16350: Planning Techniques for Robotics, Homework 2

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1. Running Instructions

To run my code, use the following commands:
mex planner.cpp;
clear all; close all;
startQ = [pi/2 pi/4 pi/2 pi/4 pi/2];
goalQ = [pi/8 3*pi/4 pi 0.9*pi 1.5*pi];
planner_id = 0;
runtest('map1.txt', startQ, goalQ, planner_id);

Each time a different start or goal configuration is tested, could you please re-compile the code as a precaution against memory leaks (for example in the plan) or use a combination of clc, clear all and close all. There is a chance of errors occuring without recompiling.

Planner ids are assigned as follows.
$0 \rightarrow RRT$
$1 \rightarrow RRTConnect$
$2 \rightarrow RRTStar$
$3 \rightarrow PRM$

2. Information common to all approaches

2.1. Checking validity of arm configuration

To check validity of a configuration, I used the function provided IsValidArmConfiguration. It was also used to always check the validity of the start and goal configuration.

2.2. Checking validity of transition between configurations

To check validity of a move, I divided the interval between the 2 nodes into a number of steps. I wrote a function to check validity of every configuration in the interval of the distance between the 2 nodes at a resolution of distance/steps.

2.3. Procuring random node

To generate a random node, a while loop was used and a series of random angles were generated. If these angles formed a valid configuration, the loop was terminated. For RRT and RRTConnect, **the goal was sampled 15 percent of the time.** For RRT star, the goal was sampled 15 percent of the time until it was added to the graph as a node.

2.4. Finding closest node

To find the closest node, rms error of the difference between the joint angle of the node in question and each node in the graph/tree is calculated and the node with minimum distance is selected.

2.5. State of nodes

For RRT, RRTConnect and RRTStar, we have the state of the system as a structure with angles, previous node, cost and node number as attributes. For PRM, the state of the system is a class with angles, previous node, cost, node number, a vector of nearest neighbors and several member functions. A class is used for PRM because accessing each member's vector container, inserting and deleting is easier.

3. Summary of approach

3.1. RRT

For the RRT algorithm, I used an loop which is conditioned to break when the goal is reached. It selects nodes at random, calculates the nearest neighbour from the existing nodes on the tree and attempts to reach the nearest neighbour. If the distance between the closest node on the tree and the random node is greater than a certain threshold $epsilon$, a new node is added to the tree in the direction of the random node at a distance epsilon. Otherwise, the random node and nearest neighbour are connected. Validity of a configuration and transitions between configurations are checked in every iteration. The algorithm is the same as the one in the slides. Epsilon is 0.5. Number of steps is 100.

3.2. RRTConnect

For the RRTConnect algorithm, the extend function is the same as the one in RRT. The only difference is there are 2 graphs now. A swap of graphs occurs at the end of every extension and the connect function commences. In the connect function, the newest node generated attempts to connect to the closest neighbor on the other tree. If a situation arises where the search is trapped during extension, the graphs are simply swapped and the extend function is called again. Validity of a configuration and transitions between configurations are checked in every iteration. The algorithm is the same as the one in the slides. Epsilon is 0.5. Number of steps for the extend function to check validity of configuration is 100. Number of steps for the connect function is 1000 as it may sometimes attempt to connect a distance greater than epsilon.

3.3. RRTStar

RRT star extend function is the same as RRT. Except it does not terminate when the goal is reached. Instead once the goal is reached, rewiring is done. The graph is rewired an arbitary number of times to get the best possible path during and after the goal is reached. The number of times rewiring occurs after the goal is reached depends on an arbitary number of samples which is set to 50 in this scenario.

The radius of neighbors shrinks as the number of nodes added increases in accordance with the lecture slides. The constant chosen when computing radius is 250 as per the given formula. Epsilon is 0.5.

3.4. PRM

PRM always constructs a graph of 5000 random nodes plus the start and goal state. It attempts to connect these nodes if they are not already connected. The criteria for connection is a radius of 2 m. The number of neighbors per node are prioritized on the basis of the distances between vertices. An arbitrary priority queue with a vector container and a heap are deployed for the purpose. The number of contents in this container is limited to 3. The contents are popped and then pushed into the nearest neighbour vector container belonging to each node. A Dijkstra search is then performed using the graph and the path is computed.

