Introduction to Point-Cloud Processing

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Introduction: Three-D sensing is increasingly common in robotics. Example sources of 3-D data include tilting or rotating LIDARs, stereo cameras, or structured-light processing, such as the Microsoft Kinect sensor. Each of these sensors has its own virtues and limitations. Rotating LIDAR instruments can require a relatively long acquisition time to achieve reasonable 3-D sampling. The resulting 3-D images can be fairly noisy (on the order of cm, for the Hokuyo). However, such sensors have good range and work outdoors. Stereo vision can be relatively inexpensive, can be high resolution, and can augment range information with color and intensity. However, the range and field of view are restrictive, relative to LIDARs. Further, stereo vision depends on viewing targets that have suitable "texture", which helps to address the left/right camera pixel correspondence problem for generating disparity maps. The useful range of stereo vision depends on the interocular distance; wider separation between the cameras is required for greater depth range, but this also limits the near range (i.e., making the system far-sighted). On the other hand, optics can be designed over huge variations—from telescopes to microscopes.

The Kinect sensor uses a structured-light source of infra-red, projecting a "speckle" pattern. A single camera detects this projected pattern and interprets range from triangulation, equivalently deducing the shape of illuminated scenes from how the speckle pattern is projected over surfaces. The Kinect camera has surprisingly good performance for its low price. The depth points are "colorized" by associating corresponding data from a 2nd (color) camera. The density of points is high. However, the field of view and the range are limited (optimized for gaming applications), and this device does not work in sunlight.

This document will focus on use of the Kinect sensor and interactions with Rviz, but the principles are applicable to 3D images from other sources.

Point Clouds: There are a variety of representations of 3-D images. Many variations are accommodated with the "PointCloud" definition. (see http://pointclouds.org/about/).

A point-cloud has a header, with fields for a time stamp and for a reference frame. A point-cloud also has fields for "height," "width," and "is_dense."

One style of representation is to merely list "points" in a random order, where each point has associated data. This is an "unordered" point cloud. Unordered point clouds have a "height" of 1, and a "width" equal to the number of points. Data that originates from a rotating LIDAR typically results in unordered point clouds, since this data is not acquired in a simple raster pattern. Alternatively, stereo cameras and the Kinect camera produce "ordered" point clouds. Points in an *ordered* point cloud can be accessed by row and column (though index computations are required). The row and column indices of the point-cloud structure correspond to row and column indices of the image plane. At each such [i][j] location, one may find N-dimensional data, e.g. (x,y,z,R,G,B). In contrast to an unordered point cloid, an ordered point cloud can offer computational efficiencies, since points that are close together in [i][j] space are (typically) close together in (x,y,z,R,G,B) space—at least when these points correspond to samples on a smooth patch of surface in the scene.

The "is_dense" field of a point cloud declares whether or not (true/false) every point in the point cloud has valid data. Commonly, sensors provide imperfect results. Stereo vision, for example, typically suffers from inability to resolve the correspondence problem where there is insufficient texture in the scene, and corresponding points lack computable depth. Coordinates for such points may containt "inf" or "NaN" to indicate they are not valid. Such points may be included in the point-cloud so as to preserve order in an ordered point cloud, or they may be included in a stream if the sensor is not smart or fast enough to remove such points. If the point cloud is not "dense", your processing code must test each value for validity.

A point-cloud may be constructed from a single view (e.g., from a robot standing still, staring at a scene). Alternatively a point-cloud may be the result of multiple sensing devices (but with all points transformed to a common reference frame), or possibly from a single sensor moving around in the environment (but, again, with each sensor-data contribution transformed into a common reference frame). If it is known that a range image is acquired from a single viewpoint, this information can be used to help reduce confusion in perceptual processing from occlusions and shadowing.

