EFFICIENT INDEXING OF LINES WITH THE MQR-TREE

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Abstract: This paper presents an evaluation of the mqr-tree for indexing a database of line data. Many spatial access methods have been proposed for handling either point or region data, with the vast majority able to handle these data types efficiently. However, line segment data presents challenges for most spatial access methods. Recent work on the mqr-tree showed much potential for efficiently indexing line data. We identify limitations of the data sets in the initial evaluation. Then, we further evaluate the ability of the mqr-tree to efficiently index line sets with different organizations that address the limitations of the initial test. A comparison versus the R-tree shows that the mqr-tree achieves significantly lower overlap and overcoverage, which makes the mqr-tree a significant candidate for indexing line and line-segment data.

1 INTRODUCTION

Many applications exist that store and manipulate spatial data such as objects, points and lines. A spatial database (Samet, 1990; Shekhar and Chawla, 2003; Rigaux et al., 2001) contains a large collection of objects that are located in multidimensional space. For example, the Geological Survey of Canada maintains a repository of spatial data for many geoscience applications (Geological Survey of Canada, 2006), while the Protein Data Bank (Research Collaboratory For Structural Bioinformatics, 2004) contains many three-dimensional protein structures. An important issue in spatial data management is to efficiently retrieve objects based on their location by using a spatial access method (i.e., spatial index).

Many spatial access methods have been proposed in the literature (see (Gaede and Günther, 1998; Rigaux et al., 2001; Shekhar and Chawla, 2003) for comprehensive surveys). Most spatial access methods that have been proposed handle objects of arbitrary shape by utilizing a minimum bounding rectangle that estimates the extent of the object in all its dimensions. This works well for point data (a minimum bounding rectangle of zero area) and for most arbitrarily shaped objects. However, minimum bounding rectangles do not work well when representing lines or line segments. The problem is that a significant amount of whitespace is indexed because a potentially large minimum bounding rectangle is representing a small amount of data (Lin, 2008a; Lin, 2008b). This is depicted in Figure 1.

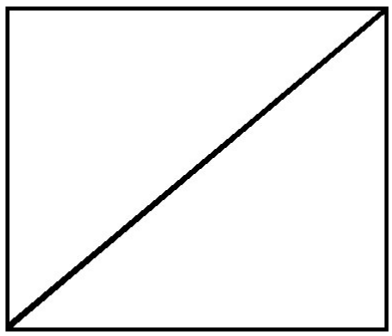
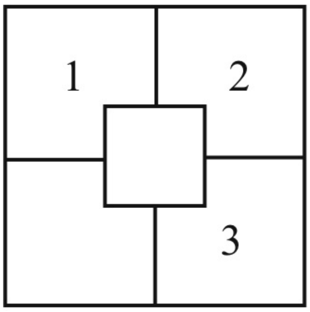


Figure 1: The MBR representation of a Line.

Over many lines, this problem results in significant overcoverage of whitespace and overlap of covered regions in space. One potential solution to this is to represent an n-dimensional line as a 2n-dimensional point. Although this would reduce overcoverage, the spatial locality of the line and its spatial relationship to other lines would be lost. Therefore another solution needs to be found.

A recently proposed spatial access method, the mqr-tree (Moreau and Osborn, 2008; Moreau et al., 2009), focuses on minimizing overcoverage and overlap when indexing arbitrary objects. In addition to efficiently handling objects of non-zero area, the mqr-



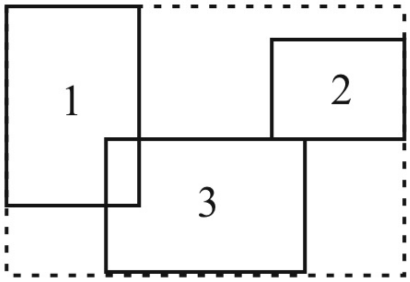


Figure 2: Node with Objects.

tree was show in an initial test to achieve significant improvements in overlap and overcoverage over a benchmark strategy when indexing line data. In addition, this initial test showed that very low overlap when indexing line data was achievable.