4. Experimental Results

4.1. Results on map1

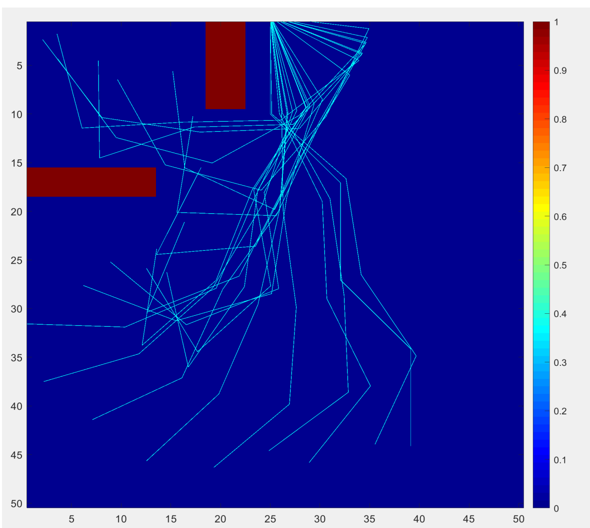

Figure 1: RRT

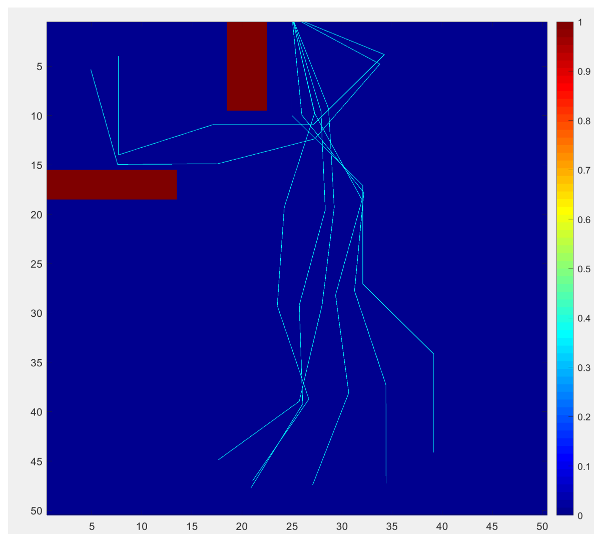

Figure 2: RRT Connect

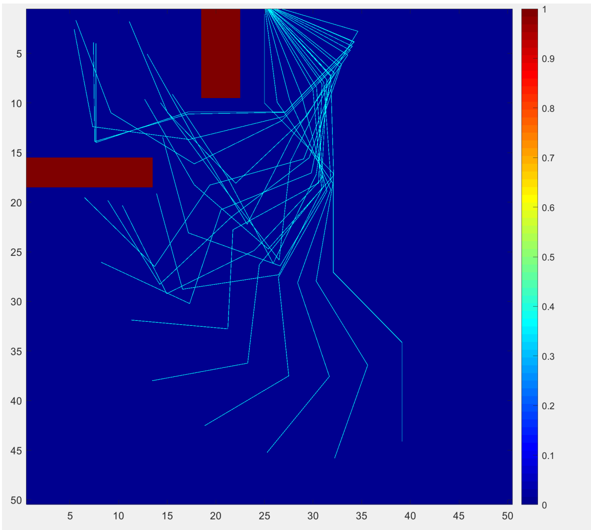

Figure 3: RRT Star

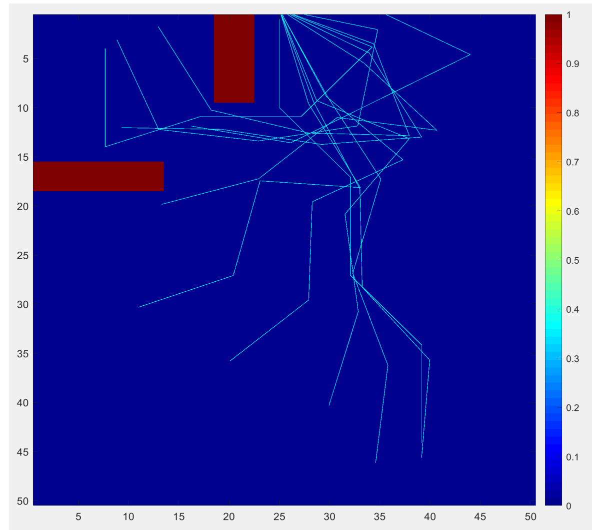

Figure 4: PRM

4.2. Experimental Set-up

For map2, I ran all 4 planners for 20 different feasible start and goal positions. For each start and goal position and a corresponding planner, I repeated the run 10 times to check the variation in path quality and to check the success rate of the planner in general. A summary of my results is recorded in the table in the result discussion subsection. A more detailed summary is given in the appendix where I have reported the start and goal pairs and the statistics for at least one of 10 iterations of the same start and goal.

4.3. Performance metrics

4.3.1 Average Time taken

Time taken is calculated using clock_t from the ctime library. It is the number of clock ticks elapsed since an epoch related to the particular program executio and can be reported in seconds. Typically the planner was made to terminate in 20 seconds if a path was not found. For PRM, it is pertinent to note that the time taken accounts only for path planning in an already constructed graph. Time for graph construction is around 46 seconds on an average.

4.3.2 Under 5 seconds

Since, we ran each planner 10 times for each of the 20 start and goal pair, a path was computed at least once during those 10 times. It could be argued that the success rate is 100 percent for finding a path for each configuration. However from a more realistic standpoint, I only took into account the first of each of the 10 runs while calculating success statistics for computing a path under 5 percent. They are shown in the table.

4.3.3 Plan Quality

Plan Quality is basically the rms distance travelled between each of the joint angles during the entire path execution. Higher the plan quality number, greater the distance traversed and poorer is the solution.

4.3.4 Tree vertices

It is the average number of nodes in the graph generated. For PRM, it remains fixed at 5000 plus the start and the goal.

4.4. Variation in plan quality

This metric computes the variation in the quality of the path over 10 iterations of the same start and goal pair. It then computes the average of this variation across all the start and goal pairs.

