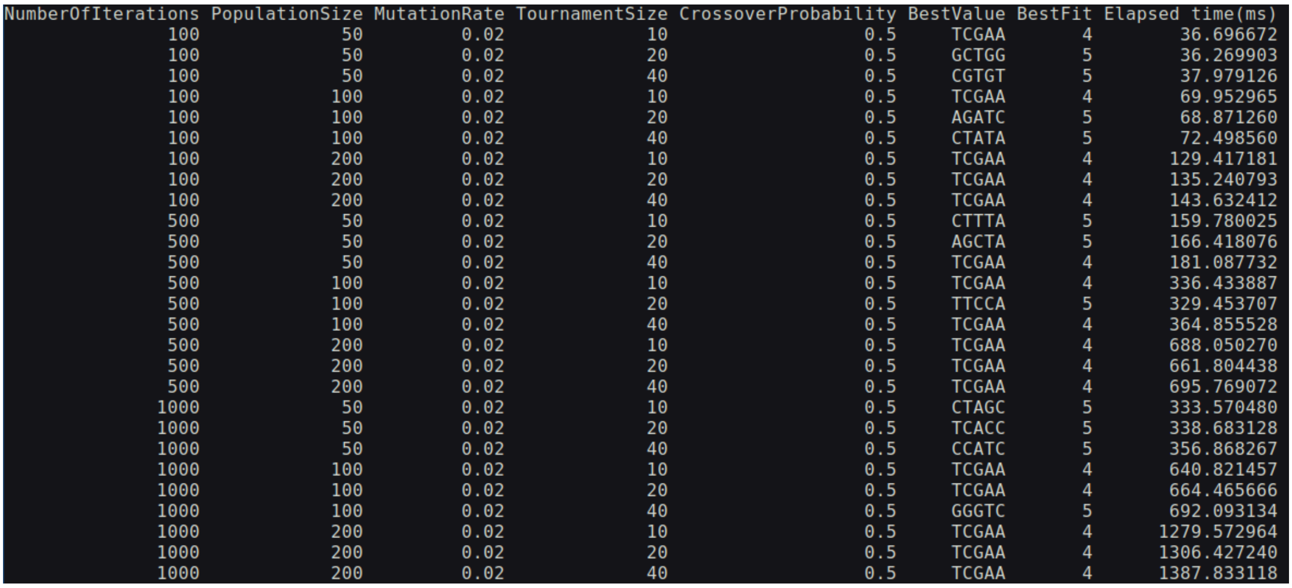
Rezultati dobijeni primenom našeg rešenja



```
 N    M   NumberOfIterations PopulationSize MutationRate TournamentSize CrossoverProbability LastIteration  BestFit Elapsed time(ms)
10  500                  100            100         0.02             20                  0.5           100      357      2106.479406
10  500                  250            100         0.02             20                  0.5           250      348      5230.440855
10  500                  500            100         0.02             20                  0.5           500      350     10396.999359

10 1000                  100            100         0.02             20                  0.5           100      717      4287.664413
10 1000                  250            100         0.02             20                  0.5           250      719     10323.371410
10 1000                  500            100         0.02             20                  0.5           500      714     20882.388115

10 2000                  100            100         0.02             20                  0.5           100      717      4287.664413
10 2000                  250            100         0.02             20                  0.5           250      719     10323.371410
10 2000                  500            100         0.02             20                  0.5           500      714     20882.388115

20  500                  100            100         0.02             20                  0.5           100      368      4092.712879
20  500                  250            100         0.02             20                  0.5           250      362     10443.640232
20  500                  500            100         0.02             20                  0.5           500      368     20387.578964

20 1000                  100            100         0.02             20                  0.5           100      733      8134.496450
20 1000                  250            100         0.02             20                  0.5           250      738     20100.555897
20 1000                  500            100         0.02             20                  0.5           500      736     40335.358858

20 2000                  100            100         0.02             20                  0.5           100     1486     16516.464233
20 2000                  250            100         0.02             20                  0.5           250     1496     40327.488661
20 2000                  500            100         0.02             20                  0.5           500     1483     80606.364489

30 500                   100            100         0.02             20                  0.5           100      372      6113.292933
30 500                   250            100         0.02             20                  0.5           250      374     15164.133549
30 500                   500            100         0.02             20                  0.5           500      373     30629.849195

30 1000                  100            100         0.02             20                  0.5           100      747     12293.381214
30 1000                  250            100         0.02             20                  0.5           250      751     30293.049097
30 1000                  500            100         0.02             20                  0.5           500      743     60312.296152

30 2000                  100            100         0.02             20                  0.5           100     1488     24464.812994
30 2000                  250            100         0.02             20                  0.5           250     1484     60608.834028
30 2000                  500            100         0.02             20                  0.5           500     1486     120390.976906

30 5000                  100            100         0.02             20                  0.5           100     3734     60367.697001
30 5000                  250            100         0.02             20                  0.5           250     3740     150128.245354
30 5000                  500            100         0.02             20                  0.5           500     3737     302905.275822
```

