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Autonomous Navigation and Mapping in a Simulated Environment

Benjamin Christie, Osama Ennasr, and Garry Glaspell

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Benjamin Christie, Osama Ennasr, and Garry Glaspell

*Geospatial Research Laboratory
U.S. Army Engineer Research and Development Center
7701 Telegraph Road
Alexandria, VA 22315*

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Abstract

Unknown Environment Exploration (UEE) with an Unmanned Ground Vehicle (UGV) is extremely challenging. This report investigates a frontier exploration approach, in simulation, that leverages Simultaneous Localization And Mapping (SLAM) to efficiently explore unknown areas by finding navigable routes. The solution utilizes a diverse sensor payload that includes wheel encoders, three-dimensional (3-D) LIDAR, and Red, Green, Blue and Depth (RGBD) cameras. The main goal of this effort is to leverage frontier-based exploration with a UGV to produce a 3-D map (up to 10 cm resolution). The solution provided leverages the Robot Operating System (ROS).

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Preface

This study was conducted for the U.S. Army Engineer Research and Development Center, Geospatial Research Laboratory (ERDC-GRL) under Program Element 622146/AT9/01, "Tactical Geospatial Information Capabilities (TGIC)," Task "Tactical Data Generation and Processing." The technical monitor was Dr. Jean Nelson.

The work was performed by the Data Representation Branch of the Topography Imagery and Geospatial Research Division, ERDC-GRL. At the time of publication, Mr. Vineet Gupta was Branch Chief; Mr. Jeffrey Murphy was Division Chief; and Mr. Ritchie Rodebaugh was the Technical Director for Geospatial Research and Engineering (GRE) business area. The Deputy Director of ERDC-GRL was Ms. Valerie Carney and the Director was Mr. Gary Blohm.

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The Commander of ERDC was COL Teresa A. Schlosser and the Director was Dr. David W. Pittman.

1 Introduction

Background

Unknown Environment Exploration (UEE) (Wang et al. 2016; Roman et al. 2019) in the Robot Operating System (ROS) typically works in tandem with a map generated by Simultaneous Localization And Mapping (SLAM) (Castellanos et al. 2001; Jacobson et al. 2018). While there are multiple ways to accomplish this, the most common approach is frontier-based exploration (Keidar and Kaminka 2014; Wan et al. 2011). In frontier-based exploration, the boundary between "known" and "unknown" points (a frontier) becomes a navigation goal. Also produced is the associated cost to clear the frontier. The path-planning node subscribes to the navigation goals and attempts to clear all goals while keeping the cost at a minimum. This process repeats for all existing frontiers and with the addition of new frontiers. The most common type of map used for analysis is a two-dimensional occupancy grid. Consequently, successful autonomous frontier-based exploration in ROS is grounded in the following:

1. Accurate odometry from the robot
2. Accurate 2D occupancy grid from SLAM
3. An efficient path-planner (avoids obstacles and detects navigable terrain)
4. A ROS node that efficiently outputs navigation goals to the path-planner

In this report, focus is placed on the problem of the frontier-based exploration. Specifically, the team identified and fused ROS packages that address each requirement listed above (1-4) to ensure successful frontier-based exploration. The combination of these packages results in a novel solution that allows autonomous exploration of 2D environments in simulation. To accomplish this, ROS leverages a layered approach. At the bottom of the stack is static layer (`map_layer`), which is the 2D map produced by the robot. The second layer (`obstacle_layer`) is comprised of obstacles detected by the sensors and is overlaid onto the static layer. The third layer (`inflation_layer`) generates a buffer around the obstacles as a safety measure to keep the robot from running into them. Finally, the combination of all layers refers to a costmap.

It is worth noting that the default `obstacle_layer` generated by `costmap2d` (a ROS package that generates occupancy grids)^{1 9} creates persistent occupancies that function well in static environments. However, in a dynamic environment, the default `obstacle_layer` requires the sensors observation path to pass through the occupied space, which can fail to fully clear the moving object from the costmap resulting in phantom obstacles. This issue is especially noticeable when a person walks by the robot or when a door, that was previously closed, is opened. These, and other, issues make navigation in dynamic environments challenging. Therefore, also investigated was a spatio-temporal plugin to `costmap2d` designed specifically for dynamic environments by removing occupied spaces from the costmap if they are not re-observed after a set time.

Objective

This report addresses the Army Warfighting Challenges 2015 and the Army Robotic and Autonomous System (RAS) near-term objective of “Enhancing stand-off from threats and improve situation awareness” and their mid-term objective to “Enhance Platoon, Squad, and Soldier situation awareness.” At a theatre level (CNA 17-21), the Army Critical Capability Gap(s) specifically list the following items²³:

1. Gap #500459: “The Army units at Theater level lacks the capacity to integrate host-nation or third nation security forces into friendly sustainment area and base security operations during decisive action 100% of the time”
2. Gap #500915: “The Army at theater level lacks the capability under decisive operations to detect personnel, material and facilities that are subsurface down to 100 meters”
3. Gap #500917: “The Army at theater level lacks the capability under decisive operations to maintain situational awareness of subsurface structure down to 100 meters”
4. Gap #500918: “The Army at theater level lacks the capability under decisive operations to Map a subsurface structure as specified in the mission with Standard Shareable Geospatial.”

¹ http://wiki.ros.org/costmap_2d

² [ArmyWarfightingChallenges.pdf](#)

³ [robototic_autonomous_systems_strategy.pdf\(army.gov.au\)](#)

Overview of approach

This report focuses on getting a robot, specifically a turtlebot3,¹ to map autonomously in simulations leveraging both ROS Melodic² and Gazebo³. There are three models of the turtlebot3 available, specifically the "burger," "waffle," and "waffle pi." Only the "waffle" is equipped with an Red, Green, Blue, and Depth (RGBD) camera, and as a result, used throughout the report. The original turtlebot3 configuration was modified to include an additional rear RGBD camera and centrally mounted 3D LIDAR. The addition of a rear camera increases the frequency of loop closure and improves the accuracy of the SLAM-generated map.

The simulated turtlebot3 comes equipped with an odometry plugin. An additional plugin to track ground truth position of the robot was added to verify accuracy. The output of these plugins was compared with the odometry of the turtlebot3. Fortunately, the robot's odom matched that of the ground truth. This was not the case when other virtualized robots were tested. Ultimately, the turtlebot3's odom ensured the first requirement (R1) was satisfied and did not require modification.

For the second requirement (R2), the SLAM_toolbox ROS package was chosen⁴. SLAM_toolbox will be the defacto standard in ROS 2.0. This package shows promise in generating accurate 2D occupancy grids and is discussed in length later in this report. As a 2D SLAM approach, it does not inherently produce 3-D point clouds of the mapped environment. Therefore, additional ROS packages were incorporated to produce 3-D point clouds to increase functionality.

To satisfy the third requirement (R3), the team down selected from a list of global and local path planners. For global planners, the three most common path planners are carrot planner⁵, nav2fn⁶, and global_planner⁷. For this study, the global_planner was chosen because it allowed for tuning of the variables "neutral cost," "lethal cost," and "cost factor."

¹ <https://emanual.robotis.com/docs/en/platform/turtlebot3/overview/>

² <http://wiki.ros.org/melodic>

³ <http://gazebo.org/>

⁴ https://github.com/SteveMacenski/slam_toolbox

⁵ http://wiki.ros.org/carrot_planner

⁶ <http://wiki.ros.org/navfn>

⁷ http://wiki.ros.org/global_planner

Neutral cost is the value assigned to open space and lethal cost assigned to obstacles. The cost factor is used to spread cost values evenly over the output range so free space and lethal obstacles are well separated. The package `global_planner` also allows to choose between A/* or Dijkstra algorithms to produce paths. As for local planners, Dynamic Window Approach (DWA)¹, Elastic Band (EB)², and Timed Elastic Band (TEB)³ are the most common implementations. EB was chosen since it is not as computationally as expensive as TEB and the team has observed the robot unable to move, on more than one occasion, when using DWA.

In ROS Kinetic, there are many options for frontier-based exploration, as noted in Glaspell et al. (2020). However, in a newer distribution such as ROS Melodic, there are significantly less options for frontier-based exploration. The aforementioned packages either do not compile on newer ROS distributions or do not function as intended. To satisfy the fourth requirement (R4), the ROS package `explore_lite`⁴ was utilized for autonomous frontier-based exploration. In the remainder of this report, each step of this approach will be discussed in more detail and how it addresses the requirements for frontier-based exploration.

¹ http://wiki.ros.org/dwa_local_planner

² http://wiki.ros.org/eband_local_planner

³ http://wiki.ros.org/teb_local_planner

⁴ http://wiki.ros.org/explore_lite

2 Bringup and Robot Odometry

The turtlebot3 comes pre-equipped with a forward facing RGBD camera and a 2D laser. The original model was modified to incorporate the rear camera and the 2D laser was replaced with a 3-D LIDAR. The xacro configuration files for the modified turtlebot3 and the launch file for the willow garage world are provided in Appendix A. The willow garage world was specifically chosen since it is one of the larger simulated worlds. To launch the willow garage world with the modified turtlebot3 run the following command from the directory containing the launch file below:

```
terminal 1, launch world and robot: roslaunch  
turtlebot3_willow_3d_2.launch
```

```
terminal 2, launch SLAM module: roslaunch tb3_online_sync_rtab
```

```
terminal 3, launch movebase: roslaunch  
tb3_move_base_slambox_basic_EBLP.launch
```

```
terminal 4, launch explore lite: roslaunch explore_lite  
explore_lite_gridmap.launch
```

After running the command in terminal 1, gazebo launches the willow garage world and the modified turtlebot3 (Figure 1).

Figure 1. Modified turtlebot3 with 3-D LIDAR and front and rear RGBD cameras loaded in the willow garage world (left). Odometry generated from the turtlebot3 compared to ground truth (right).

