Appendix G: Simulation Procedure

Pre-requisite: *mrs_env_simulator*, *cfe_module*, *env_stats*, *fyp_commands*

Pre-Simulation Set-up

Create a catkin workspace and download the first three packages into the src folder. An additional folder titled *store* can be created for storage of map related files produced in step 6. The *.sh files can be obtained by pasting the files from *fyp_commands* into the workspace. See Figure G1 for recommended file structure.

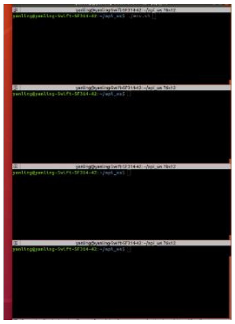
```
catkin_ws
   -   devel
   -   build
   -   src
          -   cfe_module
          -   env_stats
          -   mrs_env_simulator

   -   store
   -   *.sh
```

Figure G1: Recommended file structure for workspace

Simulation Procedure

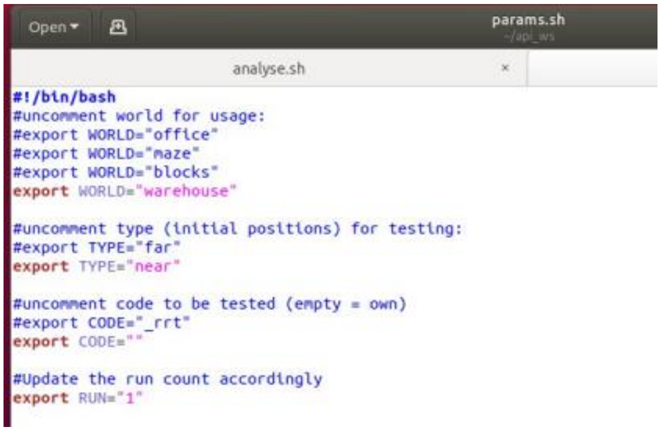
Step 1: In the catkin_ws, open up 4 terminals (terminator was used in this case). If not already done, run this command: chmod +x *.sh



```
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$ ./env.sh
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$
```

Figure G2: 4 empty terminals created with *terminator* in the catkin_ws

Step 2: Bring up the params.sh file which contains details about the simulation.



```
#!/bin/bash
#uncomment world for usage:
#export WORLD="office"
#export WORLD="maze"
#export WORLD="blocks"
export WORLD="warehouse"

#uncomment type (initial positions) for testing:
#export TYPE="far"
export TYPE="near"

#uncomment code to be tested (empty = own)
#export CODE="_rrt"
export CODE=""

#Update the run count accordingly
export RUN="1"
```

Figure G3: params.sh

WORLD refers to one of the four simulation environments.

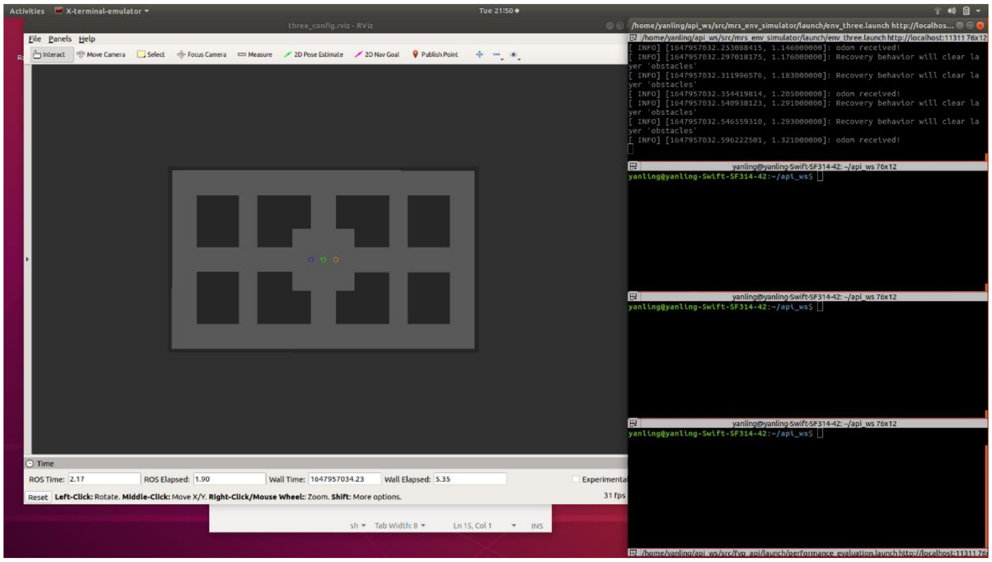
TYPE refers to the initial configuration.