Point-cloud processing can be demanding of required memory, computation time and bandwidth. A 640x480 image from a Kinect sensor provides over 300k points, each with (x,y,z,R,G,B). Updated at 30Hz, this consumes approximately 300MB/sec of communication bandwidth (transmitting point clouds as ROS messages). Mere seconds of "bagging" such data can rapidly fill files on the order of gigabytes.

Because point-cloud processing can be demanding, it is important that algorithms analyzing point clouds are particularly efficient. Algorithms within the "Point Cloud Library" (PCL; see http://pointclouds.org) are optimized for efficiency in C++ code. Further, some of the core routines exploit Intel's Streaming SIMD Extensions (SSE), and some of the algorithms exploit multi-core CPU capabilities. Some of the internal computations use the "Eigen" library (see http://eigen.tuxfamily.org), which performs linear-algebra computations efficiently.

Tutorials on how to use the "Point Cloud Library" can be found at: http://pointclouds.org/documentation/tutorials/. Methods within this library are available for a useful variety of point-cloud processing, and all of the source code is openly available.

Some additional useful PCL resources include theses by Rodrigues, http://robotica.unileon.es/mediawiki/index.php/PhD-3D-Object-Tracking, and by Rusu, https://c5155196669c564620ef9c12a25f195f52ea786c.googledrive.com/host/0By7jPChnijtHSlp1QnlYanNhOE0/PCL/tutorials/html/how_features_work.html#rusudissertation. Introductory slides describing pointclouds can be found at http://ais.informatik.uni-freiburg.de/teaching/ws10/robotics2/pdfs/rob2-12-ros-pcl.pdf, and an intro to PCL processing can be found at http://www.jeffdelmerico.com/wp-content/uploads/2014/03/pcl_tutorial.pdf.

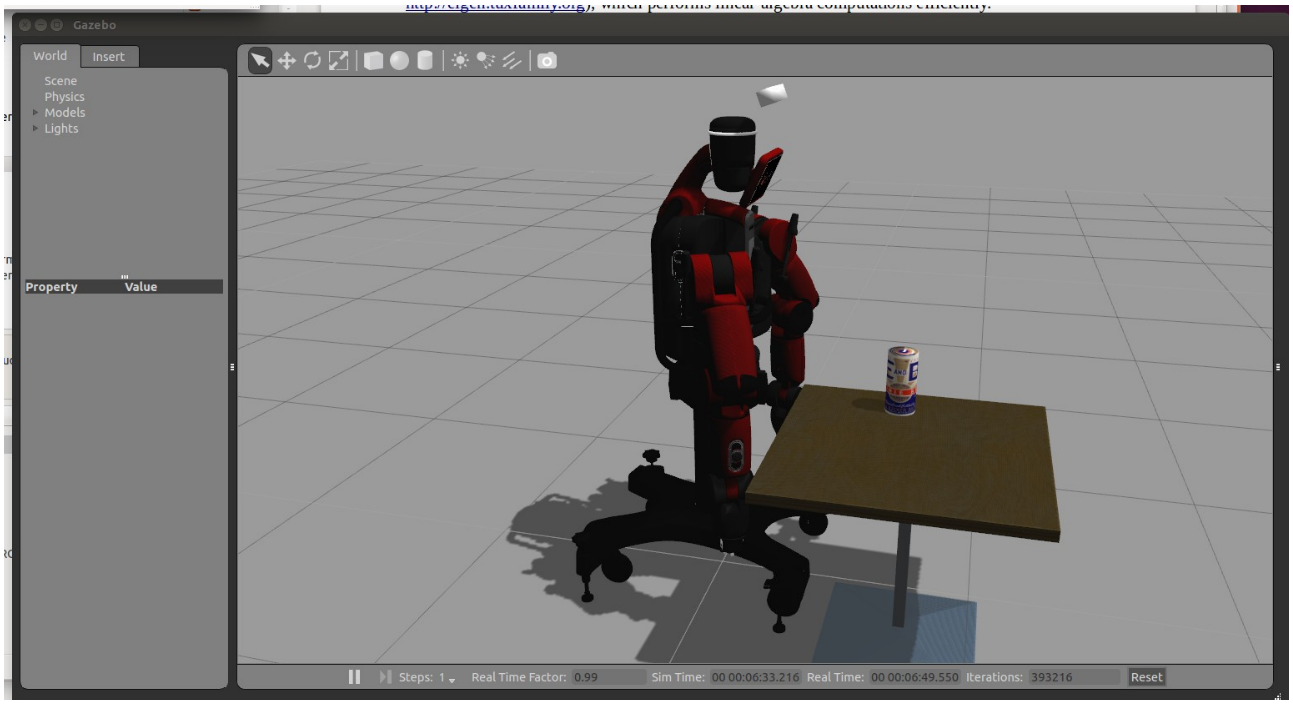
Since point clouds can be large, it is important to avoid making copies of these. Instead, point clouds are passed to functions via pointers. This provides a significant speed-up, but at the cost of some confusion regarding pointers and pointer dereferencing. It can be helpful to emulate working examples to construct new point-cloud processing code.