Figure 1 also shows the odometry from the turtlebot3 compared to the ground truth generated from the p3d_base_controller plugin. The odometry from the robot when compared to ground truth shows a near 1:1 correspondence, which is not always the case with simulated robots. Note that the accurate odometry satisfies the first requirement for successful frontier-based exploration. Provided below is the p3d_base_controller plugin code.

```
<gazebo>
  <plugin name="p3d_base_controller"
filename="libgazebo_ros_p3d.so">
    <alwaysOn>true</alwaysOn>
    <updateRate>30.0</updateRate>
    <bodyName>base_link</bodyName>
    <topicName>ground_truth/state</topicName>
    <gaussianNoise>0.0</gaussianNoise>
    <frameName>world</frameName>
    <xyzOffsets>0 0 0</xyzOffsets>
    <rpyOffsets>0 0 0</rpyOffsets>
  </plugin>
</gazebo>
```

3 Accurate Mapping using SLAM Toolbox

At its core, successful frontier-based exploration relies heavily on SLAM for localization and navigation. If the SLAM-generated grid map is inaccurate, the robot will have difficulty avoiding obstacles and reaching its intended goal. In addition, phantom obstacles (obstacles that do not exist in reality but show in the cost map) can cause the path-planning software to fail. For this report, the team focused on the SLAM_toolbox built by Steve Macenski¹. SLAM_toolbox is a 2D SLAM approach that has multiple modes of operation. In addition to localization and mapping modes, mapping can be broken down into synchronous (all scans are processed), asynchronous (not all scans are processed, but useful for large spaces >200,000 ft²), and lifetime mode. In this report, the team focused on synchronous mode, but lifetime mode is of particular interest since existing maps are updated with subsequent scans. Within the SLAM_toolbox configuration file, the ROS parameters are as follows:

```
odom_frame: odom
# odom frame from turtlebot 3
map_frame: map
base_frame: base_footprint
# turtlebot 3 uses base_footprint instead of base_link
scan_topic: /velodyne_scan
# velodyne_scan is the output of pointcloud_to_laserscan
mode: mapping
# can be switched to localization
```

SLAM toolbox accepts a laser scan topic; however, in this report, the pointcloud_to_laserscan nodelet was leveraged, which converts a 3-D PointCloud2 message from the LiDAR to a 2D LaserScan message. In short, the pointcloud_to_laserscan node analyzes all points from the 3-D point cloud that overlap along the z-axis and returns the point closest to the robot. SLAM toolbox uses this modified LaserScan message for grid_map construction and localization. Using pointcloud_to_laserscan to a compressed 3-D point cloud into 2D allows the robot to detect obstacles that a 2D laser scan device would typically miss while still mapping (and processing) in 2D. Shown below is an example of the pointcloud_to_laserscan nodelet launch.

¹ https://github.com/SteveMacenski/slam_toolbox

```

<node pkg="nodelet" type="nodelet"
name="pointcloud_to_laserscan_manager" output="screen"
respawn="true" args="manager"/>
<!-- push pointcloud_to_laserscan nodelet into sensor's nodelet
manager-->
<node pkg="nodelet" type="nodelet" name="pointcloud_to_laserscan"
args="standalone
pointcloud_to_laserscan/pointcloud_to_laserscan_nodelet">

    <remap from="cloud_in" to="/velodyne_points"/>
    <remap from="scan" to="velodyne_scan"/>
    <rosparam>
        target_frame: velodyne # Leave disabled to output scan in
pointcloud frame
        transform_tolerance: 0.01
        min_height: -0.3
        max_height: 0.5

        angle_min: -3.14159274101
        angle_max: 3.14159274101
        angle_increment: 0.00700000021607
        scan_time: 0.3333
        range_min: 0.2
        range_max: 130.0
        use_inf: true
        inf_epsilon: 1.0

        # Concurrency level, affects number of pointclouds queued
for processing, thread number governed by nodelet manager
        # 0 : Detect number of cores
        # 1 : Single threaded
        # 2->inf : Parallelism level
        concurrency_level: 2
    </rosparam>
</node>

```

In this example, "cloud_in" is the output from the simulated velodyne LIDAR. The parameter "min_height" is with respect to the 3-D LIDAR frame and is set to 2 cm above ground level. This ensures the collapsed LaserScan topic does not clip the ground when moving. The "max_height" variable is set to the robot's height. The variables "angle_min" and "angle_max" are set for a 360-degree LIDAR. The "angle_increment" parameter is $2\pi / (\text{number of horizontal laser points from LIDAR})$. In addition, "range_min" and "range_max" are set to match the velodyne's output. The nodelet outputs the topic velodyne_scan, which were passed to the SLAM toolbox. It is significant to note that SLAM toolbox does not produce 3-D point clouds. Several attempts were made to integrate 3-D

pointclouds with varying degrees of success. Specifically, the attempts were made with `laser_assembler`¹, `ocotomap_server`², and `RTABMap`³.

Laser_assembler

The first attempt leveraged the nodes `laser_assembler` and `periodic_snapshotter`. Note that the `periodic_snapshotter` node requires compiling `laser_assembler` from source. The sample code to launch these is provided below.

```
<node type="point_cloud2_assembler" pkg="laser_assembler"
name="my_assembler">
  <remap from="cloud" to="/velodyne_points"/>
  <param name="max_clouds" type="int" value="400" />
  <param name="fixed_frame" type="string" value="map" />
</node>

<node pkg="laser_assembler" type="periodic_snapshotter"
output="screen" name="periodic_snapshotter" />
```

In this setup, the `laser_assembler` node builds a queue of collected `PointCloud2` messages, ~400, and the `periodic_snapshotter` writes the queue to a file every 10 seconds. While this allowed the team to generate a 3-D point cloud as it mapped, there was a significant drawback to this approach. Specifically, loop closure does not correct point clouds already written to the file. Thus, any drift that occurred before loop closure is apparent when viewing the files in `CloudCompare`. To work around this limitation with `periodic_snapshotter`, two runs were made in the willow garage. The first run used mapping mode to generate a serialized map, which can be seen in Figure 2. Due to successful loop closure, the resulting map does not possess any double walls, the wall thickness is uniform, and opposite walls are parallel. Any incurred drift over the 900 m mapped area was negligible. It is significant to note that the occupancy grid generated from the SLAM Toolbox outperforms other SLAM modules regarding accuracy and fully satisfies the second requirement for successful frontier-based exploration.

¹ https://github.com/ros-perception/laser_assembler

² https://github.com/OctoMap/octomap_mapping

³ https://github.com/introlab/rtabmap_ros

Figure 2. 2D occupancy grid of willow garage generated by SLAM toolbox.

To generate the 3-D pointcloud with `periodic_snapshotter`, a second run was made with the SLAM Toolbox in localization mode. This approach was quite effective, as can be seen in Figure 3. However, in large areas, this approach may not be realistic due to battery limitations of the robot or the time required making two complete runs. Limitations aside, the resulting 3-D map also showed negligible drift like the 2-D map.

Figure 3. 3-D point cloud generated using the SLAM Toolbox in localization mode leveraging `periodic_snapshotter`.

Octomap_server

The second attempt leveraged `octomap_server` to generate a 3-D point cloud. The main advantage of `octomap_server` is that it only required a single mapping run, in contrast to the two runs required by the

periodic_snapshotter approach. Since the point cloud was exported at end of the run, all loop closures were accounted for. One drawback was noticed while using ocotmap server; more RAM was consumed the longer octomap server ran. The base configuration, without octomap_server running, typically consumes ~4.3 GB of RAM. After mapping half of willow garage, RAM usage was >6 GB and when nearly done it was >8 GB. On our physical robot, the current onboard computer only has 8 GB of RAM so this could be a potential issue for long scans. It is possible to reduce RAM consumption by decreasing the resolution of the 3-D pointcloud in octomap_server. Shown below is the sample code for octomap_server node. Also shown below in Figure 4 is the 3-D point cloud generated by octomap_server. Like the previous approach, the octomap_server produced a 3-D point cloud that did not have double walls, the wall thickness is uniform, and opposite walls are parallel.

```
<node pkg="octomap_server" type="octomap_server_node"
name="octomap_server">
  <param name="resolution" value="0.05" />
  <!-- fixed map frame (set to 'map' if SLAM or localization
running!) -->
  <param name="frame_id" type="string" value="map" />
  <!-- maximum range to integrate (speedup!) -->
  <param name="sensor_model/max_range" value="20.0" />
  <!-- data source to integrate (PointCloud2) -->
  <remap from="cloud_in" to="/voxel_grid/output" />
</node>
```

Figure 4. 3-D point cloud generated using ocotomap_server.

RTABMap

The third option leverages RTABMap (Labbé and Michaud 2019, 2017, 2014, 2013, and 2011). RTABMap is very capable of producing quality 3-D point clouds. Thus, the team attempted to fuse the two approaches. Running two SLAM modules at the same time is problematic, especially regarding overlapping nodes. Thus, the `data_recorder` node was leveraged in RTABMap. After mapping, the node will write the RTABMap database to construct a 3-D pointcloud. This approach allowed for utilization of the `SLAM_toolbox` to generate the occupancy grid map. Shown below is the code for the `data_recorder`. A number of these parameters have been discussed in previous reports.

```
<node name="data_recorder" pkg="rtabmap_ros" type="rtabmap"
  output="screen" args="--delete_db_on_start">
  <param name="Mem/RehearsalSimilarity" type="string"
    value="1.0"/>    <!-- deactivate rehearsal -->
```

```

    <param name="Kp/MaxFeatures"          type="string" value="-
1"/>    <!-- deactivate keypoints extraction -->
    <param name="Rtabmap/MaxRetrieved"    type="string" value="0"/>
<!-- deactivate global retrieval -->
    <param name="RGBD/MaxLocalRetrieved"  type="string" value="0"/>
<!-- deactivate local retrieval -->
    <param name="Mem/MapLabelsAdded"      type="string"
value="false"/> <!-- don't create map labels -->
    <param name="Rtabmap/MemoryThr"       type="string" value="2"/>
<!-- keep the WM empty -->
    <param name="Mem/STMSize"             type="string" value="1"/>
<!-- STM=1 -->
    <param name="publish_tf"              type="bool"
value="false"/> <!-- don't publish TF -->
    <param name="RGBD/ProximityBySpace"   type="string"
value="false"/>
    <param name="RGBD/LinearUpdate"       type="string" value="0"/>
    <param name="RGBD/AngularUpdate"      type="string" value="0"/>
    <param name="RGBD/CreateOccupancyGrid" type="string"
value="false"/>
    <param name="Rtabmap/DetectionRate"    type="string" value="1"/>
    <param name="DbSqlite3/InMemory"       type="string"
value="false"/>
    <param name="frame_id"                type="string"
value="base_footprint"/>
    <param name="queue_size"              type="int"
value="10"/>
    <param name="approx_sync"              type="bool"
value="true"/>
    <param name="Reg/Force3DoF"            type="string"
value="true"/> <!-- 2D SLAM -->
    <param name="Reg/Strategy"             type="string" value="1"/>
<!-- 0=Visual, 1=ICP, 2=Visual+ICP -->
    <param name="Grid/FromDepth"          type="string"
value="false"/> <!-- Create 2D occupancy grid from laser scan -->

    <param name="subscribe_rgb"            type="bool"
value="false"/>
    <param name="subscribe_scan"           type="bool"
value="false"/>
    <param name="subscribe_scan_cloud"     type="bool"
value="true"/>
    <param name="subscribe_rgbd"           type="bool"
value="true"/>
    <param name="subscribe_odometry"       type="bool"
value="true"/>
    <param name="subscribe_depth"          type="bool"
value="false"/>

    <remap from="odom"                    to="/odom"/>

```

```

    <remap from="scan"                to="/velodyne_scan"/>
    <remap from="scan_cloud"          to="/voxel_grid/output"/>
    <remap from="rgb/image"
to="/camera_0/rgb/image_raw"/>
    <remap from="depth/image"
to="/camera_0/depth/image_raw"/>
    <remap from="rgb/camera_info"
to="/camera_0/rgb/camera_info"/>

    <param name="rgbd_cameras"        type="int"    value="2"/>
    <remap from="rgbd_image0"         to="rgbd_image0"/>
    <remap from="rgbd_image1"         to="rgbd_image1"/>
</node>

```

For completeness, the 2-D occupancy grid collected generated by the SLAM Toolbox is shown in Figure 5.