CODE refers to the algorithm that is being tested.

RUN refers to the simulation count (e.g., 1st run, 5th run)

Uncomment the lines for usage.

Step 3: In one terminal, run the command: ./env.sh



ROS Time: 2.17 ROS Elapsed: 1.90 Wall Time: 1647957034.23 Wall Elapsed: 5.35

Left-Click: Rotate. Middle-Click: Move X/Y. Right-Click/Mouse Wheel: Zoom. Shift: More options.

```
/home/yanling/api_ws/src/mrs_env_simulator/launch/env_three.launch http://localhost:11311 76x12
[ INFO] [1647957032.253088415, 1.146000000]: odom received!
[ INFO] [1647957032.297018175, 1.176000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.311996576, 1.183000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.354419814, 1.205000000]: odom received!
[ INFO] [1647957032.540938123, 1.291000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.546559310, 1.293000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.596222501, 1.321000000]: odom received!
```

```
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$
```

```
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$
```

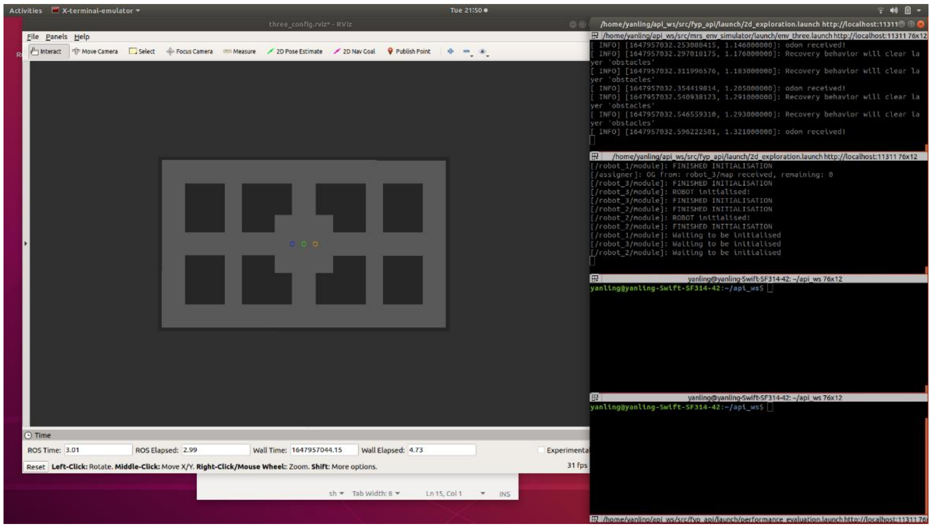
```
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$
```

```
/home/yanling/api_ws/src/top_api/launch/performance_evaluation.launch http://localhost:11311 76
```

Figure G4: Screenshot of interface after ./env.sh is run.

The environment will be brought up with ./env.sh. The Gazebo simulation has been suppressed in the env_three.launch file (in *mrs_env_simulator*) for speed and can be enabled by changing the <*gui*> tag.
Environment is fully simulated after "odom_received" appears as the last line.

Step 4: In another terminal, run the command: ./run.sh



ROS Time: 3.01 ROS Elapsed: 2.99 Wall Time: 1647957044.15 Wall Elapsed: 4.73

Left-Click: Rotate. **Middle-Click:** Move X/Y. **Right-Click/Mouse Wheel:**: Zoom. **Shift:** More options.