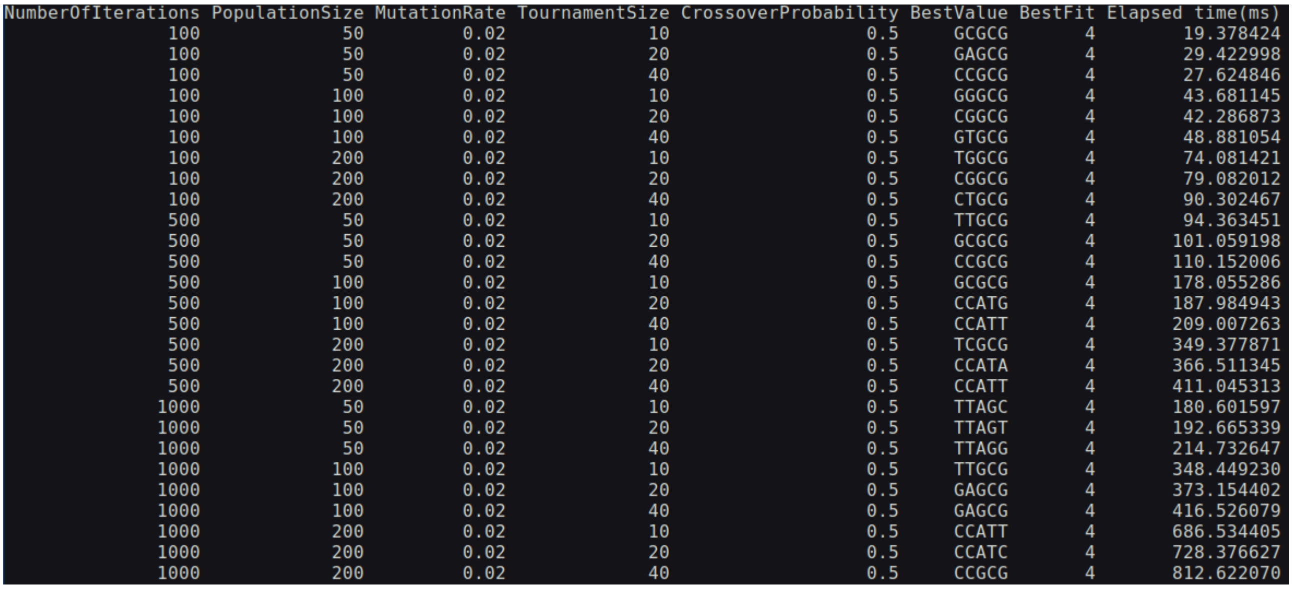
Slika 6: A = {A, C, T, G}

Rezultati našeg rešenja



```
NumberOfIterations PopulationSize MutationRate TournamentSize CrossoverProbability BestValue BestFit Elapsed time(ms)
               100             50         0.02             10                  0.5     TCGAA       4         36.696672
               100             50         0.02             20                  0.5     GCTGG       5         36.269903
               100             50         0.02             40                  0.5     CGTGT       5         37.979126
               100            100         0.02             10                  0.5     TCGAA       4         69.952965
               100            100         0.02             20                  0.5     AGATC       5         68.871260
               100            100         0.02             40                  0.5     CTATA       5         72.498560
               100            200         0.02             10                  0.5     TCGAA       4        129.417181
               100            200         0.02             20                  0.5     TCGAA       4        135.240793
               100            200         0.02             40                  0.5     TCGAA       4        143.632412
               500             50         0.02             10                  0.5     CTTTA       5        159.780025
               500             50         0.02             20                  0.5     AGCTA       5        166.418076
               500             50         0.02             40                  0.5     TCGAA       4        181.087732
               500            100         0.02             10                  0.5     TCGAA       4        336.433887
               500            100         0.02             20                  0.5     TTCCA       5        329.453707
               500            100         0.02             40                  0.5     TCGAA       4        364.855528
               500            200         0.02             10                  0.5     TCGAA       4        688.050270
               500            200         0.02             20                  0.5     TCGAA       4        661.804438
               500            200         0.02             40                  0.5     TCGAA       4        695.769072
              1000             50         0.02             10                  0.5     CTAGC       5        333.570480
              1000             50         0.02             20                  0.5     TCACC       5        338.683128
              1000             50         0.02             40                  0.5     CCATC       5        356.868267
              1000            100         0.02             10                  0.5     TCGAA       4        640.821457
              1000            100         0.02             20                  0.5     TCGAA       4        664.465666
              1000            100         0.02             40                  0.5     GGGTC       5        692.093134
              1000            200         0.02             10                  0.5     TCGAA       4       1279.572964
              1000            200         0.02             20                  0.5     TCGAA       4       1306.427240
              1000            200         0.02             40                  0.5     TCGAA       4       1387.833118
```

