Planar Maximal Covering with Ellipses

Danilo F. Tedeschi Orientadora: Dra. Marina Andretta

Instituto de Ciências Matemáticas e Computação

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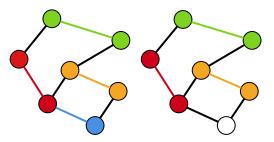
Contents

- Introduction
- 2 Preliminaries
- Maximal Covering by Disks
 - Maximum Weight Clique Problem
- Maximal Covering by Ellipses
- 5 Future Work

Introduction

- Covering problems
 - Minimum Cover Problem (Karp 1972)
 - Maximal Covering Problem (Church and Velle 1974)

Figure: Minimum Vertex Cover and its maximal counterpart. The colored edges are in the cover.



Source: Elaborated by the author.

Introduction

- Maximal Covering Location Problem (MCLP)
 - Introduce at first for networks. Facilities are placed on nodes, covering a radius of neighboring vertexes.
- Planar Maximal Covering Location Problem (PMCLP)
 - One disk is 3SUM-Hard (Kopelowitz, Pettie, and Porat 2014).
 - One disk: $\mathcal{O}(n^2)$ and $\mathcal{O}(n^2 \log n)$ algorithms.
 - m disks: $\mathcal{O}(n^{2m-1} \log n)$ algorithm.
- Goals
 - Develop a $\mathcal{O}(n^2 \log n)$ algorithm for the one disk case.
 - Adapt it for the m ellipses case creating a $\mathcal{O}(n^{2m})$ algorithm.

Maximal Covering by Disks

One disk

 $MCD(\mathcal{P},1)$ is the problem of placing one disk on the plane to cover a subset of a demand set \mathcal{P} , with n points, maximizing the weights of the covered points.

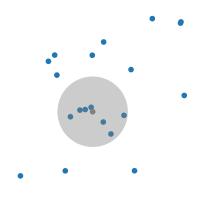
$$\max_{q} w(\mathscr{P} \cap D(q)),$$

- $\mathscr{P} = \{p_1, \dots, p_n\}$ is the demand set with weights $w(p_i) > 0$.
- w(A), $A \subset \mathcal{P}$, is the sum of weights of the points in A.
- D(q) is a unit disk with center at point q.

Maximal Covering by Disks

One disk

Figure: An instance of $MCD(\mathcal{P}, 1)$.



Maximal Covering By Disks One disk

Works and results found in the literature:

- *MCD* is as difficult the problem of given *n* numbers, find three of them that sum to 0. Proved by (Aronov and Har-Peled 2008).
- In (Drezner 1981) a $\mathcal{O}(n^2 \log n)$ algorithm was developed. The idea of our algorithm to sort the intersections by their angles comes from here.
- In (M. Chazelle and Lee 1986), a $\mathcal{O}(n^2)$ algorithm was developed. It actually solves an equivalent problem which is introduced next.

Let $\mathcal{D} = \{D_1, \dots, D_n\}$ be a set of n unit disks with weights $w_i > 0$. The maximum weight clique is defined as

$$\max_{q} \sum_{D_k \cap q \neq \emptyset} w_k,$$

- The disks are fixed with centers at $\mathscr{P} = \{p_1, \dots, p_n\}$ with $w_k = w(p_k)$.
- A clique is a non-empty intersection area of a subset of disks. We search for only a point in an optimal clique.
- An optimal solution for the maximum weight clique is an optimal solution for $MCD(\mathcal{P}, 1)$.

Figure: An instance of $MCD(\mathcal{P}, 1)$.



Figure: An instance of the Maximum Weight Clique Problem obtained from an instance of $MCD(\mathcal{P},1)$.

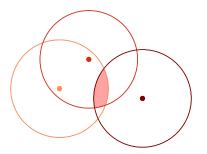
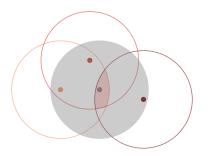


Figure: An instance of the Maximum Weight Clique Problem obtained from an instance of $MCD(\mathcal{P},1)$. In gray, the optimal solution.



Algorithm

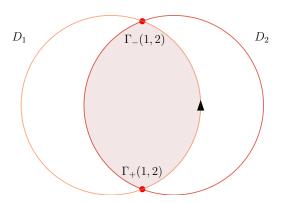
Defining
$$\Gamma_+(i,j)$$
 and $\Gamma_-(i,j)$:

Let D_i (at the origin) and D_j be two unit disks that intersect at two points.

- We know that the two intersection points define two arcs in D_i .
- One of the arcs bounds $D_i \cap D_j$. That is the one we want to determine.
- We can determine the polar angles of the two intersection points.
- Assuming counter-clockwise direction, we define $\Gamma_+(i,j)$ and $\Gamma_-(i,j)$ as the angles of intersection that determines the arc of D_i that bounds $D_i \cap D_j$.

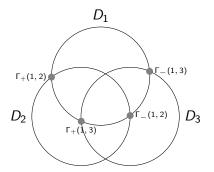
Algorithm

Figure: $\Gamma_+(1,2)$ and $\Gamma_-(1,2)$ example.