/home/yanling/api_ws/src/fyp_api/launch/2d_exploration.launch http://localhost:11311

/home/yanling/api_ws/src/mrs_env_simulator/launch/env_three.launch http://localhost:11311 76x12

```
[ INFO] [1647957032.253088415, 1.146000000]: odom received!
[ INFO] [1647957032.297018175, 1.176000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.311996576, 1.183000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.354419814, 1.285000000]: odom received!
[ INFO] [1647957032.540938123, 1.291000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.546559310, 1.293000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.596222501, 1.321000000]: odom received!
```

/home/yanling/api_ws/src/fyp_api/launch/2d_exploration.launch http://localhost:11311 76x12

```
[/robot_1/module]: FINISHED INITIALISATION
[/assigner]: OG from: robot_3/map received, remaining: 0
[/robot_3/module]: FINISHED INITIALISATION
[/robot_3/module]: ROBOT initialised!
[/robot_3/module]: FINISHED INITIALISATION
[/robot_2/module]: FINISHED INITIALISATION
[/robot_2/module]: ROBOT initialised!
[/robot_2/module]: FINISHED INITIALISATION
[/robot_1/module]: Waiting to be initialised
[/robot_3/module]: Waiting to be initialised
[/robot_2/module]: Waiting to be initialised
```

yanling@yanling-Swift-SF314-42: ~/api_ws 76x12

```
yanling@yanling-Swift-SF314-42:~/api_ws$
```

yanling@yanling-Swift-SF314-42: ~/api_ws 76x12

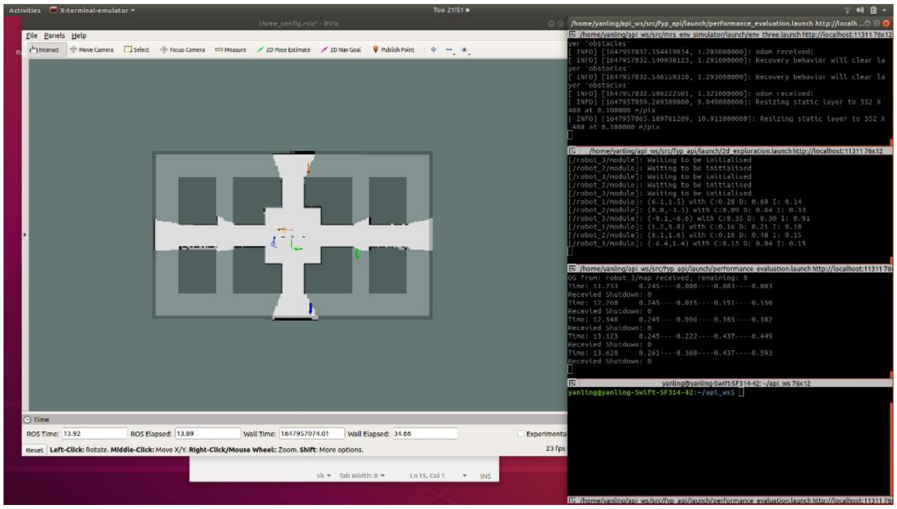
```
yanling@yanling-Swift-SF314-42:~/api_ws$
```

/home/yanling/api_ws/src/fyp_api/launch/performance_evaluation.launch http://localhost:11311 76

Figure G5: Screenshot of interface after ./run.sh is run.

This starts the exploration with CFE by launching the necessary nodes in the *cfe_module*. The functionality of CFE is described in Section 4 and is characterised by the nodes which are: the *detector*, the *filter* and the *allocator*. The robots will start moving towards their target points through the *move_base_node*.