*Slika 7: **A** = {A, C, T, G}, N = 20, M = 5*



```
NumberOfIterations PopulationSize MutationRate TournamentSize CrossoverProbability BestValue BestFit Elapsed time(ms)
               100             50         0.02             10                  0.5     GCGCG       4         19.378424
               100             50         0.02             20                  0.5     GAGCG       4         29.422998
               100             50         0.02             40                  0.5     CCGCG       4         27.624846
               100            100         0.02             10                  0.5     GGGCG       4         43.681145
               100            100         0.02             20                  0.5     CGGCG       4         42.286873
               100            100         0.02             40                  0.5     GTGCG       4         48.881054
               100            200         0.02             10                  0.5     TGGCG       4         74.081421
               100            200         0.02             20                  0.5     CGGCG       4         79.082012
               100            200         0.02             40                  0.5     CTGCG       4         90.302467
               500             50         0.02             10                  0.5     TTGCG       4         94.363451
               500             50         0.02             20                  0.5     GCGCG       4        101.059198
               500             50         0.02             40                  0.5     CCGCG       4        110.152006
               500            100         0.02             10                  0.5     GCGCG       4        178.055286
               500            100         0.02             20                  0.5     CCATG       4        187.984943
               500            100         0.02             40                  0.5     CCATT       4        209.007263
               500            200         0.02             10                  0.5     TCGCG       4        349.377871
               500            200         0.02             20                  0.5     CCATA       4        366.511345
               500            200         0.02             40                  0.5     CCATT       4        411.045313
              1000             50         0.02             10                  0.5     TTAGC       4        180.601597
              1000             50         0.02             20                  0.5     TTAGT       4        192.665339
              1000             50         0.02             40                  0.5     TTAGG       4        214.732647
              1000            100         0.02             10                  0.5     TTGCG       4        348.449230
              1000            100         0.02             20                  0.5     GAGCG       4        373.154402
              1000            100         0.02             40                  0.5     GAGCG       4        416.526079
              1000            200         0.02             10                  0.5     CCATT       4        686.534405
              1000            200         0.02             20                  0.5     CCATC       4        728.376627
              1000            200         0.02             40                  0.5     CCGCG       4        812.622070
```

Slika 8: A = {A, C, T, G}, N = 10, M = 5

Specifikacije sistema

CPU:	Intel© Core™ i5-7200U CPU @ 2.50GHz × 2
RAM:	7.7 GiB
Grafička kartica:	NVIDIA GeForce 940MX
Operativni sistem:	Linux Mint 19 Cinnamon, 3.8.9
Kompajler:	g++ (Ubuntu 7.3.0-27ubuntu1~18.04) 7.3.0

Zaključak

U ovom radu, razmatrali smo rešavanje problema najbližeg stringa pomoću heuristike genetskog algoritma. Promenama parametara algoritma, pokušali smo da dođemo do što boljeg rešenja, ali ono na kraju nije bilo dobro kao rešenja iz literature sa kojima smo upoređivali rezultate.

Jedna od mogućnosti unapređivanja algoritma je paralelizacija rada programa, koju planiramo da uradimo u bliskoj budućnosti.

Kao što smo videli, rešenja problema najbližeg stringa, imaju značajnu primenu u oblastima bioinformatike i kriptografije, tako da je preciznost izvršavanja algoritma od presudnog značaja za njegov kvalitet, ali odmah pored preciznosti se može uvrstiti i brzina izračunavanja.

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