One can visualize a point-cloud display in rviz, given a real or an emulated point-cloud source. We can get a point-cloud stream from the Baxter simulator with the following commands.

In one terminal start up the Baxter simulator (modified to include a Kinect camera) with:

```
roslaunch   cwru_baxter_sim   baxter_world.launch
```

The Gazebo view will look like the following:



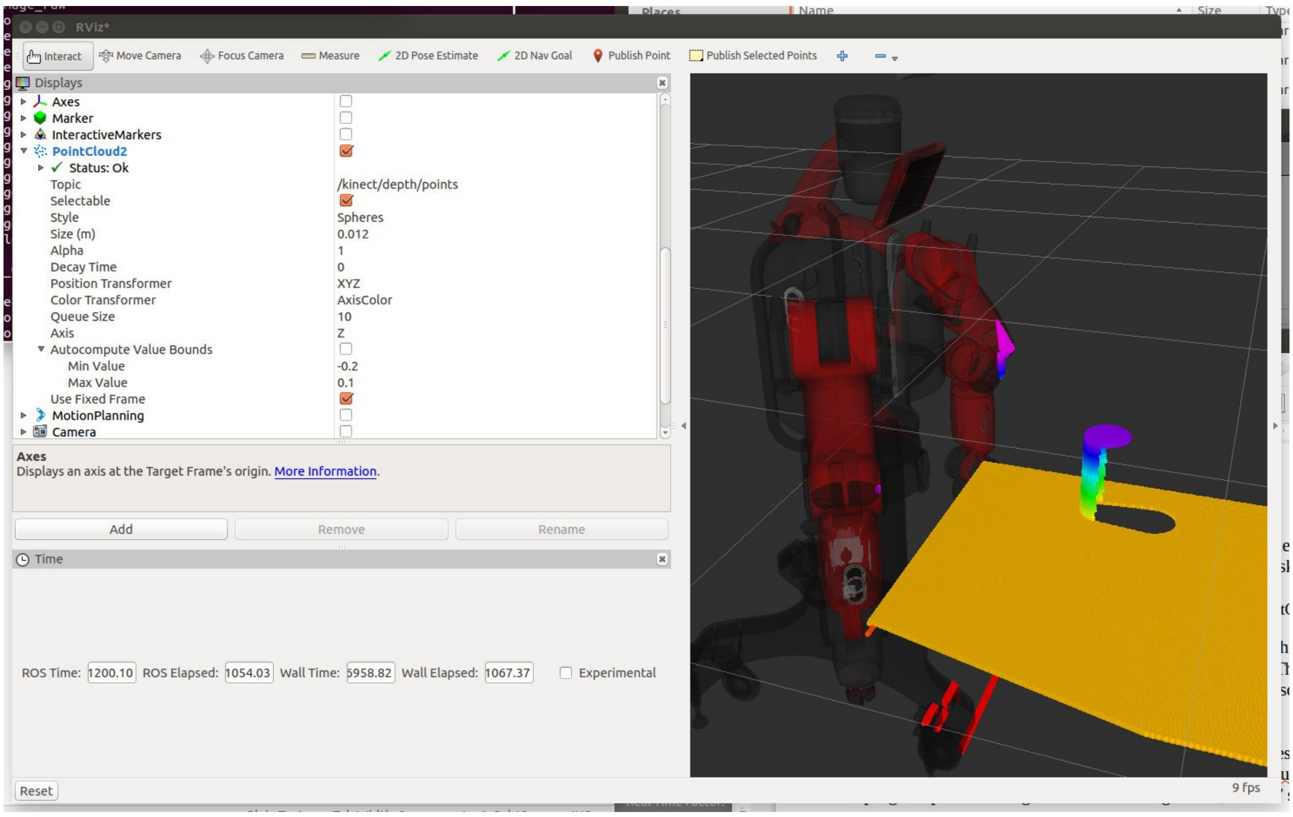
This view shows all of the models contained in the virtual world, including the robot, the ground plane, a cafe table and a beer can. The sensor element within the Kinect link has a transform with respect to the Kinect-link frame, and this transform is not part of the URDF. We need to publish this relationship on the “tf” topic. This is accomplished using the (ROS-provided) node tf::static_transform_publisher. This node can be started up conveniently (along with the necessary transform coordinates) via a launch file. From a second terminal, run:

```
   roslaunch     cwru_baxter_sim     kinect_xform.launch
```