Algorithm

Figure: Three disks and their intersection points and angles.



Algorithm

For a disk D_i , a counter-clockwise traversal visits every $\Gamma_+(i,j)$ and $\Gamma_-(i,j)$ in counter-clockwise order.

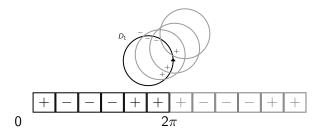
- An intersection region of disks is bounded by arcs.
- The arc $\Gamma_+(i,j)$, $\Gamma_-(i,j)$ (counter-clockwise) determines a region where i and j intersect.
- In a counter-clockwise traversal, the arcs where $\Gamma_+(i,j) > \Gamma_-(i,j)$ can be a problem for the implementation. The traversal is on a circle, where to start?
- If the traversal reaches a opening angle, we mark the intersecting disk as active. If it reaches a closing angle we unmark it.
- We want to find a point in the traversal with the most active disks.

Algorithm

For every disk, traverse the sorted list of intersection angles twice, keeping a set of active disks, and the current best solution.

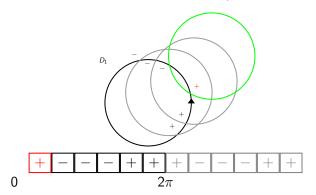
Doing the traversal twice solves the problem of deciding where to start.

Figure: The intersections list of a disk with three other disks.



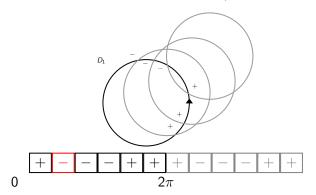
Algorithm

Figure: A traversal for D_1 with green disks representing the active set and red signs representing the current angle being visited (some are omitted).



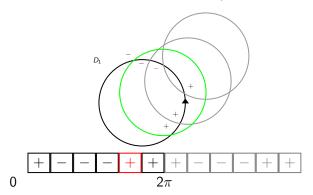
Algorithm

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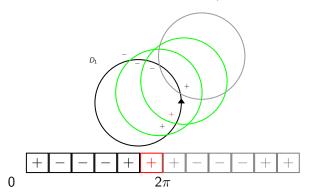
Algorithm

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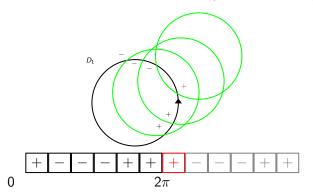
Algorithm

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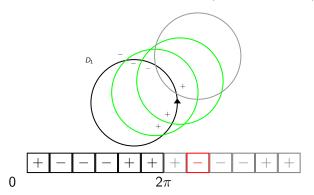
Algorithm

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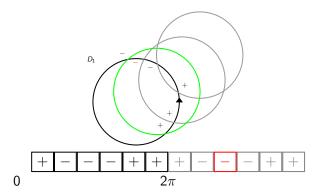
Algorithm

Figure: A traversal for D_1 with green disks representing the active set and red signs representing the current angle being visited (some are omitted).



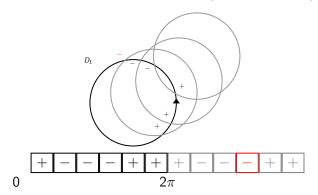
Algorithm

Figure: A traversal for D_1 with green disks representing the active set and red signs representing the current angle being visited (some are omitted).



Algorithm

Figure: A traversal for D_1 with green disks representing the active set and red signs representing the current angle being visited (some are omitted).



Algorithm

The run-time complexity of the algorithm is $\mathcal{O}(n^2 \log n)$.

- There are $\mathcal{O}(n^2)$ intersections among n disks.
- Sorting takes $\mathcal{O}(n^2 \log n)$.
- The traversal takes $\mathcal{O}(n)$ for every disk.
- It can be implemented in K log n where K is the number of intersections (L. Bentley and A. Ottmann 1979).

Maximum Covering by Disks Multiple disks

Works found in the literature:

- In (Berg, Cabello, and Har-Peled 2006) a $\mathcal{O}(n^{2m-1})$ algorithm was proposed. Also a (1ϵ) -approximation that runs in $\mathcal{O}(n \log n)$ was introduced.
- In (He et al. 2015) a heuristic method using an algorithm called mean-shift was developed. The mean-shift algorithm converges to a local density maxima of any probability distribution and it is used to find a smaller candidate list of centers for the disks.

Because of the similarities, we will discuss only the multiple ellipses algorithm later.

Ellipses

Ellipse

Given a center $c \in \mathbb{R}^2$ and $Q \in \mathbb{R}^{2 \times 2}$, an ellipse is the set of points that satisfy

$$||u-c||_Q^2 = (u-c)^T Q(u-c) = 1,$$

with \leq representing the set of covered points.