4.5. Result Discussion

Average	Time Taken (sec)	Plan Quality	Tree vertices	Under 5 seconds(%)	Variation in plan quality
RRT	0.2266	20.21	1226	85	32.269
RRT Connect	0.000	17.01	52	100	29.635
RRT Star	1.59	8.403	1454	90	9.63
PRM	0.0001	9.281	5002	95	7.72

Figure 5: A summary of results shown for map 2

RRT has the second greatest average planning time. It fails to generate a path under 5 seconds nearly 15 percent of the time. In terms of path variation, it is also the highest. This comes as no surprise as RRT is a purely randomized approach. Plan Quality is also the worst. This is because the path is not optimized once it is generated. In terms of the number of tree vertices, on an average there were 1226 which was less than RRT Connect and RRT Star. It is a sub-optimal solution

RRT Connect is definitely the fastest algorithm, though its speed comes with a penalty on its path quality. It generates a path under 5 seconds 100 percent of the time. Since it attempts to connect at a distance greater than epsilon and consequently does not optimize the traversed path further, the path often has poor quality as demonstrated in the table. In terms of tree vertices, it has the fewest as compared to all the remaining algorithms. Variation in path qualities is also quite high which is indicative of the randomized process. It is a sub-optimal solution as demonstrated by path quality.

RRT star is probably the slowest of all the algorithms if you dont taken into account graph construction time for PRM. This is because it is optimized or rewired as many times as the number of samples indicated. In terms of path quality, it is probably the best because of rewiring. Variation is also quite low. It success rate for path generation under 5 seconds is 90 percent. It is asymptotically optimal in the limit of the number of samples as demonstrated by the path quality value.

PRM is probably almost as fast as RRT Connect if you only taken into account execution time after the graph is constructed. It has the smallest path variation. 5000 nodes plus the start and the goal are used in each case. It generates a path in under 5 seconds 95 percent of the time. The one time it failed is probably because the necessary sampled were not sampled in graph construction. Plan quality is also pretty good.