With this running, there is enough information (from the robot model on the parameter server, plus all of the transforms being published on tf, plus the emulated Kinect data being published on topic “kinect/depth/points”) for Rviz to receive the Kinect's 3-D point data, transform it to world coordinates, and display the results in 3-D. To do so, start rviz:

```
    rosrun rviz rviz
```

Which produces the result below.



Axes	☐
Marker	☐
InteractiveMarkers	☐
PointCloud2	✓
✓ Status: Ok	
Topic	/kinect/depth/points
Selectable	✓
Style	Spheres
Size (m)	0.012
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	AxisColor
Queue Size	10
Axis	Z
Autocompute Value Bounds	☐
Min Value	-0.2
Max Value	0.1
Use Fixed Frame	✓
MotionPlanning	☐
Camera	☐

Axes
Displays an axis at the Target Frame's origin. More Information.

ROS Time: 1200.10 ROS Elapsed: 1054.03 Wall Time: 5958.82 Wall Elapsed: 1067.37 ☐ Experimental

In the above view, the point-cloud data has been colorized by choosing options for the display. The rviz "Displays" panel has added a topic "PointCloud2." Expanding the menu options for this item, the "Topic" is set to "kinect/depth/points", which is the name of the topic to which the Kinect gazebo emulation publishes. The "Style" of points was chosen to be "Spheres" of 0.012m diameter. The "Color Transformer" was set to "AxisColor" with the axis chosen to be the z-axis. Point colors range from red (lowest z value) to violet (highest z value). The range of z values applied to variable color can be automatically applied, or it can be manually specified, as in the present case, having set z-min to -0.2m and z-max to 0.1m. With this "zoom" on color, the beer can is yellow at the surface of the table, and the color varies up to purple at the top of the can. This visualization is similar to that which we introduced earlier, using the minimal robot. But we can do more with the point-cloud data than display it. We can operate on the data to try to make sense of it. This will be explored in the "cwru_baxter" repository within the packages "pcl_perception_node" and "cwru_pcl_utils."