Figure 5. 2-D occupancy grid generated from the SLAM Toolbox when fused with RTABMap.

Then, RTABMap leverages the 2-D map generated by the SLAM Toolbox to construct the 3-D point clouds from the collected database. Figure 6 shows the 3-D point cloud generated from this approach. To reduce the database file size, the `voxel_grid` nodelet^{1 30} was used to remove the ground points. In addition, adding color to the point clouds has been previously

¹ https://github.com/ros-perception/perception_pcl

discussed, but is the result of combining RTABMap's pointcloud_to_depthimage and rgbd_sync nodelets for the front and rear RGBD cameras.

Figure 6. 3-D point cloud of willow garage world generated by the SLAM Toolbox / RTABMap fusion.

Initially, the willow garage world was chosen due to its large size. However, to highlight benefits of combining the SLAM Toolbox with RTABMap, Clearpath's playpen world was also mapped. The playpen world has significantly more visual elements compared to willow garage and highlights the benefits of this dual approach. To measure the accuracy of the generated 3-D point clouds in simulation each scan was repeated with the odometry set to ground truth. Then, the point clouds were compared in Cloudcompare and it was determined that the RMS was ~3 cm for both willow garage and the playpen worlds. Figure 7 shows the 3-D point cloud generated from mapping the playpen world. The full launch and configuration files can be found in Appendix B.

Figure 7. 3-D point cloud of play pen world generated by the SLAM Toolbox / RTABMap fusion.

4 Path planning using Move_base and STVL

The purpose of the move_base package is to move the robot to its intended goal. It accomplishes this feat by utilizing global and local path planners and their respective cost maps. In this report, global_planner and eband_local_planner is used. The global_planner is quite versatile since there are choices of using A/* or Dijkstra's algorithms. When on fast moving vehicles, A/* may be preferable. Dijkstra was chosen for this study, which maximized coverage when determining the optimal path. The global_planner also possesses an orientation filter. Hypothetically, if the robot was equipped with a single camera, it would be possible to drive down a hallway and then drive backwards, using the orientation filter, on the return trip to ensure loop closures occurred in order to minimize drift. However, a dual camera approach was used; as a result, the orientation filter was not modified. Finally, the team modified the cost_factor (0.55), neutral_cost (66), and lethal_cost (253). These values are based on a report published by Kaiyuzheng. The eband_local_planner seemed to work well in this test environment. When comparing eband to the teb_local_planner out of the box, eband mapped ~730 m in 30 min while TEB mapped ~430 m. However, development for eband seems to have stopped at kinetic in favor of teb_local_planner, which has a noetic release. However, eband did compile successfully in melodic without any issues. The global and local planners were set with the following parameters:

```
<param name="base_local_planner"
value="eband_local_planner/EBandPlannerROS" />
<param name="base_global_planner" type="string"
value="global_planner/GlobalPlanner" />
```

The move_base file is comprised of four sections; the global_costmap, the local_costmap, move_base and EBandPlannerROS.

Navigating in dynamic level environments is more complicated since the grid_map can change unexpectedly when objects appear, disappear, or change position within the environment. Thus, a spatio-temporal solution is necessary. The default obstacle_layer plugin generated by costmap2d can mark and clear the local_costmap using specified observation sources, such as a laser scan or pointcloud2 topic. By detecting what surfaces are obstacles and what is free space, clearing can occur within the costmap. Thus, if an obstacle moves, the space that the obstacle occupied is now

free, and cleared. This was accomplished by using the `spatio_temporal_voxel_layer::rgbd_obstacle_layer` (STVL) plugin. The STVL is a direct drop-in replacement for the `costmap2d::voxel_layer` plugin for collision avoidance, path planning, and control¹. In dynamic environments, STVL can leverage depth cameras or a 3-D LiDAR. In this report, the pointcloud from the 3-D LiDAR was chosen for marking and clearing and shown in Figure 8. The complete launch file for `move_base` including STVL can be found in Appendix C.

Figure 8. Costmap, with inflation layer, generated using the `spatio_temporal_voxel_layer`.

¹ https://github.com/SteveMacenski/spatio_temporal_voxel_layer

5 Autonomous Frontier-based Exploration using Explore Lite

In this report, `explore_lite` was leveraged to send goals to the path planner. However, `explore_lite` does not have the same virtual fencing capabilities that exists in `frontier_exploration`, another popular frontier-based exploration application. Ultimately, this means that in unbounded environments, `explore_lite` will endlessly send new navigation goals to the path-planning software. The cycle repeats if there are new frontiers to navigate. This can be seen in Figure 9. Consequently, a virtual fence was added to `explore_lite`. This was accomplished by modifying `FrontierSearch::isNewFrontierCell` to remove frontiers whose pose did not meet a specified positional requirement. As a proof-of-concept, maximum `x` and `y` values were used to create a square virtual fence in simulation. `Explore_lite` explored the square in an open, unbounded environment, and `explore_lite` did not endlessly explore. Furthermore, `Explore::stop` was modified to send a navigation goal to the path-planner once exploration was finished so the robot could return to its original position, or a specified ending position. The files modified for virtual fencing and return to home are found in Appendix D.

Figure 9. Frontier-based exploration using `explore_lite` over time. The frontiers are blue, and their associated costs are depicted by the green circles. The red dots depict the path of the robot and obstacles are marked with an inflation layer.

6 Conclusion

Finally, autonomy exploration and navigating locally in a 2-D environment is achievable by implementing all the previously discussed packages. This report has demonstrated that 3-D RGB point clouds can be generated in simulation mapping >900 m with an RMS of ~3 cm. To increase the robustness of this approach for a real-world application, `pointcloud_to_laserscan` was leveraged for obstacle detection and STVL for environments with dynamic obstacles. Eventually, moving towards a voxel-based implementation for automating 3-D environments may be in the team's best interest. In this approach, maps are projected to a two-dimensional occupancy grid for navigation. However, if a tunnel spirals back on itself such that a point $A(X,Y,a)$ exists within the map and also a point $B(X,Y,b)$ exists within the map such that A and B are vertically coincident while $a \neq b$, the terrain immediately surrounding A and B will become superimposed within the `global_costmap`, and navigation will likely fail. However, octomaps use a three-dimensional approach instead, with voxels instead of two-dimensional cells. Consequently, unique points with the same X and Y values, but unique Z values, can exist and affect navigation separately. Unfortunately, not many implementations of this idea exist. One package that has this idea is MoveIt. Future work will focus on leveraging this type of package to enhance global navigation.

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Appendix A

turtlebot3_waffle_3d2.gazebo.xacro

```
<?xml version="1.0"?>
<robot name="turtlebot3_waffle_sim"
xmlns:xacro="http://ros.org/wiki/xacro">
  <xacro:arg name="laser_visual" default="false"/>
  <xacro:arg name="camera_visual" default="false"/>
  <xacro:arg name="imu_visual" default="false"/>

  <gazebo reference="base_link">
    <material>Gazebo/DarkGrey</material>
  </gazebo>

  <gazebo reference="wheel_left_link">
    <mu1>0.1</mu1>
    <mu2>0.1</mu2>
    <kp>500000.0</kp>
    <kd>10.0</kd>
    <minDepth>0.001</minDepth>
    <maxVel>0.1</maxVel>
    <fdir1>1 0 0</fdir1>
    <material>Gazebo/FlatBlack</material>
  </gazebo>

  <gazebo reference="wheel_right_link">
    <mu1>0.1</mu1>
    <mu2>0.1</mu2>
    <kp>500000.0</kp>
    <kd>10.0</kd>
    <minDepth>0.001</minDepth>
    <maxVel>0.1</maxVel>
    <fdir1>1 0 0</fdir1>
    <material>Gazebo/FlatBlack</material>
  </gazebo>

  <gazebo reference="caster_back_right_link">
    <mu1>0.1</mu1>
    <mu2>0.1</mu2>
    <kp>1000000.0</kp>
    <kd>100.0</kd>
    <minDepth>0.001</minDepth>
    <maxVel>1.0</maxVel>
    <material>Gazebo/FlatBlack</material>
  </gazebo>

  <gazebo reference="caster_back_left_link">
    <mu1>0.1</mu1>
```

```

    <mu2>0.1</mu2>
    <kp>1000000.0</kp>
    <kd>100.0</kd>
    <minDepth>0.001</minDepth>
    <maxVel>1.0</maxVel>
    <material>Gazebo/FlatBlack</material>
  </gazebo>

  <gazebo reference="imu_link">
    <sensor type="imu" name="imu">
      <always_on>true</always_on>
      <visualize>$(arg imu_visual)</visualize>
    </sensor>
    <material>Gazebo/Grey</material>
  </gazebo>

  <gazebo>
    <plugin name="turtlebot3_waffle_controller"
filename="libgazebo_ros_diff_drive.so">
      <commandTopic>cmd_vel</commandTopic>
      <odometryTopic>odom</odometryTopic>
      <odometryFrame>odom</odometryFrame>
      <odometrySource>world</odometrySource>
      <publishOdomTF>true</publishOdomTF>
      <robotBaseFrame>base_footprint</robotBaseFrame>
      <publishWheelTF>false</publishWheelTF>
      <publishTf>true</publishTf>
      <publishWheelJointState>true</publishWheelJointState>
      <legacyMode>false</legacyMode>
      <updateRate>30</updateRate>
      <leftJoint>wheel_left_joint</leftJoint>
      <rightJoint>wheel_right_joint</rightJoint>
      <wheelSeparation>0.287</wheelSeparation>
      <wheelDiameter>0.066</wheelDiameter>
      <wheelAcceleration>1</wheelAcceleration>
      <wheelTorque>10</wheelTorque>
      <rosDebugLevel>na</rosDebugLevel>
    </plugin>
  </gazebo>

  <gazebo>
    <plugin name="imu_plugin" filename="libgazebo_ros_imu.so">
      <alwaysOn>true</alwaysOn>
      <bodyName>imu_link</bodyName>
      <frameName>imu_link</frameName>
      <topicName>imu</topicName>
      <serviceName>imu_service</serviceName>
      <gaussianNoise>0.0</gaussianNoise>
      <updateRate>200</updateRate>
      <imu>