Axis-parallel ellipse

Any 2 by 2 diagonal d.p. matrix determines an axis-parallel ellipse, which can also be described by

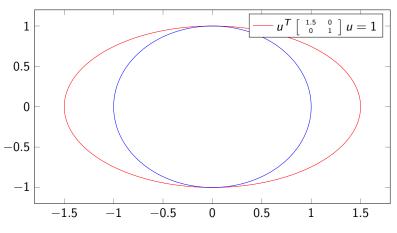
$$\frac{(x-c_x)^2}{a^2} + \frac{(y-c_y)^2}{b^2} = 1,$$

where (a, b) are the shape parameters and $c = (c_x, c_y)$ is the center.

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Ellipses

Figure: The ellipse seen as just a linear transformation of a circle.



One ellipse

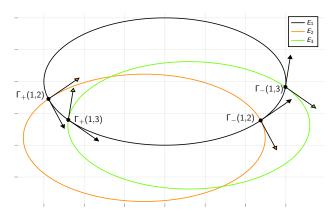
Let $MCE(\mathcal{P}, a, b)$ be an instance of the maximal covering by one ellipse, with E being an ellipse with shape parameters $(a, b) \in \mathbb{R}^2_{>0}$, an optimal solution of $MCE(\mathcal{P}, a, b)$ is given by

$$\max_{q} |\mathscr{P} \cap E(q)|,$$

- E(q) is an axis-parallel ellipse with center point q.
- Assuming unit weights for now.
- Same algorithm for one disk.

One ellipse

Figure: Intersection points of E_1 with E_2 and E_3 along with opening and closing angles indicators.



m ellipses

Let $MCE(\mathcal{P},\mathcal{E})$ be an instance of the maximal covering by ellipses, an optimal solution is given by

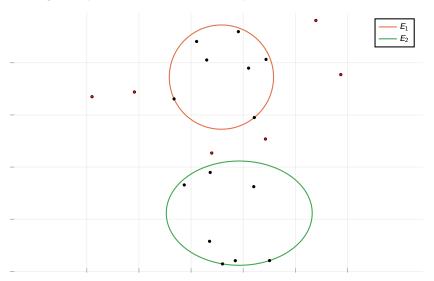
$$\max_{q_1,\ldots,q_m}\left|\bigcup_{i=1}^m\mathscr{P}\cap E_i(q_i)\right|,$$

- \mathscr{E} is a set of m ellipses.
- (Canbolat and Massow 2009) is the very first study on the problem. Slow exact method, a heuristic one was proposed.
- (Andretta and Birgin 2013) proposed a method that breaks the problem into smaller optimization ones. Also, they developed a method for the non-axis-parallel case.

Pre-processing that finds every possible coverage for ellipse E_i

```
1: A \leftarrow \bigcup_{i \in I_i} \{ \Gamma_+(i,j) \cup \Gamma_-(i,j) \}
2: Z ← {}
 3: Cov \leftarrow \{p_i\}
 4: for cnt = 1...2 do
       for a \in A do
 5.
          Let p_a be the point that intersects E_i at angle a.
 6:
    if a is a starting angle then
              Cov \leftarrow Cov \cup \{p_a\}
 8:
       else
 9.
10:
              Cov \leftarrow Cov \setminus \{p_a\}
           end if
11:
           Z \leftarrow Z \cup \{Cov\}
12:
        end for
13:
14: end for
```

Figure: Optimal solution with two ellipses for a random instance.



- The algorithm for m ellipses tries every possible assignment of coverage for every one of the ellipses.
- Run-time complexity of $\mathcal{O}(n^{2m})$.
- Simpler than the m disks algorithm proposed by (Berg, Cabello, and Har-Peled 2006). Achieves a similar complexity ($\mathcal{O}(n^{2m-1})$).
- Small improvements can be made in the pre-processing exhibited earlier in oder to reduce the size of the search space:
 - Non-maximal coverage sets.
 - Ellipses that are too distant do not need to be checked.
- The unit-weight assumption can be easily dropped.

Future Work

Primary goals:

- Study the (1ϵ) -approximation method for the planar covering with disks in (Berg, Cabello, and Har-Peled 2006) and develop an adapted version of the algorithm for ellipses with the same time complexity of $\mathcal{O}(n \log n)$.
- Develop an exact method for the version of the problem introduced in (Andretta and Birgin 2013) where the ellipses can be freely rotated.

Future Work

Secondary goals:

- Develop a probabilistic approximation algorithm based on (Aronov and Har-Peled 2008) which proposed a Monte Carlo approximation for the problem of finding the deepest point in a arrangement of regions. The method runs in $\mathcal{O}(n\epsilon^2 \log n)$ and can be applied to solve the case with one ellipse. The case with more than one ellipse is left as a challenge for us for the next steps of our research.
- In (He et al. 2015), the task of finding every center candidate, after eliminating all the non-essential ones, is done in $\mathcal{O}(n^5)$ run-time complexity. We want to generalize this for the elliptical distance function and achieve a better run-time complexity. We also intend to use the mean-shift algorithm to try to develop a greedy version for the ellipses version.

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