A Snapshot Program: In the pcl_perception_node package, the file "pcd_save.cpp" shows how to subscribe to a point-cloud topic and how to save a pointcloud to disk in "PCD" format. Line 61, in main(), is:

```
ros::Subscriber getPCLPoints = nh.subscribe<sensor_msgs::PointCloud2> ("/kinect/depth/points", 1, kinectCB);
```

which sets up a callback function, "kinectCB", to subscribe to the topic "/kinect/depth/points". This topic carries messages of type "sensor_msgs::PointCloud2." The Baxter simulation emulates a Kinect sensor and transmits data to this topic. A real Kinect sensor would publish similar data, and the example code is applicable to simulated or real data (provided the topic names are consistent).

The callback function responds to an incoming pointcloud ROS message. The callback function converts this message type to a pcl::PointCloud datatype, thus making it appropriate for use with the Point Cloud Library. However, the only PCL function used in this callback is:

```
pcl::io::savePCDFileASCII ("snapshot.pcd", *g_pclKinect);
```

which saves the pointcloud to disk under the name “snapshot.pcd” (in the current directory of the terminal that executed pcd_save). After saving the data, the callback function sets the global flag “g_got_cloud”, which informs “main” that a pointcloud has been received and saved. Main() then returns, ending the program.

This example program thus can be used to take a “snapshot” of streaming point-cloud data, saving a single scan to disk. Such snapshots can be useful for off-line data processing.

Saving the pointcloud as ASCII is larger than the alternative binary storage. However, it does allow one to manually view the data. The initial lines of “snapshot.pcd” are:

```
# .PCD v0.7 - Point Cloud Data file format
VERSION 0.7
FIELDS x y z
SIZE 4 4 4
TYPE F F F
COUNT 1 1 1
WIDTH 307200
HEIGHT 1
VIEWPOINT 0 0 0 1 0 0 0
POINTS 307200
DATA ascii
-1.3971394 -1.047308 2.4242566
-1.3927666 -1.047308 2.4242566
-1.3883936 -1.047308 2.4242566
-1.3840208 -1.047308 2.4242566
-1.3796479 -1.047308 2.4242566
-1.375275 -1.047308 2.4242566
-1.3709021 -1.047308 2.4242566
-1.3665292 -1.047308 2.4242566
-1.3621563 -1.047308 2.4242566
-1.3577834 -1.047308 2.4242566
-1.3534105 -1.047308 2.4242566
-1.3490376 -1.047308 2.4242566
-1.3446647 -1.047308 2.4242566
-1.3402919 -1.047308 2.4242566
…
```

This output shows that the header describes how the rest of the file is organized, which is 3 fields of single-precision (4-byte) values for the x, y and z sensed points. These are organized as one long list of 307,200 points. The dimensions will be in meters. From the viewpoint of the sensor, the z-axis points straight out from the camera, along the optical axis.

The data thus acquired and saved is somewhat hard to interpret, since it is in the (tilted) sensor frame. We will often be interested in surfaces that are horizontal (e.g. floors, tables) or vertical (e.g., walls, doors) with respect to the world frame. It is thus useful to transform the acquired data into a frame within which it will be easier to interpret the points.

Transforming Point-Cloud Data to Alternative Frames: The program “pcd_transform_and_save”, also within the package “pcl_perception_node”, is related to pcd_save, except it also performs a transformation to express the sensor data in the “torso” frame of the robot. This will be useful for hand/eye coordination, since we will be able to express the hand frame with respect to the torso, and we can compare this to the coordinates of an object of interest, as perceived by the Kinect but also expressed with respect to the torso frame.

To transform the Kinect data, we bring in a “transform listener” to obtain the transforms between the sensor frame and the torso. We will look up a new transform for every snapshot, since (in a more general use of this example program) we would also be interested in including the influence of pan rotation of Baxter's head, on which we have mounted the Kinect. The transform listener will be aware of such motions and will take this into account, resulting in consistent sensor transforms to the torso frame.

The function transformTFToEigen() is similar to a version introduced earlier. It takes a tf::Transform as an argument, and it converts this transform into an Eigen::Affine3f. The “f” (float) version is used instead of the “d” (double-precision float), since our pointcloud objects use 4-byte floats. This is desirable, since the sensor accuracy does not justify double-precision representation, and the 307,200 points to be saved consume significant memory (which is halved using single-precision representation).