```

```

    <noise>
      <type>gaussian</type>
      <rate>
        <mean>0.0</mean>
        <stddev>2e-4</stddev>
        <bias_mean>0.0000075</bias_mean>
        <bias_stddev>0.000008</bias_stddev>
      </rate>
      <accel>
        <mean>0.0</mean>
        <stddev>1.7e-2</stddev>
        <bias_mean>0.1</bias_mean>
        <bias_stddev>0.001</bias_stddev>
      </accel>
    </noise>
  </imu>
</plugin>
</gazebo>

<gazebo reference="base_scan">
  <material>Gazebo/FlatBlack</material>
  <sensor type="ray" name="lds_lfcd_sensor">
    <pose>0 0 0 0 0 0</pose>
    <visualize>$(arg laser_visual)</visualize>
    <update_rate>5</update_rate>
    <ray>
      <scan>
        <horizontal>
          <samples>540</samples>
          <resolution>1</resolution>
          <min_angle>-2.35619</min_angle>
          <max_angle>2.35619</max_angle>
        </horizontal>
      </scan>
      <range>
        <min>0.20</min>
        <max>20</max>
        <resolution>0.015</resolution>
      </range>
      <noise>
        <type>gaussian</type>
        <mean>0.0</mean>
        <stddev>0.01</stddev>
      </noise>
    </ray>
    <plugin name="gazebo_ros_lds_lfcd_controller"
filename="libgazebo_ros_laser.so">
      <topicName>scan</topicName>
      <frameName>base_scan</frameName>
    </plugin>
  </sensor>
</gazebo>

```

```

    </sensor>
</gazebo>

<!-- Camera_0 -->
<gazebo reference="camera_0_rgb_frame">
  <sensor type="depth" name="realsense_R200_0">
    <always_on>true</always_on>
    <visualize>$(arg camera_visual)</visualize>
    <camera>
      <horizontal_fov>1.3439</horizontal_fov>
      <image>
        <width>1920</width>
        <height>1080</height>
        <format>R8G8B8</format>
      </image>
      <depth_camera></depth_camera>
      <clip>
        <near>0.03</near>
        <far>100</far>
      </clip>
    </camera>
    <plugin name="camera_controller"
filename="libgazebo_ros_openni_kinect.so">
      <baseline>0.2</baseline>
      <alwaysOn>true</alwaysOn>
      <updateRate>30.0</updateRate>
      <cameraName>camera_0</cameraName>
      <frameName>camera_0_rgb_optical_frame</frameName>
      <imageTopicName>rgb/image_raw</imageTopicName>

      <depthImageTopicName>depth/image_raw</depthImageTopicName>
      <pointCloudTopicName>depth/points</pointCloudTopicName>

      <cameraInfoTopicName>rgb/camera_info</cameraInfoTopicName>

      <depthImageCameraInfoTopicName>depth/camera_info</depthImageCamera
aInfoTopicName>
      <pointCloudCutoff>0.4</pointCloudCutoff>
      <hackBaseline>0.07</hackBaseline>
      <distortionK1>0.0</distortionK1>
      <distortionK2>0.0</distortionK2>
      <distortionK3>0.0</distortionK3>
      <distortionT1>0.0</distortionT1>
      <distortionT2>0.0</distortionT2>
      <CxPrime>0.0</CxPrime>
      <Cx>0.0</Cx>
      <Cy>0.0</Cy>
      <focalLength>0</focalLength>
      <hackBaseline>0</hackBaseline>
    </plugin>

```

```

    </sensor>
</gazebo>

<!-- Camera_1 -->
<gazebo reference="camera_1_rgb_frame">
  <sensor type="depth" name="realsense_R200_1">
    <always_on>true</always_on>
    <visualize>$(arg camera_visual)</visualize>
    <camera>
      <horizontal_fov>1.3439</horizontal_fov>
      <image>
        <width>1920</width>
        <height>1080</height>
        <format>R8G8B8</format>
      </image>
      <depth_camera></depth_camera>
      <clip>
        <near>0.03</near>
        <far>100</far>
      </clip>
    </camera>
    <plugin name="camera_controller"
filename="libgazebo_ros_openni_kinect.so">
      <baseline>0.2</baseline>
      <alwaysOn>true</alwaysOn>
      <updateRate>30.0</updateRate>
      <cameraName>camera_1</cameraName>
      <frameName>camera_1_rgb_optical_frame</frameName>
      <imageTopicName>rgb/image_raw</imageTopicName>

      <depthImageTopicName>depth/image_raw</depthImageTopicName>
      <pointCloudTopicName>depth/points</pointCloudTopicName>

      <cameraInfoTopicName>rgb/camera_info</cameraInfoTopicName>

      <depthImageCameraInfoTopicName>depth/camera_info</depthImageCamer
aInfoTopicName>
        <pointCloudCutoff>0.4</pointCloudCutoff>
        <hackBaseline>0.07</hackBaseline>
        <distortionK1>0.0</distortionK1>
        <distortionK2>0.0</distortionK2>
        <distortionK3>0.0</distortionK3>
        <distortionT1>0.0</distortionT1>
        <distortionT2>0.0</distortionT2>
        <CxPrime>0.0</CxPrime>
        <Cx>0.0</Cx>
        <Cy>0.0</Cy>
        <focalLength>0</focalLength>
        <hackBaseline>0</hackBaseline>
      </plugin>

```

```

    </sensor>
  </gazebo>

  <gazebo>
    <plugin name="p3d_base_controller"
filename="libgazebo_ros_p3d.so">
      <alwaysOn>true</alwaysOn>
      <updateRate>30.0</updateRate>
      <bodyName>base_link</bodyName>
      <topicName>ground_truth/state</topicName>
      <gaussianNoise>0.0</gaussianNoise>
      <frameName>world</frameName>
      <xyzOffsets>0 0 0</xyzOffsets>
      <rpyOffsets>0 0 0</rpyOffsets>
    </plugin>
  </gazebo>

</robot>

```

turtlebot3_waffle_3d_2.urdf.xacro

```

<?xml version="1.0" ?>
<robot name="turtlebot3_waffle"
xmlns:xacro="http://ros.org/wiki/xacro">
  <xacro:include filename="$(find
turtlebot3_description)/urdf/common_properties.xacro"/>
  <xacro:include filename="$(find
turtlebot3_description)/urdf/turtlebot3_waffle_3d_2.gazebo.xacro"
/>
  <xacro:include filename="$(find velodyne_description)/urdf/VLP-
16_tb3.urdf.xacro"/>
  <VLP-16 parent="base_link" name="velodyne"
topic="/velodyne_points" hz="10" samples="440" gpu="false">
    <origin xyz="0 0 0.4" rpy="0 0 0" />
  </VLP-16>

  <xacro:property name="r200_cam_rgb_px" value="0.005"/>
  <xacro:property name="r200_cam_rgb_py" value="0.018"/>
  <xacro:property name="r200_cam_rgb_pz" value="0.013"/>
  <xacro:property name="r200_cam_depth_offset" value="0.01"/>

  <link name="base_footprint"/>

  <joint name="base_joint" type="fixed">
    <parent link="base_footprint"/>
    <child link="base_link" />
    <origin xyz="0 0 0.010" rpy="0 0 0"/>
  </joint>

  <link name="base_link">

```

```

    <visual>
      <origin xyz="-0.064 0 0.0" rpy="0 0 0"/>
      <geometry>
        <mesh
filename="package://turtlebot3_description/meshes/bases/waffle_base.stl" scale="0.001 0.001 0.001"/>
        </geometry>
        <material name="light_black"/>
      </visual>

    <collision>
      <origin xyz="-0.064 0 0.047" rpy="0 0 0"/>
      <geometry>
        <box size="0.266 0.266 0.094"/>
      </geometry>
    </collision>

    <inertial>
      <origin xyz="0 0 0" rpy="0 0 0"/>
      <mass value="1.3729096e+00"/>
      <inertia ixx="8.7002718e-03" ixy="-4.7576583e-05"
ixz="1.1160499e-04"
            iyy="8.6195418e-03" iyz="-3.5422299e-06"
            izz="1.4612727e-02" />
    </inertial>
  </link>

  <joint name="wheel_left_joint" type="continuous">
    <parent link="base_link"/>
    <child link="wheel_left_link"/>
    <origin xyz="0.0 0.144 0.023" rpy="-1.57 0 0"/>
    <axis xyz="0 0 1"/>
  </joint>

  <link name="wheel_left_link">
    <visual>
      <origin xyz="0 0 0" rpy="1.57 0 0"/>
      <geometry>
        <mesh
filename="package://turtlebot3_description/meshes/wheels/left_tire.stl" scale="0.001 0.001 0.001"/>
        </geometry>
        <material name="dark"/>
      </visual>

    <collision>
      <origin xyz="0 0 0" rpy="0 0 0"/>
      <geometry>
        <cylinder length="0.018" radius="0.033"/>
      </geometry>
    </collision>
  </link>

```

```

    </collision>

    <inertial>
      <origin xyz="0 0 0" />
      <mass value="2.8498940e-02" />
      <inertia ixx="1.1175580e-05" ixy="-4.2369783e-11" ixz="-
5.9381719e-09"
          iyy="1.1192413e-05" iyz="-1.4400107e-11"
          izz="2.0712558e-05" />
    </inertial>
  </link>

  <joint name="wheel_right_joint" type="continuous">
    <parent link="base_link"/>
    <child link="wheel_right_link"/>
    <origin xyz="0.0 -0.144 0.023" rpy="-1.57 0 0"/>
    <axis xyz="0 0 1"/>
  </joint>

  <link name="wheel_right_link">
    <visual>
      <origin xyz="0 0 0" rpy="1.57 0 0"/>
      <geometry>
        <mesh
filename="package://turtlebot3_description/meshes/wheels/right_tire.stl" scale="0.001 0.001 0.001"/>
        </geometry>
        <material name="dark"/>
      </visual>

      <collision>
        <origin xyz="0 0 0" rpy="0 0 0"/>
        <geometry>
          <cylinder length="0.018" radius="0.033"/>
        </geometry>
      </collision>

      <inertial>
        <origin xyz="0 0 0" />
        <mass value="2.8498940e-02" />
        <inertia ixx="1.1175580e-05" ixy="-4.2369783e-11" ixz="-
5.9381719e-09"
            iyy="1.1192413e-05" iyz="-1.4400107e-11"
            izz="2.0712558e-05" />
      </inertial>
    </link>

    <joint name="caster_back_right_joint" type="fixed">
      <parent link="base_link"/>
      <child link="caster_back_right_link"/>

```



```

    <origin xyz="-0.177 -0.064 -0.004" rpy="-1.57 0 0"/>
  </joint>

  <link name="caster_back_right_link">
    <collision>
      <origin xyz="0 0.001 0" rpy="0 0 0"/>
      <geometry>
        <box size="0.030 0.009 0.020"/>
      </geometry>
    </collision>

    <inertial>
      <origin xyz="0 0 0" />
      <mass value="0.005" />
      <inertia ixx="0.001" ixy="0.0" ixz="0.0"
        iyy="0.001" iyz="0.0"
        izz="0.001" />
    </inertial>
  </link>

  <joint name="caster_back_left_joint" type="fixed">
    <parent link="base_link"/>
    <child link="caster_back_left_link"/>
    <origin xyz="-0.177 0.064 -0.004" rpy="-1.57 0 0"/>
  </joint>

  <link name="caster_back_left_link">
    <collision>
      <origin xyz="0 0.001 0" rpy="0 0 0"/>
      <geometry>
        <box size="0.030 0.009 0.020"/>
      </geometry>
    </collision>

    <inertial>
      <origin xyz="0 0 0" />
      <mass value="0.005" />
      <inertia ixx="0.001" ixy="0.0" ixz="0.0"
        iyy="0.001" iyz="0.0"
        izz="0.001" />
    </inertial>
  </link>

  <joint name="imu_joint" type="fixed">
    <parent link="base_link"/>
    <child link="imu_link"/>
    <origin xyz="0.0 0 0.068" rpy="0 0 0"/>
  </joint>

  <link name="imu_link"/>