Therefore, we investigate further the ability of the mqr-tree to efficiently index line and line segment data. We identify limitations of the data sets in the initial evaluation that seemed to lead to the significant results. Then, we further evaluate the ability of the mqr-tree to efficiently index line sets of different arrangements that address the limitations of the initial test. A comparison versus a benchmark strategy shows that the mqr-tree achieves significantly lower overlap and overcoverage, which makes the mqr-tree a significant candidate for indexing line and line-segment data.

2 BACKGROUND

In this section, we present some background on the mqr-tree (Moreau and Osborn, 2008; Moreau et al., 2009).

The relative placement of an object in the tree is determined by using the centroid of its MBR. Figure 2 depicts the layout of the node. A node contains 5 locations. Each location can contain a pointer to either another node or an object. A node must have at least two locations that reference either an object or a subtree, unless it is the root. The origin of the node is the centre of the node. The centre is defined by the centroid of the minimum bounding rectangle for the node (called the **node MBR**). A node MBR is contains all objects in the node, and any subtrees of the node. As objects are added to and removed from the node, the node MBR may change, and therefore the centre of the node may change.

Figure 3 depicts the defined orientations, where *A* refers to the centroid of a new object, and *B* refers to the centre of the node. The orientations (NE, SE, SW, NW) are defined to include centroids that fall on the axes (E, S, W, N, respectively). Also, an equals (EQ) orientation is included, to handle two centroids that overlap.

$A_x = B_x$	$A_x > B_x$	$A_y = B_y$	$A_y > B_y$	Placement
0	0	0	0	SW
0	0	1	0	SW
0	0	0	1	NW
1	0	0	1	NW
0	1	0	0	SE
1	0	0	0	SE
0	1	0	1	NE
0	1	1	0	NE
1	0	1	0	EQ

Figure 3: Relative orientation of A with respect to B.

Figure 2 depicts a node containing three objects. Object 1 is located northwest of the centroid of the node MBR (defined by the dashed box on the diagram), while object 2 is located northeast of the centroid of the node MBR. Object 3 is located directly south of the node MBR centroid, therefore it is placed in the southeast quadrant.

3 EVALUATION

In this section, we present the results of our empirical evaluation of the mqr-tree. We compare the performance of the mqr-tree insertion algorithm with the R-tree insertion algorithm (Guttman, 1984), which is considered a benchmark strategy for spatial indexing. We first present the overall framework for evaluation across all tests, and the evaluation criteria. This is followed by the results of some initial tests on line segment data from road and railroad data sets that was obtained from (Theodoridis, 2005). Then, we present our strategy for further evaluation the mqr-tree as a tool for efficiently indexing line data. We present our generated data sets followed by the results of our evaluation on these data sets.

Table 1: Road and Railroad Data.

#lines	index	#nodes	height	coverage	overcoverage	overlap	sp. util
10,060(MXrrline)	mqr-tree	6735	12(9)	1294.95	541.89	2.20	49.87
	R-tree	3628	6	8834.97	4081.43	3541.75	74.94
11,381(CArrline)	mqr-tree	7755	14(9)	248.10	94.13	1.01	49.35
	R-tree	4061	6	9343.56	4441.01	4347.91	75.57
21,831(CArdline)	mqr-tree	14118	14(9)	352.01	97.20	4.19	50.93
	R-tree	7806	7	21061.17	9588.49	9495.51	75.38
36,074(CDrrline)	mqr-tree	23108	14(10)	4324.47	1561.67	18.18	50.36
	R-tree	12579	7	35258.29	15548.15	14004.79	75.10
92,392(MXrdline)	mqr-tree	58849	14(10)	2038.99	553.05	16.87	51.40
	R-tree	32871	8	93818.31	41733.99	41197.96	75.97
121,416(CDrdline)	mqr-tree	76998	16(11)	9500.39	2925.65	59.95	51.54
	R-tree	43435	8	133102.54	55875.50	53009.99	75.20