Step 5: In another terminal, run this command: ./stats.sh



ROS Time: 13.92 ROS Elapsed: 13.89 Wall Time: 1647957074.01 Wall Elapsed: 34.66

```
/home/yanling/api_ws/src/fyp_api/launch/performance_evaluation.launch http://localh...
/home/yanling/api_ws/src/mrs_env_simulator/launch/env_three.launch http://localhost:11311 76x12
yer 'obstacles'
[ INFO] [1647957832.354419814, 1.285000000]: odom received!
[ INFO] [1647957832.540938123, 1.291000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957832.546559310, 1.293000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957832.596222501, 1.321000000]: odom received!
[ INFO] [1647957859.269309800, 9.049000000]: Resizing static layer to 352 X
480 at 0.100000 m/pix
[ INFO] [1647957865.189761209, 10.911000000]: Resizing static layer to 352 X
 480 at 0.100000 m/pix
```

```
/home/yanling/api_ws/src/fyp_api/launch/2d_exploration.launch http://localhost:11311 76x12
[/robot_3/module]: Waiting to be initialised
[/robot_2/module]: Waiting to be initialised
[/robot_3/module]: Waiting to be initialised
[/robot_2/module]: Waiting to be initialised
[/robot_3/module]: Waiting to be initialised
[/robot_1/module]: (6.1,1.5) with C:0.28 D: 0.69 I: 0.14
[/robot_2/module]: (0.0,-3.1) with C:0.09 D: 0.64 I: 0.33
[/robot_3/module]: (-0.1,-6.6) with C:0.35 D: 0.30 I: 0.91
[/robot_1/module]: (1.2,5.8) with C:0.16 D: 0.21 I: 0.10
[/robot_2/module]: (6.1,1.6) with C:0.16 D: 0.48 I: 0.15
[/robot_3/module]: (-6.4,1.4) with C:0.15 D: 0.04 I: 0.15
```

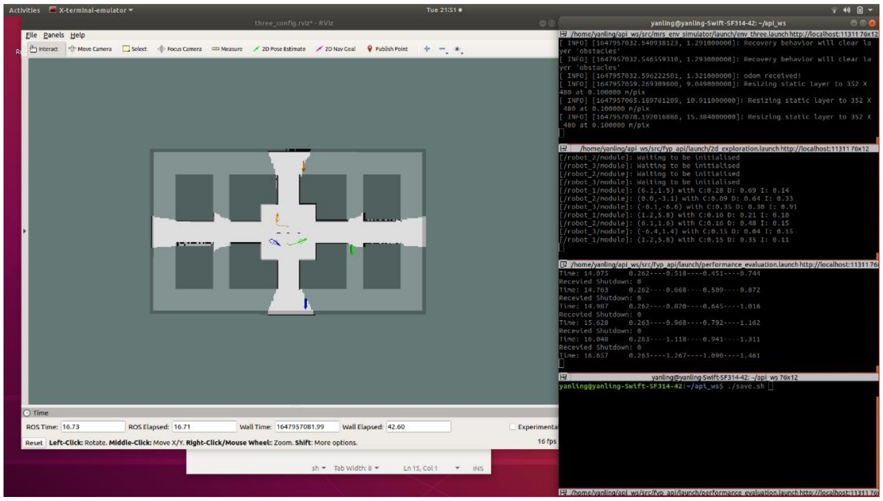
```
/home/yanling/api_ws/src/fyp_api/launch/performance_evaluation.launch http://localhost:11311 76
OG from: robot_3/map received, remaining: 0
Time: 11.733     0.245----0.000----0.083----0.083
Recevied Shutdown: 0
Time: 12.268     0.245----0.015----0.151----0.150
Recevied Shutdown: 0
Time: 12.548     0.245----0.096----0.383----0.382
Recevied Shutdown: 0
Time: 13.123     0.245----0.222----0.437----0.449
Recevied Shutdown: 0
Time: 13.620     0.261----0.368----0.437----0.593
Recevied Shutdown: 0
```

```
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$
```

```
/home/yanling/api_ws/src/fyp_api/launch/performance_evaluation.launch http://localhost:11311 76
```

Figure G6: Screenshot after ./stats.sh is run.

This kickstarts the collection of the different metrics (e.g., position, distance travelled, map completeness) by launching the *evaluator* node in *env_stats*. The merged map is also produced by the *evaluator* for visualisation of the overall exploration efforts. This merged map is superimposed over the ground truth.