```

```

<joint name="scan_joint" type="fixed">
  <parent link="base_link"/>
  <child link="base_scan"/>
  <origin xyz="-0.064 0 0.122" rpy="0 0 0"/>
</joint>

<link name="base_scan">
  <visual>
    <origin xyz="0 0 0" rpy="0 0 0"/>
    <geometry>
      <mesh
filename="package://turtlebot3_description/meshes/sensors/lds.stl
" scale="0.001 0.001 0.001"/>
      </geometry>
      <material name="dark"/>
    </visual>

    <collision>
      <origin xyz="0.015 0 -0.0065" rpy="0 0 0"/>
      <geometry>
        <cylinder length="0.0315" radius="0.055"/>
      </geometry>
    </collision>

    <inertial>
      <mass value="0.114" />
      <origin xyz="0 0 0" />
      <inertia ixx="0.001" ixy="0.0" ixz="0.0"
        iyy="0.001" iyz="0.0"
        izz="0.001" />
    </inertial>
  </link>

<!-- Camera_0 -->
<joint name="camera_0_joint" type="fixed">
  <origin xyz="0.064 -0.065 0.094" rpy="0 0 0"/>
  <parent link="base_link"/>
  <child link="camera_0_link"/>
</joint>

<link name="camera_0_link">
  <visual>
    <origin xyz="0 0 0" rpy="1.57 0 1.57"/>
    <geometry>
      <mesh
filename="package://turtlebot3_description/meshes/sensors/r200.d
e" />
      </geometry>
    </visual>

```

```

    <collision>
      <origin xyz="0.003 0.065 0.007" rpy="0 0 0"/>
      <geometry>
        <box size="0.012 0.132 0.020"/>
      </geometry>
    </collision>

    <!-- This inertial field needs doesn't contain reliable
data!! -->
<!--   <inertial>
      <mass value="0.564" />
      <origin xyz="0 0 0" />
      <inertia ixx="0.003881243" ixy="0.0" ixz="0.0"
        iyy="0.000498940" iyz="0.0"
        izz="0.003879257" />
    </inertial>-->
</link>

<joint name="camera_0_rgb_joint" type="fixed">
  <origin xyz="{r200_cam_rgb_px} {r200_cam_rgb_py}
${r200_cam_rgb_pz}" rpy="0 0 0"/>
  <parent link="camera_0_link"/>
  <child link="camera_0_rgb_frame"/>
</joint>
<link name="camera_0_rgb_frame"/>

<joint name="camera_0_rgb_optical_joint" type="fixed">
  <origin xyz="0 0 0" rpy="-1.57 0 -1.57"/>
  <parent link="camera_0_rgb_frame"/>
  <child link="camera_0_rgb_optical_frame"/>
</joint>
<link name="camera_0_rgb_optical_frame"/>

<joint name="camera_0_depth_joint" type="fixed">
  <origin xyz="{r200_cam_rgb_px} {r200_cam_rgb_py} +
r200_cam_depth_offset" rpy="0 0 0"/>
  <parent link="camera_0_link"/>
  <child link="camera_0_depth_frame"/>
</joint>
<link name="camera_0_depth_frame"/>

<joint name="camera_0_depth_optical_joint" type="fixed">
  <origin xyz="0 0 0" rpy="-1.57 0 -1.57"/>
  <parent link="camera_0_depth_frame"/>
  <child link="camera_0_depth_optical_frame"/>
</joint>
<link name="camera_0_depth_optical_frame"/>

<!-- Camera 1 -->
<joint name="camera_1_joint" type="fixed">

```

```

    <origin xyz="-0.2 -0.065 0.094" rpy="0 0 0"/>
    <parent link="base_link"/>
    <child link="camera_1_link"/>
  </joint>

  <link name="camera_1_link">
    <visual>
      <origin xyz="0 0 0" rpy="1.57 0 1.57"/>
      <geometry>
        <mesh
filename="package://turtlebot3_description/meshes/sensors/r200.dae" />
        </geometry>
      </visual>
      <collision>
        <origin xyz="0.003 0.065 0.007" rpy="0 0 0"/>
        <geometry>
          <box size="0.012 0.132 0.020"/>
        </geometry>
      </collision>

      <!-- This inertial field needs doesn't contain reliable
data!! -->
      <!-- <inertial>
        <mass value="0.564" />
        <origin xyz="0 0 0" />
        <inertia ixx="0.003881243" ixy="0.0" ixz="0.0"
          iyy="0.000498940" iyz="0.0"
          izz="0.003879257" />
      </inertial>-->
    </link>

    <joint name="camera_1_rgb_joint" type="fixed">
      <origin xyz="{r200_cam_rgb_px} {r200_cam_rgb_py}
${r200_cam_rgb_pz}" rpy="0 0 3.14"/>
      <parent link="camera_1_link"/>
      <child link="camera_1_rgb_frame"/>
    </joint>
    <link name="camera_1_rgb_frame"/>

    <joint name="camera_1_rgb_optical_joint" type="fixed">
      <origin xyz="0 0 0" rpy="-1.57 0 -1.57"/>
      <parent link="camera_1_rgb_frame"/>
      <child link="camera_1_rgb_optical_frame"/>
    </joint>
    <link name="camera_1_rgb_optical_frame"/>

    <joint name="camera_1_depth_joint" type="fixed">
      <origin xyz="{r200_cam_rgb_px} {r200_cam_rgb_py} +
r200_cam_depth_offset" rpy="0 0 3.14"/>

```

```

    <parent link="camera_1_link"/>
    <child link="camera_1_depth_frame"/>
  </joint>
  <link name="camera_1_depth_frame"/>

  <joint name="camera_1_depth_optical_joint" type="fixed">
    <origin xyz="0 0 0" rpy="-1.57 0 -1.57"/>
    <parent link="camera_1_depth_frame"/>
    <child link="camera_1_depth_optical_frame"/>
  </joint>
  <link name="camera_1_depth_optical_frame"/>

</robot>

```

turtlebot3_willow_3d_2.launch

```

<launch>
  <arg name="model" default="$(env TURTLEBOT3_MODEL)" doc="model
type [burger, waffle, waffle_pi]"/>
  <arg name="x_pos" default="-2.0"/>
  <arg name="y_pos" default="-0.5"/>
  <arg name="z_pos" default="0.0"/>

  <include file="$(find gazebo_ros)/launch/empty_world.launch">
    <arg name="world_name" value="worlds/willowgarage.world"/>
    <arg name="paused" value="false"/>
    <arg name="use_sim_time" value="true"/>
    <arg name="gui" value="true"/>
    <arg name="headless" value="false"/>
    <arg name="debug" value="false"/>
  </include>

  <param name="robot_description" command="$(find xacro)/xacro --
inorder $(find turtlebot3_description)/urdf/turtlebot3_$(arg
model)_3d_2.urdf.xacro" />

  <node pkg="gazebo_ros" type="spawn_model" name="spawn_urdf"
args="-urdf -model turtlebot3_$(arg model) -x $(arg x_pos) -y
$(arg y_pos) -z $(arg z_pos) -param robot_description" />

  <node pkg="tf" type="static_transform_publisher"
name="world_to_map"
args="0 0 0 0 0 0 /world /map 100" />

</launch>

```

Appendix B

tb3_online_sync_rtab.launch

```
<launch>

  <node pkg="nodelet" type="nodelet"
name="pointcloud_to_laserscan_manager" output="screen"
respawn="true" args="manager"/>

  <!-- push pointcloud_to_laserscan nodelet into sensor's nodelet
manager-->
  <node pkg="nodelet" type="nodelet"
name="pointcloud_to_laserscan" args="standalone
pointcloud_to_laserscan/pointcloud_to_laserscan_nodelet">

    <remap from="cloud_in" to="/velodyne_points"/>
    <remap from="scan" to="velodyne_scan"/>
    <rosparam>
      target_frame: velodyne # Leave disabled to output scan in
pointcloud frame
      transform_tolerance: 0.01
      min_height: -0.3
      max_height: 0.5

      angle_min: -3.14159274101 # -M_PI/2 orig
      angle_max: 3.14159274101 # M_PI/2 orig
      angle_increment: 0.00700000021607 # M_PI/360.0
      scan_time: 0.3333
      range_min: 0.2
      range_max: 130.0
      use_inf: true
      inf_epsilon: 1.0

      # Concurrency level, affects number of pointclouds queued
for processing, thread number governed by nodelet manager
      # 0 : Detect number of cores
      # 1 : Single threaded
      # 2->inf : Parallelism level
      concurrency_level: 2
    </rosparam>
  </node>

  <node pkg="slam_toolbox" type="sync_slam_toolbox_node"
name="slam_toolbox" output="screen">
    <rosparam command="load" file="$(find
slam_toolbox)/config/tb3_mapper_params_online_sync.yaml" />
  </node>
```

```

    <node pkg="tf" type="static_transform_publisher"
name="foot_to_scan" args="-0.064 0 0.122 0 0 0 /base_footprint
/base_scan 100" />
    <node pkg="tf" type="static_transform_publisher"
name="foot_to_velodyne" args="0 0 0.44 0 0 0 /base_footprint
/velodyne 100" />
    <node pkg="tf" type="static_transform_publisher"
name="foot_to_rgb_0" args="0.064 -0.065 0.094 -1.57 0 -1.57
/base_footprint /camera_0_rgb_optical_frame 100" />
    <node pkg="tf" type="static_transform_publisher"
name="foot_to_depth_0" args="0.064 -0.065 0.094 -1.57 0 -1.57
/base_footprint /camera_0_depth_optical_frame 100" />
    <node pkg="tf" type="static_transform_publisher"
name="foot_to_rgb_1" args="-0.2 -0.065 0.094 1.57 0 -1.57
/base_footprint /camera_1_rgb_optical_frame 100" />
    <node pkg="tf" type="static_transform_publisher"
name="foot_to_depth_1" args="-0.2 -0.065 0.094 1.57 0 -1.57
/base_footprint /camera_1_depth_optical_frame 100" />

    <node pkg="nodelet" type="nodelet" name="pcl_manager"
args="manager" output="screen" />
    <node pkg="nodelet" type="nodelet" name="voxel_grid" args="load
pcl/VoxelGrid pcl_manager" output="screen">
    <remap from="~/input" to="/velodyne_points" />
    <rosparam>
        filter_field_name: z
        filter_limit_min: -0.4 # -1000 is abs min
        filter_limit_max: 10 # 1000 is abs max
        filter_limit_negative: False
        leaf_size: 0.01
    </rosparam>
</node>

    <node pkg="nodelet" type="nodelet"
name="pointcloud_to_depthimage_0" args="standalone
rtabmap_ros/pointcloud_to_depthimage" output="screen">
    <remap from="camera_info"
to="/camera_0/rgb/camera_info"/>
    <remap from="cloud" to="/voxel_grid/output"/>
    <remap from="depth_topic" to="image_raw"/>
    <remap from="image_raw" to="image_raw_0"/>
    <param name="fixed_frame_id" type="string"
value="velodyne"/>
    <param name="fill_holes_size" type="int" value="30"/>
    <param name="decimation" type="int" value="1"/>
</node>
    <node pkg="nodelet" type="nodelet" name="rgbd_sync_0"
args="standalone rtabmap_ros/rgbd_sync" output="screen">
    <remap from="rgb/image"