3.1 Tests and Evaluation Criteria

For each data set, we create 100 trees using each algorithm. Each tree was built using randomly ordered data. The number of nodes, height (both worst-case and average-case), average space utilization in each node, total coverage of all minimum bounding rectangles, total overcoverage (i.e., whitespace) of all minimum bounding rectangles, and the total overlap between all minimum bounding rectangles was calculated for each tree. We discuss 4 of those performance factors below:

- Average space utilization this is the average number of minimum bounding rectangles per node. Ideally, the higher the number of minimum bounding rectangles per node, the lower the number of nodes and height of the tree. Both the minimum bounding rectangles encompassing line segments and those encompassing other minimum bounding rectangles are included in this calculation.
- Overcoverage - the amount of white space (i.e., area with no lines) that is contains in the minimum bounding rectangles of a spatial access method. Ideally, this value should be very low. A higher overcoverage will result in searches along paths that will lead to no lines.
- Overlap - the amount of space covered by two or more minimum bounding rectangles. Overlap should be zero or very low. Significant amounts of overlap will cause searches to proceed down multiple paths of the tree that cover the same area. This will also likely result in unnecessary searching of space containing no lines.
- Height - The number of nodes from the root to the leaf node on the longest path of the index. The shorter the path, the shorter the search from root to leaf. However, shorter paths may result in trees with higher overlap and overcoverage. Since the R-tree is balanced, all paths are the same length and therefore the worst-case and average case height will be the same. Since the mqr-tree is not balanced, both the longest path and the average path length will be recorded. On all result tables, this will be indicated by the length of the longest path, followed by the average path length in parentheses.

3.2 Initial Results on Road and Railroad Data

Table 1 shows some initial results for the road and railroad data. The most significant results from this test is the significant improvement in overlap. In all cases, the mqr-tree achieves a 99% improvement in overlap over the R-tree. In addition, the mqr-tree achieves an improvement of 85-93% in coverage and of 86-95% in overcoverage. Although the mqr-tree has a higher tree height than the R-tree, it is expected that more efficient searching will be achieved due to the lower coverage, overcoverage and overlap. In addition, the space utilization of the mqr-tree is lower than that of the R-tree, it is still around 50%, which is considered a minimum space utilization for tree-based indices.

3.3 Initial Discussion

The results from the indexing of line segment data using the mqr-tree were very surprising. In particular, almost zero overlap is achieved when the mqr-tree is used to index the line segments. Further investigation has revealed some possible cause for this. First, the line segments representing roads are very small. Second, the data sets tend to have many roads that are

Table 2: Vertical and Horizontal Lines.

#lines	index	#nodes	height	coverage	overcoverage	overlap	sp. util
100	mqr-tree	57	6(4)	34571.13	12653.28	1309.00	54.74
	R-tree	39	3	40488.63	13807.45	2463.17	69.84
500	mqr-tree	293	8(5)	251619.56	67535.15	10782.32	54.06
	R-tree	194	4	294575.02	85176.98	28424.15	70.73
1,000	mqr-tree	587	8(6)	544531.26	132311.38	24121.85	54.04
	R-tree	393	4	692841.56	179163.89	70974.36	70.48
5,000	mqr-tree	2914	10(7)	3294526.16	655888.20	137649.08	54.31
	R-tree	1963	6	4949100.35	1205484.20	687245.10	70.38
10,000	mqr-tree	5810	10(7)	7001261.27	1292190.54	272790.92	54.42
	R-tree	3928	6	11279666.07	2815631.07	1796231.45	70.30
50,000	mqr-tree	28890	12(9)	41092930.57	6506622.52	1444385.16	54.61
	R-tree	19617	7	85868673.52	19473033.51	14410796.21	70.51
100,000	mqr-tree	58068	14(9)	87417415.91	13027973.89	2915851.35	54.44
	R-tree	39219	8	205702687.17	47676629.83	37564507.56	70.50

Table 3: Lines of Slope Between -∞ and ∞.