ROS Time: 16.73 ROS Elapsed: 16.71 Wall Time: 1647957081.99 Wall Elapsed: 42.60

```
yanling@yanling-Swift-SF314-42: ~/api_ws
/home/yanling/api_ws/src/mrs_env_simulator/launch/env_three.launch http://localhost:11311 76x12
[ INFO] [1647957032.540938123, 1.291000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.546559310, 1.293000000]: Recovery behavior will clear la
yer 'obstacles'
[ INFO] [1647957032.596222501, 1.321000000]: odom received!
[ INFO] [1647957059.269309800, 9.049000000]: Resizing static layer to 352 X
480 at 0.100000 m/pix
[ INFO] [1647957065.189761209, 10.911000000]: Resizing static layer to 352 X
 480 at 0.100000 m/pix
[ INFO] [1647957078.192016886, 15.384000000]: Resizing static layer to 352 X
 480 at 0.100000 m/pix
```

```
/home/yanling/api_ws/src/fyp_api/launch/2d_exploration.launch http://localhost:11311 76x12
[/robot_2/module]: Waiting to be initialised
[/robot_3/module]: Waiting to be initialised
[/robot_2/module]: Waiting to be initialised
[/robot_3/module]: Waiting to be initialised
[/robot_1/module]: (6.1,1.5) with C:0.28 D: 0.69 I: 0.14
[/robot_2/module]: (0.0,-3.1) with C:0.09 D: 0.64 I: 0.33
[/robot_3/module]: (-0.1,-6.6) with C:0.35 D: 0.30 I: 0.91
[/robot_1/module]: (1.2,5.8) with C:0.16 D: 0.21 I: 0.10
[/robot_2/module]: (6.1,1.6) with C:0.16 D: 0.48 I: 0.15
[/robot_3/module]: (-6.4,1.4) with C:0.15 D: 0.04 I: 0.15
[/robot_1/module]: (1.2,5.8) with C:0.15 D: 0.35 I: 0.11
```

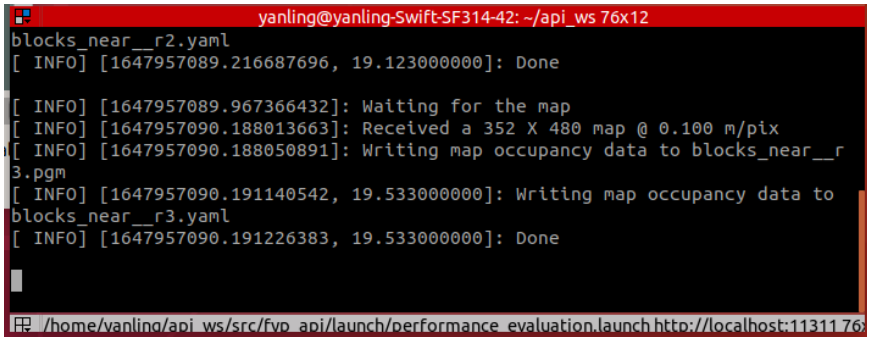
```
/home/yanling/api_ws/src/fyp_api/launch/performance_evaluation.launch http://localhost:11311 76
Time: 14.075     0.262----0.518----0.451----0.744
Recevied Shutdown: 0
Time: 14.763     0.262----0.668----0.509----0.872
Recevied Shutdown: 0
Time: 14.987     0.262----0.820----0.645----1.016
Recevied Shutdown: 0
Time: 15.628     0.263----0.968----0.792----1.162
Recevied Shutdown: 0
Time: 16.048     0.263----1.118----0.941----1.311
Recevied Shutdown: 0
Time: 16.657     0.263----1.267----1.090----1.461
```

```
yanling@yanling-Swift-SF314-42: ~/api_ws 76x12
yanling@yanling-Swift-SF314-42:~/api_ws$ ./save.sh
```

```
/home/yanling/api_ws/src/fyp_api/launch/performance_evaluation.launch http://localhost:11311 76
```

Figure G7: Exploration Run

Step 6: When the exploration is finished (as indicated by the evaluator in the third terminal) or earlier termination is wanted, run this command in the last terminal: ./save.sh



```
blocks_near__r2.yaml
[ INFO] [1647957089.216687696, 19.123000000]: Done

[ INFO] [1647957089.967366432]: Waiting for the map
[ INFO] [1647957090.188013663]: Received a 352 X 480 map @ 0.100 m/pix
[ INFO] [1647957090.188050891]: Writing map occupancy data to blocks_near__r
3.pgm
[ INFO] [1647957090.191140542, 19.533000000]: Writing map occupancy data to
blocks_near__r3.yaml
[ INFO] [1647957090.191226383, 19.533000000]: Done
```

/home/yanling/api_ws/src/fvp_api/launch/performance_evaluation.launch http://localhost:11311 76x

Figure G8: Screenshot after ./save.sh is run shows occupancy grids saved

./save.sh runs two processes for data collection.