A second helper function is: transform_cloud(). This function shows a way to perform coordinate transformation of a pointcloud. This function takes input arguments of a source pointcloud, an Eigen::Affine3f transform, and a destination pointcloud to be populated with transformed data. Within this function, we manually copy over the header information from the input pointcloud to the output pointcloud. We then transform each 3-D point from the original sensor frame to the desired torso frame using the line:

```
        outputCloud->points[i].getVector3fMap() = A * inputCloud->points[i].getVector3fMap();
```

This operation is repeated for all of the points in the pointcloud. This somewhat odd syntax allows one to extract the 3-D pointcloud data into an Eigen-compatible vector (which is then pre-multiplied by the transform “A”). It also allows one to put 3-D data back into a pointcloud, converting from an Eigen-type vector into compatible components of the pointcloud points.

The callback function, which responds to incoming pointcloud data on the Kinect topic, uses these two helper functions to transform the received data into world coordinates.

The transformed pointcloud data is saved to a file named "snapshot_wrt_torso.pcd.” The first part of this file appears as:

```
# .PCD v0.7 - Point Cloud Data file format
VERSION 0.7
FIELDS x y z
SIZE 4 4 4
TYPE F F F
COUNT 1 1 1
WIDTH 307200
HEIGHT 1
VIEWPOINT 0 0 0 1 0 0 0
POINTS 307200
DATA ascii
2.0545802 1.3971394 -0.9300018
2.0545802 1.3927666 -0.9300018
2.0545802 1.3883936 -0.9300018
2.0545802 1.3840208 -0.9300018
2.0545802 1.3796479 -0.9300018
2.0545802 1.375275 -0.9300018
```

```
2.0545802 1.3709021 -0.9300018
2.0545802 1.3665292 -0.9300018
```

The z-value of -0.930 m is repeated for a large number of points. This value corresponds to the height of the floor relative to the torso. For ideal Kinect data (no noise was added to the Kinect emulator), the z-height of the floor is precisely uniform.

Another group of point data appears as:

```
1.171401 -0.53229457 -0.15530008
1.171401 -0.53478777 -0.15530008
1.171401 -0.53728098 -0.15530008
1.171401 -0.53977412 -0.15530008
1.171401 -0.54226732 -0.15530008
1.171401 -0.54476053 -0.15530008
1.171401 -0.54725367 -0.15530008
1.171401 -0.54974687 -0.15530008
1.171401 -0.55224007 -0.15530008
1.171401 -0.55473322 -0.15530008
1.171401 -0.55722642 -0.15530008
1.171401 -0.55971962 -0.15530008
```

The z-value of -0.155 corresponds to the height of the table relative to the torso. A large number of points share this same z value, corresponding to the surface of the table.

A smaller set of points looks like the following:

```
0.68502676 -0.02413924 0.075000226
0.68502682 -0.025927335 0.075000107
0.68502688 -0.027715432 0.074999988
0.68502688 -0.029503522 0.074999988
0.68502694 -0.031291619 0.074999928
0.68502682 -0.033079706 0.075000048
0.68502682 -0.034867797 0.075000048
0.68502682 -0.036655892 0.075000048
0.68502682 -0.038443983 0.075000048
0.68502682 -0.040232074 0.075000048
0.68502682 -0.042020168 0.075000048
0.68502682 -0.043808259 0.075000048
```

The z-height of 0.075 presumably corresponds to points on the top of the beer can.

Within this new representation, it will be much easier to find horizontal or vertical surfaces of interest. This will be explored further with additional Point Cloud Library processing examples.