#lines	index	#nodes	height	coverage	overcoverage	overlap	sp. util
100	mqr-tree	59	6(4)	40021.36	11006.88	2441.98	53.56
	R-tree	39	3	47617.87	12800.31	4280.03	69.81
500	mqr-tree	289	8(5)	277018.50	56623.55	16207.52	54.53
	R-tree	197	4	311150.03	70262.15	30377.82	70.18
1,000	mqr-tree	572	8(6)	580037.86	108356.88	33389.45	54.93
	R-tree	391	4	776383.87	166387.47	92305.85	70.64
5,000	mqr-tree	2903	10(7)	3486989.73	537944.78	184403.61	54.44
	R-tree	1961	6	5137856.52	1063871.31	717682.80	70.45
10,000	mqr-tree	5818	10(7)	7371817.91	1051413.82	363377.43	54.37
	R-tree	3922	6	11436671.65	2472594.46	1800878.18	70.42
50,000	mqr-tree	28979	12(9)	42915843.65	5285883.19	1887563.59	54.51
	R-tree	19615	7	89757562.40	18564483.16	15266092.75	70.44
100,000	mqr-tree	58083	12(9)	91056946.13	10614180.99	3835949.08	54.43
	R-tree	39237	8	213156257.09	45368411.29	38807141.90	70.36

Table 4: Lines of Slope Between -2 and 2.

#lines	index	#nodes	height	coverage	overcoverage	overlap	sp. util
100	mqr-tree	55	6(4)	38648.07	9522.76	2265.87	56.00
	R-tree	38	3	43818.03	9755.68	2473.23	71.63
500	mqr-tree	284	8(5)	271315.60	50635.87	15181.68	55.14
	R-tree	197	4	314879.74	68341.60	33133.60	69.92
1,000	mqr-tree	581	8(6)	586703.65	100469.17	34995.16	54.39
	R-tree	394	4	772562.40	160297.46	96321.57	70.02
5,000	mqr-tree	2907	10(7)	3506656.31	492314.22	188213.63	54.39
	R-tree	1958	6	5216373.80	1035264.79	741290.20	70.56
10,000	mqr-tree	5760	10(7)	7445892.12	978976.22	386760.41	54.72
	R-tree	3920	6	11478278.50	2353996.93	1784494.27	70.55
50,000	mqr-tree	28909	12(9)	43421521.54	4935490.51	2017537.17	54.59
	R-tree	19613	7	88260071.68	17518910.22	14743746.56	70.38
100,000	mqr-tree	57942	12(9)	91993440.97	9851272.75	4044739.59	54.52
	R-tree	39201	8	206456490.77	42566148.58	37070996.81	70.62

predominantly horizontal or vertical (more or less).

This lead to the following questions - what would happen if:

1. More diagonal line segments are indexed?
2. The line segments are longer?

We are interested to see if the above affect overlap, overcoverage, and tree height.

3.4 Data Sets

For our follow-up evaluation, we generated collections of lines that vary in set size and slope. Each line set contains between 100 and 100,000 lines. We use a line length of 10 units in all cases. We chose to generate our own line sets for the follow-up evaluation because this would allow us to generate data that reflects the best-case, average-case and worst-case scenarios, and determine according how the mqr-tree will perform for each scenario.

For slope, we test both vertical and horizontal lines, as well as diagonal lines.