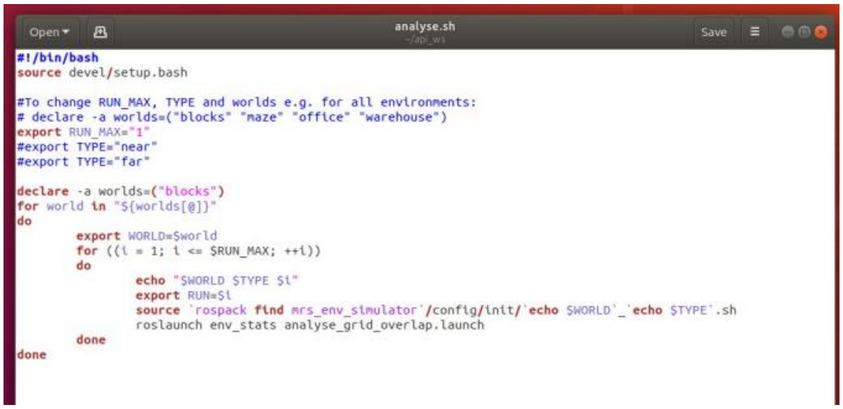
First, it takes a screenshot of the trajectory and saves the individual maps and merged map through *map_server* package for analysis. The (4) maps are saved as .pgm and .yaml files in the ~/(catkin_ws)/store directory. Recall that .yaml describes properties of the environment while .pgm contains the layout of the environment. This directory can be altered in the save.sh script. The filenames, however, follow this format: [WORLD]_[TYPE]_[CODE]_[RUN].pgm/.yaml, where WORLD, TYPE, CODE, and RUN are defined in params.sh file. For example, blocks_near_1_ is the first simulation in the Blocks using CFE.

Second, it sends a terminating condition to the *evaluator* node for output into a .txt file (e.g., stats.txt). If the exploration was terminated before completion without save.sh, no information will be collected. The .txt file is found in the data folder in the *cfe_module* package. The name for the .txt file as well as the directory can be edited in the performance_evaluator.launch file found in *cfe_module* package.

Post Simulation (Performance Analysis)

At this point, the exploration has concluded. The following steps are focused on the analysis of the maps related file (.pgm and .yaml) and the .txt file.

Step 7: To calculate the map overlap, run this command: ./analyse.sh



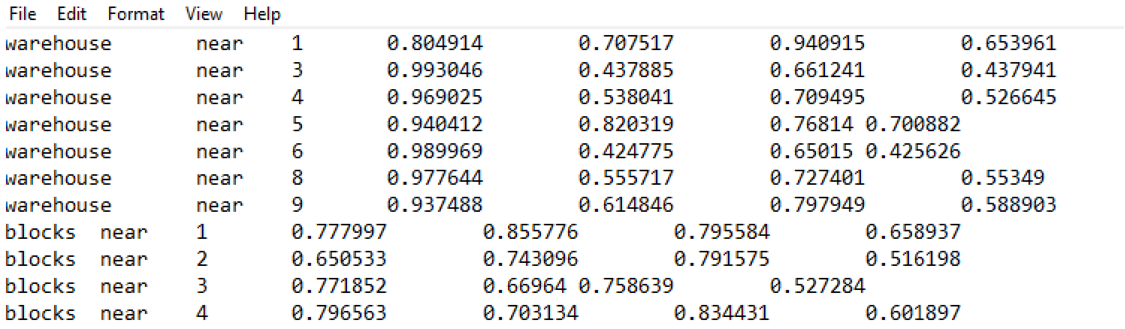
```
#!/bin/bash
source devel/setup.bash

#To change RUN_MAX, TYPE and worlds e.g. for all environments:
# declare -a worlds=("blocks" "maze" "office" "warehouse")
export RUN_MAX="1"
#export TYPE="near"
#export TYPE="far"

declare -a worlds=("blocks")
for world in "${worlds[@]}"
do
        export WORLD=$world
        for ((i = 1; i <= $RUN_MAX; ++i))
        do
                echo "$WORLD $TYPE $i"
                export RUN=$i
                source `rospack find mrs_env_simulator`/config/init/`echo $WORLD`_`echo $TYPE`.sh
                roslaunch env_stats analyse_grid_overlap.launch
        done
done
```