A PCL Utility Library: Within cwru_baxter, the package "cwru_pcl_utils" encapsulates the preceding functions within a library, called cwru_pcl_utils. The header file (in the subdirectory /include/cwru_pcl_utils/cwru_pcl_util.h) describes the class CwruPclUtils with its member variables and useful functions. These include:

Eigen::Affine3f transformTFToEigen(const tf::Transform &t); (converts from tf to Eigen::Affine3f)

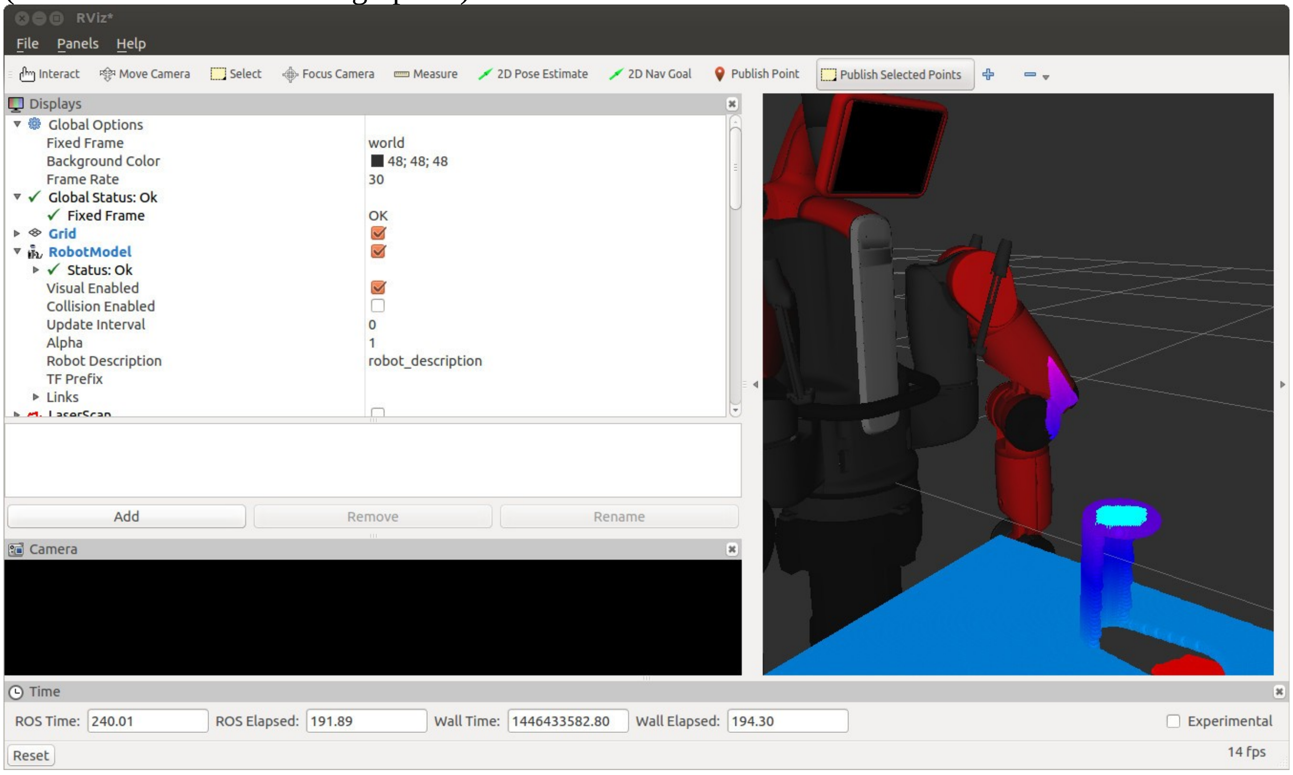
void transform_kinect_cloud(Eigen::Affine3f A); (transforms a received Kinect pointcloud using the provided transform matrix)

void save_kinect_snapshot(); (saves a Kinect pointcloud to disk)

void save_transformed_kinect_snapshot() (saves a transformed Kinect pointcloud to disk)
void transform_selected_points_cloud(Eigen::Affine3f A); (transforms data from rviz pointCloud selection tool, using provided transform matrix)
void fit_xformed_selected_pts_to_plane(Eigen::Vector3f &plane_normal, double &plane_dist); (fits a plane to transformed, selected points pointcloud, returning the plane normal and offset)
void get_transformed_selected_points(pcl::PointCloud<pcl::PointXYZ> & outputCloud); (makes a copy of the transformed, selected points, populating the provided pointCloud object).
void get_gen_purpose_cloud(pcl::PointCloud<pcl::PointXYZ> & outputCloud); (makes a copy of a general-purpose pointCloud member variable, populating the provided object).