5. Conclusion

In terms of time taken, RRT connect is probably the fastest. It can be used when a fast solution is needed even if it is sub-optimal. PRM is probably the best planner if you don't take into account time taken for one time path generation. Provided the graph is well constructed and you use an algorithm like A star search, the solution is quite optimal. Repeated replanning in the same environment will be best suppported by PRM. PRM is the best if a trade-off is required in temrs of optimality and time taken for execution.

PRM and RRT star are the best in terms of path qualities and optimality. RRT connect is good if optimality is not an issue and a fast path generation is required.

6. Appendix

	Start state					Goal state				
1	0.2416	1.8585	2.9219	0.5657	2.8103	0.2219	3.2610	1.0928	1.6832	1.1329
2	1.8707	0.7739	4.2335	5.4700	2.8084	1.1114	6.0218	2.3960	1.3565	4.3026
3	0.7839	5.9265	3.2728	1.7361	1.7749	1.8600	1.7432	0.1360	3.9053	0.8199
4	1.7150	0.7607	1.5674	2.6126	0.3315	0.8964	2.7177	0.3622	4.7154	1.9524
5	1.7190	1.7660	1.6350	6.1710	2.1870	1.4520	1.1560	4.4670	1.2360	2.3020
6	1.5708	1.0472	2.0944	1.0472	1.5708	1.5708	1.0472	2.0944	1.0472	1.5708
7	0.8107	1.7198	0.0027	5.7902	3.7948	1.5708	1.0472	2.0944	3.1416	2.3562
8	0.5910	5.8370	2.2340	2.9970	5.1811	1.6688	0.2652	2.0959	6.1956	4.8930
9	1.4353	2.0702	6.0606	0.3448	5.4481	0.8443	0.3528	3.7543	1.7448	0.9551
10	0.8592	0.5087	0.7183	2.4646	6.2609	0.6015	3.4368	0.8803	1.1662	0.4894
11	1.4238	0.6355	2.9122	4.8964	0.2577	0.2608	2.5087	1.9737	0.4491	2.4801
12	0.3026	2.3469	1.0374	2.6907	2.5287	1.2126	2.0548	1.8194	0.9624	1.7154
13	0.7741	2.2073	5.3012	5.6220	3.0310	0.3361	1.5676	2.3891	1.2366	3.3062
14	0.3620	6.1938	2.0370	4.4696	3.3262	1.6916	6.0613	2.3394	0.8399	6.2688
15	0.6583	0.2775	3.8002	2.1041	4.7984	1.8094	2.8249	0.5891	0.2602	1.6134
16	0.5818	2.0376	0.7739	5.8776	1.8796	1.2054	2.1691	0.8322	3.8098	2.7973
17	0.5904	0.3845	5.3321	2.9731	6.1346	1.7870	3.0928	0.2922	5.7323	0.2692
18	1.7421	5.7532	0.5864	4.7250	1.8224	1.7584	1.2429	2.3609	3.2705	0.8061
19	0.8462	2.8688	2.7367	5.7564	6.0788	0.7358	2.1313	0.3099	3.3622	3.0953
20	0.8709	2.4322	2.1785	6.1890	0.7653	1.6788	1.4213	3.0564	0.6297	0.9850