We create three types of files:

- half horizontal, half vertical lines. This is considered to be the best-case scenario. Every line in this set will have a minimum bounding rectangle with an overcoverage of zero. Overcoverage will still exist in higher-level minimum bounding rectangles that encompass the lines.
- equal distribution between horizontal,vertical, slope of 1/2, slope of 1, slope of 2, slope of -1/2, slope of -1 and slope of -2. This is considered the average case. Here we have both lines that can be contained with a minimum bounding rectangle with zero overcoverage, lines that will achieve the worst overcoverage when contained with a minimum bounding rectangle.
- equal distribution between slope of 1/2, slope of 1, slope of 2, slope of -1/2, slope of -1 and slope of -2. This is considered to be the worst case. Here, all minimum bounding rectangles that contain lines are all of non-zero overlap.

Using these data sets, we run the same tests as above for the road and railroad data.

3.5 Evaluation on Vertical and Horizontal Data Sets

Our first evaluation was to compare the mqr-tree with the R-tree on indexing the horizontal and vertical line sets. This is expected to produce the best results since at the leaf level, the overcoverage of minimum bounding rectangles will be zero and the overlap will be very low (effectively, the only overlap are the intersection points between two lines).

Table 2 presents the results for the horizontal and vertical line sets. Again, we find the most significant result to be in the improvement in overlap. The mqr-tree achieves lower overlap in all cases. Although the improvement amounts are not as high as with the road and railroad data, they are still significant, especially in the data sets with the higher number of line segments. Overall, we find in the smaller sets an improvement of approximately 45-50% lower overlap over the R-tree, while in the larger sets the improvement is as high as 92%. We also find the same trends for coverage and overcoverage, with improvements that increase from 3% to 58% for coverage and from 9% to 73% for overcoverage. The height, although still high in the mqr-tree, is comparable to those obtained in the initial road and railroad data tests.

3.6 Evaluation on Uniform Data Sets

Our next evaluation is to compare the mqr-tree and R-tree using the uniform data sets, where in each there are an equal number of vertical and horizontal lines, and lines of varying slope. Table 3 presents this results. We find results that are very similar to those for the horizontal and vertical line sets. We find that the mqr-tree achieves an improvement in overlap that ranges from 43% for the smaller data sets to 90% for the largest one. Similarly, we find improvements in coverage that fall between 3% and 57%, and for overcoverage that fall between 14% and 77%. This is very reassuring because it appears that diagonal lines (which in this case, make up 3/4ths of each data set) do not significantly affect the performance criteria.

3.7 Evaluation on Sloped Lines Only

Our last test is to compare the performance of the mqr-tree and R-tree on data sets containing only sloped lines, and no horizontal or vertical lines. This is considered to be our worse-case scenario because at the leaf level, all minimum bounding rectangles will have significant overcoverage. However, we still find in Table 4 that for the most part the performance improvements of the mqr-tree over the R-tree are as significant as those found in the other evaluations. The only improvement that is not as significant is in the overlap decrease for the smallest test set. However, the mqr-tree still achieves lower overlap in this case.

4 CONCLUSIONS AND FUTURE WORK

In this paper, we present our investigation into the indexing of line and line-segment data using the mqr-tree, based on initial results that showed its potential for efficiently indexing such data. Our experiments showed that the mqr-tree outperforms the R-tree for indexing line data by achieving significantly lower overlap, coverage and overcoverage.

Future work includes the following. First, the mqr-tree was evaluated for coverage, overcoverage and overlap via multiple insertions. It is equally important to determine if significant reductions in these performance criteria are still possible after updates and deletions are performed. Second, the mqr-tree needs to be evaluated for its ability to be utilized for region and exact-match searches in the presence of line data. This would also be compared with the searching ability of the R-tree and other benchmark strategies. Third, although we compared the mqr-tree with the R-tree, its performance also needs to be compared with other proposed strategies, such as (Hoel and Samet, 1991; Lin, 2008a; Lin, 2008b). Finally, our most important goal is to both decrease the height and increase the node size (i.e., node capacity) of the mqr-tree without sacrificing its improvement in overcoverage and overlap.

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