```

```

to="/camera_0/rgb/image_raw"/>
  <remap from="depth/image"      to="image_raw_0"/>
  <remap from="rgb/camera_info"
to="/camera_0/rgb/camera_info"/>
  <remap from="rgbd_image"      to="rgbd_image0"/>
  <param name="approx_sync"      value="false"/>
</node>

  <node pkg="nodelet" type="nodelet"
name="pointcloud_to_depthimage_1" args="standalone
rtabmap_ros/pointcloud_to_depthimage" output="screen">
  <remap from="camera_info"
to="/camera_1/rgb/camera_info"/>
  <remap from="cloud"          to="/voxel_grid/output"/>
  <remap from="depth_topic"    to="image_raw"/>
  <remap from="image_raw"      to="image_raw_1"/>
  <param name="fixed_frame_id" type="string"
value="velodyne"/>
  <param name="fill_holes_size" type="int" value="30"/>
  <param name="decimation" type="int" value="1"/>
</node>

  <node pkg="nodelet" type="nodelet" name="rgbd_sync_1"
args="standalone rtabmap_ros/rgbd_sync" output="screen">
  <remap from="rgb/image"
to="/camera_1/rgb/image_raw"/>
  <remap from="depth/image"      to="image_raw_1"/>
  <remap from="rgb/camera_info"
to="/camera_1/rgb/camera_info"/>
  <remap from="rgbd_image"      to="rgbd_image1"/>
  <param name="approx_sync"      value="false"/>
</node>

  <node name="data_recorder" pkg="rtabmap_ros" type="rtabmap"
output="screen" args="--delete_db_on_start">
  <param name="Mem/RehearsalSimilarity" type="string"
value="1.0"/>    <!-- deactivate rehearsal -->
  <param name="Kp/MaxFeatures"          type="string" value="-
1"/>    <!-- deactivate keypoints extraction -->
  <param name="Rtabmap/MaxRetrieved"     type="string"
value="0"/>    <!-- deactivate global retrieval -->
  <param name="RGBD/MaxLocalRetrieved"   type="string"
value="0"/>    <!-- deactivate local retrieval -->
  <param name="Mem/MapLabelsAdded"       type="string"
value="false"/> <!-- don't create map labels -->
  <param name="Rtabmap/MemoryThr"        type="string"
value="2"/>    <!-- keep the WM empty -->
  <param name="Mem/STMSize"              type="string"
value="1"/>    <!-- STM=1 -->
  <param name="publish_tf"               type="bool"
value="false"/> <!-- don't publish TF -->

```



```

    <param name="RGBD/ProximityBySpace"    type="string"
value="false"/>    <!-- Local loop closure detection (using
estimated position) with locations in WM -->
    <param name="RGBD/LinearUpdate"        type="string"
value="0"/>
    <param name="RGBD/AngularUpdate"       type="string"
value="0"/>
    <param name="RGBD/CreateOccupancyGrid" type="string"
value="false"/>
    <param name="Rtabmap/DetectionRate"    type="string"
value="1"/>
    <param name="DbSqlite3/InMemory"       type="string"
value="false"/>
    <param name="frame_id"                 type="string"
value="base_footprint"/>
    <param name="queue_size"               type="int"
value="10"/>
    <param name="approx_sync"              type="bool"
value="true"/>
    <param name="Reg/Strategy"              type="string"
value="1"/>    <!-- 0=Visual, 1=ICP, 2=Visual+ICP -->
    <param name="Reg/Force3DoF"            type="string"
value="true"/> <!-- 2D SLAM -->
    <param name="Grid/FromDepth"           type="string"
value="false"/> <!-- Create 2D occupancy grid from laser scan -->
    <param name="RGBD/ProximityPathMaxNeighbors" type="string"
value="10"/> <!-- Do also proximity detection by space by merging
close scans together. -->
    <param name="Kp/DetectorStrategy"      type="string"
value="10"/>
    <param name="Vis/FeatureType"          type="string"
value="10"/>
    <param name="Vis/EstimationType"       type="string"
value="0"/>
    <param name="Optimizer/Strategy"       type="string"
value="3"/>
    <param name="Vis/BundleAdjustment"     type="string"
value="3"/>
    <param name="Kp/RoiRatios"             type="string"
value="0.0 0.0 0.0 0.4"/>

    <param name="subscribe_rgb"            type="bool"
value="false"/>
    <param name="subscribe_scan"           type="bool"
value="true"/>
    <param name="subscribe_scan_cloud"     type="bool"
value="false"/>
    <param name="subscribe_rgbd"           type="bool"
value="true"/>
    <param name="subscribe_odometry"       type="bool"

```

```

value="true"/>
  <param name="subscribe_depth"          type="bool"
value="false"/>

  <remap from="odom"                      to="/odom"/>
  <remap from="scan"                      to="/velodyne_scan"/>
  <remap from="scan_cloud"
to="/voxel_grid/output"/>
  <remap from="rgb/image"
to="/camera_0/rgb/image_raw"/>
  <remap from="depth/image"
to="/camera_0/depth/image_raw"/>
  <remap from="rgb/camera_info"
to="/camera_0/rgb/camera_info"/>

  <param name="rgbd_cameras"      type="int"    value="2"/>
  <remap from="rgbd_image0"      to="rgbd_image0"/>
  <remap from="rgbd_image1"      to="rgbd_image1"/>
</node>
</launch>

```

tb3_mapper_params_online_sync.my_assembler

```

# Plugin params
solver_plugin: solver_plugins::CeresSolver
ceres_linear_solver: SPARSE_NORMAL_CHOLESKY
ceres_preconditioner: SCHUR_JACOBI
ceres_trust_strategy: LEVENBERG_MARQUARDT
ceres_dogleg_type: TRADITIONAL_DOGLEG
ceres_loss_function: None

# ROS Parameters
odom_frame: odom
map_frame: map
base_frame: base_footprint
scan_topic: /velodyne_scan
mode: mapping #localization

# if you'd like to immediately start continuing a map at a given
pose
# or at the dock, but they are mutually exclusive, if pose is
given
# will use pose
#map_file_name: test_steve
#map_start_pose: [0.0, 0.0, 0.0]
#map_start_at_dock: true

debug_logging: false
throttle_scans: 1
transform_publish_period: 0.02 #if 0 never publishes odometry

```

```
map_update_interval: 1.0
resolution: 0.05
max_laser_range: 100.0 #for rastering images
minimum_time_interval: 0.5
transform_timeout: 0.2
tf_buffer_duration: 30.
stack_size_to_use: 40000000 #// program needs a larger stack size
to serialize large maps
enable_interactive_mode: true
```

General Parameters

```
use_scan_matching: true
use_scan_barycenter: true
minimum_travel_distance: 0.5
minimum_travel_heading: 0.5
scan_buffer_size: 10
scan_buffer_maximum_scan_distance: 10
link_match_minimum_response_fine: 0.1
link_scan_maximum_distance: 1.5
loop_search_maximum_distance: 3.0
do_loop_closing: true
loop_match_minimum_chain_size: 10
loop_match_maximum_variance_coarse: 3.0
loop_match_minimum_response_coarse: 0.35
loop_match_minimum_response_fine: 0.45
```

Correlation Parameters - Correlation Parameters

```
correlation_search_space_dimension: 0.5
correlation_search_space_resolution: 0.01
correlation_search_space_smear_deviation: 0.1
```

Correlation Parameters - Loop Closure Parameters

```
loop_search_space_dimension: 8.0
loop_search_space_resolution: 0.05
loop_search_space_smear_deviation: 0.03
```

Scan Matcher Parameters

```
distance_variance_penalty: 0.5
angle_variance_penalty: 1.0

fine_search_angle_offset: 0.00349
coarse_search_angle_offset: 0.349
coarse_angle_resolution: 0.0349
minimum_angle_penalty: 0.9
minimum_distance_penalty: 0.5
use_response_expansion: true
```

Appendix C

tb3_move_base_slambox_STVL_eband.launch

```

<launch>
  <!-- Arguments -->
  <arg name="model" default="$(env TURTLEBOT3_MODEL)" doc="model
type [burger, waffle, waffle_pi]"/>
  <arg name="cmd_vel_topic" default="/cmd_vel" />
  <arg name="odom_topic" default="odom" />
  <arg name="move_forward_only" default="false"/>

  <!-- move_base -->
  <node pkg="move_base" type="move_base" respawn="false"
name="move_base" output="screen">
    <param name="base_local_planner"
value="eband_local_planner/EBandPlannerROS" />
    <param name="base_global_planner" type="string"
value="global_planner/GlobalPlanner" />
    <rosparam ns="global_costmap">

      obstacle_range: 6.0
      raytrace_range: 7.0

      footprint: [[-0.205, -0.155], [-0.205, 0.155], [0.077,
0.155], [0.077, -0.155]]

      cost_scaling_factor: 3.0

      map_type: costmap

      transform_tolerance: 1
      footprint_padding: 0.03
      controller_patience: 2.0

      recovery_behaviors: [
        {name: conservative_clear, type:
clear_costmap_recovery/ClearCostmapRecovery},
        {name: aggressive_clear, type:
clear_costmap_recovery/ClearCostmapRecovery},
        {name: rotate_recovery, type:
rotate_recovery/RotateRecovery}
      ]

      conservative_clear:
        reset_distance: 3.00
      aggressive_clear:
        reset_distance: 1.84
    </rosparam>
  </node>

```

```

    global_frame: map
    robot_base_frame: base_footprint
    update_frequency: 0.5
    publish_frequency: 0.5
    static_map: true

    GlobalPlanner:
      allow_unknown: true
      cost_factor: 0.55
      neutral_cost: 66 #check
      kaiyuzheng.me/documents/navguide.pdf
      lethal_cost: 253

  </rosparam>
  <rosparam ns="local_costmap">

    obstacle_range: 6.0
    raytrace_range: 7.0

    footprint: [[-0.205, -0.155], [-0.205, 0.155], [0.077,
0.155], [0.077, -0.155]]

    cost_scaling_factor: 3.0

    map_type: costmap

    transform_tolerance: 1
    footprint_padding: 0.03
    controller_patience: 2.0

    recovery_behaviors: [
      {name: conservative_clear, type:
clear_costmap_recovery/ClearCostmapRecovery},
      {name: aggressive_clear, type:
clear_costmap_recovery/ClearCostmapRecovery},
      {name: rotate_recovery, type:
rotate_recovery/RotateRecovery}
    ]

    conservative_clear:
      reset_distance: 3.00
    aggressive_clear:
      reset_distance: 1.84

    global_frame: odom
    robot_base_frame: base_footprint
    update_frequency: 2.0
    publish_frequency: 2.0