Figure 6: Start and Goal states

	RRT
1	Time elapsed: 0.015000 | Node number 132 | Path Quality 17.964916 | Plan Length 7
2	Time elapsed: 0.012000 | Node number 92 | Path Quality 23.273711 | Plan Length 8
3	Time elapsed: 0.045000 | Node number 296 | Path Quality 38.531944 | Plan Length 16
4	Time elapsed: 0.004000 | Node number 36 | Path Quality 16.161152 | Plan Length 8
5	Time elapsed: 0.006000 | Node number 36 | Path Quality 7.676240 | Plan Length 3
6	Time elapsed: 0.011000 | Node number 59 | Path Quality 14.231683 | Plan Length 6
7	Time elapsed: 0.000000 | Node number 21 | Path Quality 21.711191 | Plan Length 8
8	Time elapsed: 2.259000 | Node number 8176 | Path Quality 33.099943 | Plan Length 12
9	Time elapsed: 0.036000 | Node number 289 | Path Quality 21.551370 | Plan Length 8
10	Time elapsed: 0.030000 | Node number 253 | Path Quality 31.707353 | Plan Length 9
11	Time elapsed: 0.052000 | Node number 152 | Path Quality 27.137063 | Plan Length 13
12	Time elapsed: 0.006000 | Node number 55 | Path Quality 15.799768 | Plan Length 7
13	Time elapsed: 0.009000 | Node number 62 | Path Quality 23.332854 | Plan Length 13
14	Time elapsed: 0.020000 | Node number 228 | Path Quality 38.355132 | Plan Length 12
15	Time elapsed: 0.060000 | Node number 527 | Path Quality 35.625697 | Plan Length 16
16	Time elapsed: 0.004000 | Node number 26 | Path Quality 11.679134 | Plan Length 5
17	Time elapsed: 0.505000 | Node number 4070 | Path Quality 34.317305 | Plan Length 17
18	Time elapsed: 0.030000 | Node number 132 | Path Quality 18.956984 | Plan Length 8
19	Time elapsed: 0.005000 | Node number 9 | Path Quality 7.905663 | Plan Length 4
20	Time elapsed: 0.016000 | Node number 157 | Path Quality 6.912795 | Plan Length 4

Figure 7: RRT

	RRT CONNECT
1	Time elapsed: 0.000000 | Node number 3 | Path Quality 3.062002 | Plan Length 3
2	Time elapsed: 0.008000 | Node number 31 | Path Quality 25.193538 | Plan Length 10
3	Time elapsed: 0.040000 | Node number 344 | Path Quality 19.400812 | Plan Length 11
4	Time elapsed: 0.000000 | Node number 3 | Path Quality 3.605752 | Plan Length 3
5	Time elapsed: 0.004000 | Node number 18 | Path Quality 12.21000 | Plan Length 10
6	Time elapsed: 0.000000 | Node number 3 | Path Quality 1.000000 | Plan Length 3
7	Time elapsed: 0.000000 | Node number 13 | Path Quality 7.728295 | Plan Length 5
8	Time elapsed: 0.024000 | Node number 141 | Path Quality 31.243856 | Plan Length 8
9	Time elapsed: 0.004000 | Node number 30 | Path Quality 22.202843 | Plan Length 12
10	Time elapsed: 0.008000 | Node number 32 | Path Quality 23.580794 | Plan Length 14
11	Time elapsed: 0.008000 | Node number 13 | Path Quality 13.188178 | Plan Length 6
12	Time elapsed: 0.004000 | Node number 12 | Path Quality 3.874876 | Plan Length 6
13	Time elapsed: 0.008000 | Node number 70 | Path Quality 37.039877 | Plan Length 14
14	Time elapsed: 0.044000 | Node number 332 | Path Quality 41.319314 | Plan Length 17
15	Time elapsed: 0.004000 | Node number 6 | Path Quality 6.631006 | Plan Length 4
16	Time elapsed: 0.004000 | Node number 5 | Path Quality 2.743149 | Plan Length 4
17	Time elapsed: 0.012000 | Node number 38 | Path Quality 31.915984 | Plan Length 14
18	Time elapsed: 0.012000 | Node number 56 | Path Quality 22.587451 | Plan Length 10
19	Time elapsed: 0.004000 | Node number 24 | Path Quality 11.562288 | Plan Length 8
20	Time elapsed: 0.000000 | Node number 6 | Path Quality 20.558251 | Plan Length 5