Figure G9: analyse.sh

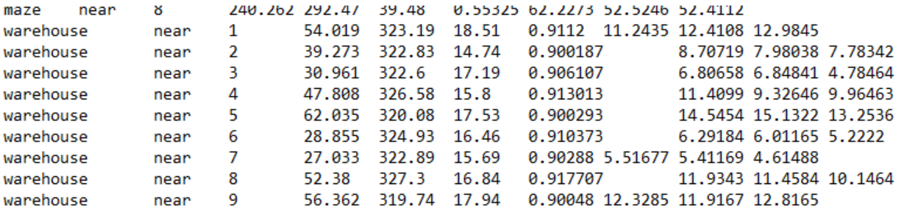
The standardisation of the filename automates the process of analysis, specifically, the calculation of map overlap. Ensure that the env variables RUN_MAX, TYPE, and worlds are properly set. The map overlaps will be recorded in a .txt file (e.g., overlaps.txt) in the /config folder of *env_stats* package. The values are reported in the order of: environment, type, run number, overlap in robot 1's map, robot 2's map robot 3's map, and the merged map as seen in Figure G10.



```
warehouse       near    1       0.804914        0.707517        0.940915        0.653961
warehouse       near    3       0.993046        0.437885        0.661241        0.437941
warehouse       near    4       0.969025        0.538041        0.709495        0.526645
warehouse       near    5       0.940412        0.820319        0.76814 0.700882
warehouse       near    6       0.989969        0.424775        0.65015 0.425626
warehouse       near    8       0.977644        0.555717        0.727401        0.55349
warehouse       near    9       0.937488        0.614846        0.797949        0.588903
blocks  near    1       0.777997        0.855776        0.795584        0.658937
blocks  near    2       0.650533        0.743096        0.791575        0.516198
blocks  near    3       0.771852        0.66964 0.758639        0.527284
blocks  near    4       0.796563        0.703134        0.834431        0.601897
```

Figure G10: Sample overlaps.txt file

Step 8: To access the .txt file collected by *evaluator* node (stats.txt), navigate to */data* folder in the *cfe_module* package. The values are reported in the order of: environment, type, run number, exploration time, free areas, occupied areas, explored ratio, r1 dist, r2 dist, r3 dist as seen in Figure G11.



```
maze    near    8       240.262 292.47  39.48   0.55325 62.2273 52.5246 52.4112
warehouse       near    1       54.019  323.19  18.51   0.9112  11.2435 12.4108 12.9845
warehouse       near    2       39.273  322.83  14.74   0.900187        8.70719 7.98038 7.78342
warehouse       near    3       30.961  322.6   17.19   0.906107        6.80658 6.84841 4.78464
warehouse       near    4       47.808  326.58  15.8    0.913013        11.4099 9.32646 9.96463
warehouse       near    5       62.035  320.08  17.53   0.900293        14.5454 15.1322 13.2536
warehouse       near    6       28.855  324.93  16.46   0.910373        6.29184 6.01165 5.2222
warehouse       near    7       27.033  322.89  15.69   0.90288 5.51677 5.41169 4.61488
warehouse       near    8       52.38   327.3   16.84   0.917707        11.9343 11.4584 10.1464
warehouse       near    9       56.362  319.74  17.94   0.90048 12.3285 11.9167 12.8165
```

Figure G11: Sample stats.txt file

The values are separated by tabs and can be pasted into excel for analysis.