```

```

static_map: false
rolling_window: true
width: 6.0
height: 6.0
resolution: 0.01 #velodyne resolution is 0.001
origin_x: -5.0
origin_y: -5.0

plugins:
  - {name: rgbd_obstacle_layer, type:
"spatio_temporal_voxel_layer/SpatioTemporalVoxelLayer"}
  - {name: inflation_layer, type:
'costmap_2d::InflationLayer'}

  rgbd_obstacle_layer:
    enabled: true
    voxel_decay: 15 # seconds if linear, e^n
if exponential
    decay_model: 0 # 0=linear,
1=exponential, -1=persistent
    voxel_size: 0.05 # meters
    track_unknown_space: true # default space is known
    max_obstacle_height: 0.5 # meters
    unknown_threshold: 15 # voxel height
    mark_threshold: 0 # voxel height
    update_footprint_enabled: true
    combination_method: 1 # 1=max, 0=override
    obstacle_range: 6.0 # meters
    origin_z: 0.0 # meters
    publish_voxel_map: true # default off
    transform_tolerance: 0.2 # seconds
    mapping_mode: false # default off, saves map
not for navigation
    map_save_duration: 60 # default 60s, how often
to autosave
    observation_sources: rgbd1_mark rgbd1_clear
    rgbd1_mark:
      data_type: PointCloud2
      topic: /velodyne_points
      marking: true
      clearing: false
      min_obstacle_height: 0.1 # default 0, meters
      max_obstacle_height: 0.5 # default 3, meters
      expected_update_rate: 0.0 # default 0, if not
updating at this rate at least, remove from buffer
      observation_persistence: 0.0 # default 0, use all
measurements taken during now-value, 0=latest
      inf_is_valid: false # default false, for laser
scans
      voxel_filter: false # default off, apply voxel

```

```

filter to sensor, recommend on
    voxel_min_points: 0          # default 0, minimum
points per voxel for voxel filter
    clear_after_reading: true    # default false, clear the
buffer after the layer gets readings from it
    rgbdl_clear:
        enabled: true            #default true, can be
toggled on/off with associated service call
        data_type: PointCloud2
        topic: /velodyne_points
        marking: false
        clearing: true
        max_z: 7.0                # default 0, meters
        min_z: 0.2                # default 10, meters
        vertical_fov_angle: 0.523 # default 0.7, radians. For
3D lidars it's the symmetric FOV about the planar axis.
        vertical_fov_padding: 0.05 # 3D Lidar only. Default
0, in meters
        horizontal_fov_angle: 6.29 # 3D lidar scanners like
the VLP16 have 360 deg horizontal FOV.
        decay_acceleration: 5.0   # default 0, 1/s^2.
        model_type: 1             # default 0, model type for
frustum. 0=depth camera, 1=3d lidar like VLP16 or similar

    inflation_layer:
        obstacle_range: 10.0
        raytrace_range: 10.5
        #robot_radius: sqrt(2) / 2 * (0.205+0.077) = 0.199404
        inflation_radius: 0.4 # ~2*robot_radius
</rosparam>

<rosparam ns="move_base">
shutdown_costmaps: false
controller_frequency: 10.0
planner_patience: 5.0
controller_patience: 15.0
conservative_reset_dist: 3.0
planner_frequency: 5.0
oscillation_timeout: 10.0
oscillation_distance: 0.2
</rosparam>

<rosparam>
EBandPlannerROS:

# Robot Configuration Parameters
max_vel_x: 0.26
min_vel_x: -0.26

max_vel_y: 0.0

```

```
    min_vel_y: 0.0

    # The velocity when robot is moving in a straight line
    max_vel_trans: 0.26
    min_vel_trans: -0.26

    max_vel_theta: 1.82
    min_vel_theta: -1.82

    acc_lim_x: 2.5
    acc_lim_y: 0.0
    acc_lim_theta: 1.1

    # Common Parameters
    xy_goal_tolerance: 0.1 # Distance tolerance for reaching
the goal pose
    yaw_goal_tolerance: 0.15 # Orientation tolerance for
reaching the desired goal pose
    rot_stopped_vel: 0.05 # Angular velocity lower bound that
determines if the robot should stop to avoid limit-cycles or
locks
    trans_stopped_vel: 0.05 # Linear velocity lower bound that
determines if the robot should stop to avoid limit-cycles or
locks

    # Visualization Parameters
    marker_lifetime: 1.0 # Lifetime of eband visualization
markers

    # Trajectory Controller Parameters
    k_prop: 4.0 # Proportional gain of the PID controller
    k_damp: 3.5 # Damping gain of the PID controller
    k_int: 0.001 # I gain of the PID controller
    Ctrl_Rate: 10 # Control rate
    differential_drive: true # Denotes whether to use the
differential drive mode

</rosparam>
  <remap from="cmd_vel" to="$(arg cmd_vel_topic)"/>
  <remap from="odom" to="$(arg odom_topic)"/>
</node>
</launch>
```


Appendix D

explore.cpp

```

/*****
 *
 * Software License Agreement (BSD License)
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*****
****/

#include <explore/explore.h>

#include <thread>

inline static bool operator==(const geometry_msgs::Point& one,
                              const geometry_msgs::Point& two)
{
    double dx = one.x - two.x;
    double dy = one.y - two.y;
    double dist = sqrt(dx * dx + dy * dy);
    return dist < 0.01;
}

namespace explore
{
    Explore::Explore()
        : private_nh_("~")
        , tf_listener_(ros::Duration(10.0))
        , costmap_client_(private_nh_, relative_nh_, &tf_listener_)
        , move_base_client_("move_base")
        , prev_distance_(0)
        , last_markers_count_(0)
    {
        double timeout;
        double min_frontier_size;
        private_nh_.param("planner_frequency", planner_frequency_,
1.0);
        private_nh_.param("progress_timeout", timeout, 30.0);
        progress_timeout_ = ros::Duration(timeout);
        private_nh_.param("visualize", visualize_, false);
        private_nh_.param("potential_scale", potential_scale_, 1e-3);
        private_nh_.param("orientation_scale", orientation_scale_,
0.0);
        private_nh_.param("gain_scale", gain_scale_, 1.0);
        private_nh_.param("min_frontier_size", min_frontier_size, 0.5);
    }
}

```

```

    search_ =
frontier_exploration::FrontierSearch(costmap_client_.getCostmap()
,

potential_scale_, gain_scale_,

min_frontier_size);

    if (visualize_) {
        marker_array_publisher_ =

private_nh_.advertise<visualization_msgs::MarkerArray>("frontiers
", 10);
    }

    //change this later!
    ROS_INFO("Waiting to connect to move_base server");
    move_base_client_.waitForServer();
    ROS_INFO("Connected to move_base server");

    exploring_timer_ =
        relative_nh_.createTimer(ros::Duration(1. /
planner_frequency_),
                                [this](const ros::TimerEvent&) {
makePlan(); });
}

Explore::~~Explore()
{
    stop();
}

void Explore::visualizeFrontiers(
    const std::vector<frontier_exploration::Frontier>& frontiers)
{
    std_msgs::ColorRGBA blue;
    blue.r = 0;
    blue.g = 0;
    blue.b = 1.0;
    blue.a = 1.0;
    std_msgs::ColorRGBA red;
    red.r = 1.0;
    red.g = 0;
    red.b = 0;
    red.a = 1.0;
    std_msgs::ColorRGBA green;
    green.r = 0;
    green.g = 1.0;
    green.b = 0;
    green.a = 1.0;

```

```

    ROS_DEBUG("visualising %lu frontiers", frontiers.size());
    visualization_msgs::MarkerArray markers_msg;
    std::vector<visualization_msgs::Marker>& markers =
markers_msg.markers;
    visualization_msgs::Marker m;

    m.header.frame_id = costmap_client_.getGlobalFrameID();
    m.header.stamp = ros::Time::now();
    m.ns = "frontiers";
    m.scale.x = 1.0;
    m.scale.y = 1.0;
    m.scale.z = 1.0;
    m.color.r = 0;
    m.color.g = 0;
    m.color.b = 255;
    m.color.a = 255;
    // lives forever
    m.lifetime = ros::Duration(0);
    m.frame_locked = true;

    // weighted frontiers are always sorted
    double min_cost = frontiers.empty() ? 0. :
frontiers.front().cost;

    m.action = visualization_msgs::Marker::ADD;
    size_t id = 0;
    for (auto& frontier : frontiers) {
        m.type = visualization_msgs::Marker::POINTS;
        m.id = int(id);
        m.pose.position = {};
        m.scale.x = 0.1;
        m.scale.y = 0.1;
        m.scale.z = 0.1;
        m.points = frontier.points;
        if (goalOnBlacklist(frontier.centroid)) {
            m.color = red;
        } else {
            m.color = blue;
        }
        markers.push_back(m);
        ++id;
        m.type = visualization_msgs::Marker::SPHERE;
        m.id = int(id);
        m.pose.position = frontier.initial;
        // scale frontier according to its cost (costier frontiers
will be smaller)
        double scale = std::min(std::abs(min_cost * 0.4 /
frontier.cost), 0.5);
        m.scale.x = scale;

```

```

        m.scale.y = scale;
        m.scale.z = scale;
        m.points = {};
        m.color = green;
        markers.push_back(m);
        ++id;
    }
    size_t current_markers_count = markers.size();

    // delete previous markers, which are now unused
    m.action = visualization_msgs::Marker::DELETE;
    for (; id < last_markers_count_; ++id) {
        m.id = int(id);
        markers.push_back(m);
    }

    last_markers_count_ = current_markers_count;
    marker_array_publisher_.publish(markers_msg);
}

void Explore::makePlan()
{
    // find frontiers
    auto pose = costmap_client_.getRobotPose();
    // get frontiers sorted according to cost
    auto frontiers = search_.searchFrom(pose.position);
    ROS_DEBUG("found %lu frontiers", frontiers.size());
    for (size_t i = 0; i < frontiers.size(); ++i) {
        ROS_DEBUG("frontier %zd cost: %f", i, frontiers[i].cost);
    }
    if (frontiers.empty()) {
        stop();
        return;
    }

    // publish frontiers as visualization markers
    if (visualize_) {
        visualizeFrontiers(frontiers);
    }

    // find non blacklisted frontier
    auto frontier =
        std::find_if_not(frontiers.begin(), frontiers.end(),
                        [this](const
frontier_exploration::Frontier& f) {
                        return goalOnBlacklist(f.centroid);
                    });
    if (frontier == frontiers.end()) {
        stop();
        return;
    }