Figure 8: RRT Connect

	RRT STAR
1	Time elapsed: 0.093000 | Node number 1008 | Path Quality 3.062002 | Plan Length 8
2	Time elapsed: 3.985000 | Node number 5054 | Path Quality 19.532972 | Plan Length 41
3	Time elapsed: 1.937000 | Node number 1219 | Path Quality 10.754749 | Plan Length 23
4	Time elapsed: 0.157000 | Node number 1009 | Path Quality 3.605752 | Plan Length 9
5	Time elapsed: 0.125000 | Node number 1017 | Path Quality 7.090308 | Plan Length 16
6	Time elapsed: 0.140000 | Node number 1007 | Path Quality 2.533153 | Plan Length 7
7	Time elapsed: 0.219000 | Node number 1024 | Path Quality 5.026904 | Plan Length 12
8	Time elapsed: 0.156000 | Node number 1034 | Path Quality 8.488662 | Plan Length 18 Start
9	Time elapsed: 0.126000 | Node number 1009 | Path Quality 2.887014 | Plan Length 7
10	Time elapsed: 14.763000 | Node number 2309 | Path Quality 23.120937 | Plan Length 48
11	Time elapsed: 0.295000 | Node number 1141 | Path Quality 9.226269 | Plan Length 20
12	Time elapsed: 0.171000 | Node number 1081 | Path Quality 3.587885 | Plan Length 9
13	Time elapsed: 0.156000 | Node number 1022 | Path Quality 8.023874 | Plan Length 18
14	Time elapsed: 0.187000 | Node number 1022 | Path Quality 7.393175 | Plan Length 16
15	Time elapsed: 1.016000 | Node number 1138 | Path Quality 12.020779 | Plan Length 26
16	Time elapsed: 0.125000 | Node number 1007 | Path Quality 2.629849 | Plan Length 7
17	Time elapsed: 0.156000 | Node number 1034 | Path Quality 8.488662 | Plan Length 18
18	Time elapsed: 3.920000 | Node number 3244 | Path Quality 13.960928 | Plan Length 29
19	Time elapsed: 0.172000 | Node number 1018 | Path Quality 5.818998 | Plan Length 13
20	Time elapsed: 2.437000 | Node number 1683 | Path Quality 11.895128 | Plan Length 25

Figure 9: RRT Star

	PRM
1	Time elapsed: 0.004000 | Node number 5002 | Path Quality 5.382022 | Plan Length 9
2	Time elapsed: 0.004000 | Node number 5002 | Path Quality 20.204435 | PlanLength 23
3	Time elapsed: 0.000000 | Node number 5002 | Path Quality 13.709024 | PlanLength 17
4	Time elapsed: 0.004000 | Node number 5002 | Path Quality 7.084345 | Plan Length 12
5	Time elapsed: 0.000000 | Node number 5002 | Path Quality 8.546685 | Plan Length 12
6	Time elapsed: 0.000000 | Node number 5002 | Path Quality 0.756464 | Plan Length 3
7	Time elapsed: 0.000000 | Node number 5002 | Path Quality 7.954561 | Plan Length 11
8	Time elapsed: 0.006000 | Node number 5002 | Path Quality 13.110018 | PlanLength 16
9	Time elapsed: 0.000000 | Node number 5002 | Path Quality 11.378563 | Plan Length 14
10	Time elapsed: 0.004000 | Node number 5002 | Path Quality 10.070297 | PlanLength 14
11	Time elapsed: 0.000000 | Node number 5002 | Path Quality 10.878681 | Plan Length 14
12	Time elapsed: 0.000000 | Node number 5002 | Path Quality 5.014528 | Plan Length 8
13	Time elapsed: 0.004000 | Node number 5002 | Path Quality 11.018976 | Plan Length 16
14	Time elapsed: 0.004000 | Node number 5002 | Path Quality 9.394679 | Plan Length 10
15	Time elapsed: 0.000000 | Node number 5002 | Path Quality 9.998115 | Plan Length 15
16	Time elapsed: 0.000000 | Node number 5002 | Path Quality 5.208378 | Plan Length 10
17	Time elapsed: 0.000000 | Node number 5002 | Path Quality 15.442868 | Plan Length 19
18	Time elapsed: 0.004000 | Node number 5002 | Path Quality 20.559908 | Plan Length 27
19	Time elapsed: 0.000000 | Node number 5002 | Path Quality 7.424072 | Plan Length 11
20	Time elapsed: 0.004000 | Node number 5002 | Path Quality 9.490591 | Plan Length 14

Figure 10: PRM