```

```

    }
    geometry_msgs::Point target_position = frontier->centroid;

    // time out if we are not making any progress
    bool same_goal = prev_goal_ == target_position;
    prev_goal_ = target_position;
    if (!same_goal || prev_distance_ > frontier->min_distance) {
        // we have different goal or we made some progress
        last_progress_ = ros::Time::now();
        prev_distance_ = frontier->min_distance;
    }
    // black list if we've made no progress for a long time
    if (ros::Time::now() - last_progress_ > progress_timeout_) {
        frontier_blacklist_.push_back(target_position);
        ROS_DEBUG("Adding current goal to black list");
        makePlan();
        return;
    }

    // we don't need to do anything if we still pursuing the same
    goal
    if (same_goal) {
        return;
    }

    // send goal to move_base if we have something new to pursue
    move_base_msgs::MoveBaseGoal goal;
    goal.target_pose.pose.position = target_position;
    goal.target_pose.pose.orientation.w = 1.;
    goal.target_pose.header.frame_id =
    costmap_client_.getGlobalFrameID();
    goal.target_pose.header.stamp = ros::Time::now();
    move_base_client_.sendGoal(
        goal, [this, target_position](
            const actionlib::SimpleClientGoalState& status,
            const move_base_msgs::MoveBaseResultConstPtr&
result) {
        reachedGoal(status, result, target_position);
    });
}

bool Explore::goalOnBlacklist(const geometry_msgs::Point& goal)
{
    constexpr static size_t tolerace = 5;
    costmap_2d::Costmap2D* costmap2d =
    costmap_client_.getCostmap();

    // check if a goal is on the blacklist for goals that we're
    pursuing
    for (auto& frontier_goal : frontier_blacklist_) {

```

```

    double x_diff = fabs(goal.x - frontier_goal.x);
    double y_diff = fabs(goal.y - frontier_goal.y);

    if (x_diff < tolerace * costmap2d->getResolution() &&
        y_diff < tolerace * costmap2d->getResolution())
        return true;
    }
    return false;
}

void Explore::reachedGoal(const actionlib::SimpleClientGoalState&
status,
                        const
move_base_msgs::MoveBaseResultConstPtr&,
                        const geometry_msgs::Point&
frontier_goal)
{
    ROS_DEBUG("Reached goal with status: %s",
status.toString().c_str());
    if (status == actionlib::SimpleClientGoalState::ABORTED) {
        frontier_blacklist_.push_back(frontier_goal);
        ROS_DEBUG("Adding current goal to black list");
    }

    // find new goal immediatelly regardless of planning frequency.
    // execute via timer to prevent dead lock in move_base_client
    (this is
    // callback for sendGoal, which is called in makePlan). the
timer must live
    // until callback is executed.
    oneshot_ = relative_nh_.createTimer(
        ros::Duration(0, 0), [this](const ros::TimerEvent&) {
makePlan(); },
        true);
}

void Explore::start()
{
    exploring_timer_.start();
}

void Explore::stop()
{
    move_base_client_.cancelAllGoals();
    exploring_timer_.stop();
    ROS_INFO("Exploration stopped.");
    ROS_INFO("Returning home.");
    // send goal to move_base to go home
    move_base_msgs::MoveBaseGoal goal;
    goal.target_pose.pose.position.x = 0;

```

```

    goal.target_pose.pose.position.y = 0;
    goal.target_pose.pose.position.z = 0;
    goal.target_pose.pose.position.x = 0;
    goal.target_pose.pose.orientation.y = 0;
    goal.target_pose.pose.orientation.z = 0;
    goal.target_pose.pose.orientation.w = 1.;
    goal.target_pose.header.frame_id =
costmap_client_.getGlobalFrameID();
    goal.target_pose.header.stamp = ros::Time::now();
    move_base_client_.sendGoal(goal);
}

} // namespace explore

int main(int argc, char** argv)
{
    ros::init(argc, argv, "explore");
    if (ros::console::set_logger_level(ROSCONSOLE_DEFAULT_NAME,

ros::console::levels::Debug)) {
        ros::console::notifyLoggerLevelsChanged();
    }
    explore::Explore explore;
    ros::spin();

    return 0;
}

```

frontier_search.cpp

```

#include <explore/frontier_search.h>
#include <stdlib.h>
#include <mutex>
#include <math.h>
#include <costmap_2d/cost_values.h>
#include <costmap_2d/costmap_2d.h>
#include <geometry_msgs/Point.h>

#include <explore/costmap_tools.h>
double MAX_X = std::atof(std::getenv("MAX_X"));
double MAX_Y = std::atof(std::getenv("MAX_Y"));
namespace frontier_exploration
{
    using costmap_2d::LETHAL_OBSTACLE;
    using costmap_2d::NO_INFORMATION;
    using costmap_2d::FREE_SPACE;

    FrontierSearch::FrontierSearch(costmap_2d::Costmap2D* costmap,
                                   double potential_scale, double
gain_scale,

```



```

        double min_frontier_size)
    : costmap_(costmap)
    , potential_scale_(potential_scale)
    , gain_scale_(gain_scale)
    , min_frontier_size_(min_frontier_size)
    {
    }
std::vector<Frontier>
FrontierSearch::searchFrom(geometry_msgs::Point position)
{
    std::vector<Frontier> frontier_list;

    // Sanity check that robot is inside costmap bounds before
    searching
    unsigned int mx, my;
    if (!costmap_->worldToMap(position.x, position.y, mx, my)) {
        ROS_ERROR("Robot out of costmap bounds, cannot search for
frontiers");
        return frontier_list;
    }

    // make sure map is consistent and locked for duration of
    search
    std::lock_guard<costmap_2d::Costmap2D::mutex_t>
lock(*(costmap_->getMutex()));

    map_ = costmap_->getCharMap();
    size_x_ = costmap_->getSizeInCellsX();
    size_y_ = costmap_->getSizeInCellsY();

    // initialize flag arrays to keep track of visited and frontier
    cells
    std::vector<bool> frontier_flag(size_x_ * size_y_, false);
    std::vector<bool> visited_flag(size_x_ * size_y_, false);

    // initialize breadth first search
    std::queue<unsigned int> bfs;

    // find closest clear cell to start search
    unsigned int clear, pos = costmap_->getIndex(mx, my);
    if (nearestCell(clear, pos, FREE_SPACE, *costmap_)) {
        bfs.push(clear);
    } else {
        bfs.push(pos);
        ROS_WARN("Could not find nearby clear cell to start search");
    }
    visited_flag[bfs.front()] = true;

    while (!bfs.empty()) {
        unsigned int idx = bfs.front();

```

```

    bfs.pop();

    // iterate over 4-connected neighbourhood
    for (unsigned nbr : nhoud4(idx, *costmap_)) {
        // add to queue all free, unvisited cells, use descending
search in case
        // initialized on non-free cell
        if (map_[nbr] <= map_[idx] && !visited_flag[nbr]) {
            visited_flag[nbr] = true;
            bfs.push(nbr);
            // check if cell is new frontier cell (unvisited,
NO_INFORMATION, free
            // neighbour)
        } else if (isNewFrontierCell(nbr, frontier_flag)) {
            frontier_flag[nbr] = true;
            Frontier new_frontier = buildNewFrontier(nbr, pos,
frontier_flag);
            if (new_frontier.size * costmap_->getResolution() >=
                min_frontier_size_) {
                frontier_list.push_back(new_frontier);
            }
        }
    }
}

// set costs of frontiers
for (auto& frontier : frontier_list) {
    frontier.cost = frontierCost(frontier);
}
std::sort(
    frontier_list.begin(), frontier_list.end(),
    [](const Frontier& f1, const Frontier& f2) { return f1.cost
< f2.cost; });

return frontier_list;
}

Frontier FrontierSearch::buildNewFrontier(unsigned int
initial_cell,
                                         unsigned int reference,
                                         std::vector<bool>&
frontier_flag)
{
    // initialize frontier structure
    Frontier output;
    output.centroid.x = 0;
    output.centroid.y = 0;
    output.size = 1;
    output.min_distance = std::numeric_limits<double>::infinity();

```

```
// record initial contact point for frontier
unsigned int ix, iy;
costmap_->indexToCells(initial_cell, ix, iy);
costmap_->mapToWorld(ix, iy, output.initial.x,
output.initial.y);

// push initial gridcell onto queue
std::queue<unsigned int> bfs;
bfs.push(initial_cell);

// cache reference position in world coords
unsigned int rx, ry;
double reference_x, reference_y;
costmap_->indexToCells(reference, rx, ry);
costmap_->mapToWorld(rx, ry, reference_x, reference_y);

while (!bfs.empty()) {
    unsigned int idx = bfs.front();
    bfs.pop();

    // try adding cells in 8-connected neighborhood to frontier
    for (unsigned int nbr : nhoud8(idx, *costmap_)) {
        // check if neighbour is a potential frontier cell
        if (isNewFrontierCell(nbr, frontier_flag)) {
            // mark cell as frontier
            frontier_flag[nbr] = true;
            unsigned int mx, my;
            double wx, wy;
            costmap_->indexToCells(nbr, mx, my);
            costmap_->mapToWorld(mx, my, wx, wy);

            geometry_msgs::Point point;
            point.x = wx;
            point.y = wy;
            output.points.push_back(point);

            // update frontier size
            output.size++;

            // update centroid of frontier
            output.centroid.x += wx;
            output.centroid.y += wy;

            // determine frontier's distance from robot, going by
            // closest gridcell
            // to robot
            double distance = sqrt(pow((double(reference_x) -
            double(wx)), 2.0) +
                                pow((double(reference_y) -
            double(wy)), 2.0));
```

```

        if (distance < output.min_distance) {
            output.min_distance = distance;
            output.middle.x = wx;
            output.middle.y = wy;
        }

        // add to queue for breadth first search
        bfs.push(nbr);
    }
}

// average out frontier centroid
output.centroid.x /= output.size;
output.centroid.y /= output.size;
return output;
}

bool FrontierSearch::isNewFrontierCell(unsigned int idx,
                                       const std::vector<bool>&
                                       frontier_flag)
{
    // check that cell is unknown and not already marked as
    // frontier
    if (map_[idx] != NO_INFORMATION || frontier_flag[idx]) {
        return false;
    }

    // frontier cells should have at least one cell in 4-connected
    // neighbourhood
    // that is free
    for (unsigned int nbr : nhoud4(idx, *costmap_)) {
        // checks to make sure that x and y coords are within the
        // designated MAX_X and MAX_Y values
        unsigned int mx, my;
        double x, y;
        costmap_->indexToCells(idx, mx, my);
        costmap_->mapToWorld(mx, my, x, y);
        if (fabs(x) >= MAX_X || fabs(y) >= MAX_Y) {
            return false;
        }
        if (map_[nbr] == FREE_SPACE) {
            return true;
        }
    }

    return false;
}

double FrontierSearch::frontierCost(const Frontier& frontier)

```

```
{
    return (potential_scale_ * frontier.min_distance *
            costmap_->getResolution()) -
            (gain_scale_ * frontier.size * costmap_-
            >getResolution());
}
}
```

REPORT DOCUMENTATION PAGE

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