A CwruPclUtils object subscribes to topics of Kinect points and selected points. This object does require ros::spin() or ros::spinOnce() to service its callbacks.

Selecting Points of Interest in Rviz:
One of the callbacks, "selectCB", is configured to subscribe to the topic "selected_points" with message type sensor_msgs::PointCloud2ConstPtr. The publisher on this topic is a tool within Rviz, "Publish Selected Points." In the scene below, the "Publish Selected Points" tool has been selected (see menu bar above robot graphics).



Global Options	
Fixed Frame	world
Background Color	■ 48; 48; 48
Frame Rate	30
✓ Global Status: Ok	
✓ Fixed Frame	OK
Grid	✓
RobotModel	✓
✓ Status: Ok	
Visual Enabled	✓
Collision Enabled	☐
Update Interval	0
Alpha	1
Robot Description	robot_description
TF Prefix	
Links	
LaserScan	☐

ROS Time: 240.01 ROS Elapsed: 191.89 Wall Time: 1446433582.80 Wall Elapsed: 194.30 ☐ Experimental
14 fps

This tool allows one to click-drag the mouse over a region of points in the Rviz display, and the resulting points within the chosen window will be published to the topic "selected_points". In the above scene, a region of points on the top of the can is highlighted. These correspond to the selected points.

In the example pcl code, the main program starts a transform listener and obtains the transform between the Kinect sensor frame and the robot's torso frame. This transform is translated to an Eigen-type Affine3f, which is subsequently used to transform the sensor data into the robot's torso frame. Within a loop, the main program polls cwru_pcl_utils.got_selected_points() to see if the user selected a (new) region of points. If so, the selected points are transformed to the torso frame with:

```
cwru_pcl_utils.transform_selected_points_cloud(A_sensor_wrt_torso);
```

then the “new points selected” flag is reset with: cwru_pcl_utils.reset_got_selected_points();

The selected points are transformed to the torso frame and fit to a plane with the function:

```
	cwru_pcl_utils.fit_xformed_selected_pts_to_plane(plane_normal, plane_dist);
```

This returns the plane's normal vector and its offset from the (torso) origin.
The “publish selected points” tool is contained in our repository “external_packages” in the package “rviz_plugin_selected_points_topic.” This code is Copyright (C) 2013 Robotics & Biology Laboratory (RBO) TU Berlin, per the “readme.txt”. This readme file also describes how to install the plug-in, if it is not already in your Rviz toolbar. You may need to run “catkin_make install.” Then, from within Rviz, click the blue “+” sign in the tool bar and choose “publish selected points.” to make this tool available.

An illustrative pointcloud function: The member function “example_pcl_operation()” provides an example of one way that functions can be added to cwru_pcl_utils. This function is hard-coded to:

- copy the transformed, selected points to the general-purpose pointCloud member object
- add 5cm to the z value of all points in the general-purpose pointCloud

The result of this operation (or more useful operations) may be obtained by the main program, if desired, by requesting a copy of the internal general-purpose pointCloud. This is illustrated in the example main() program with the lines:

```
	// offset the transformed, selected points and put result in gen-purpose object
	cwru_pcl_utils.example_pcl_operation();
	//get a copy of the result
	cwru_pcl_utils.get_gen_purpose_cloud(display_cloud);
```

In the example main() program, a point-cloud publisher is instantiated:

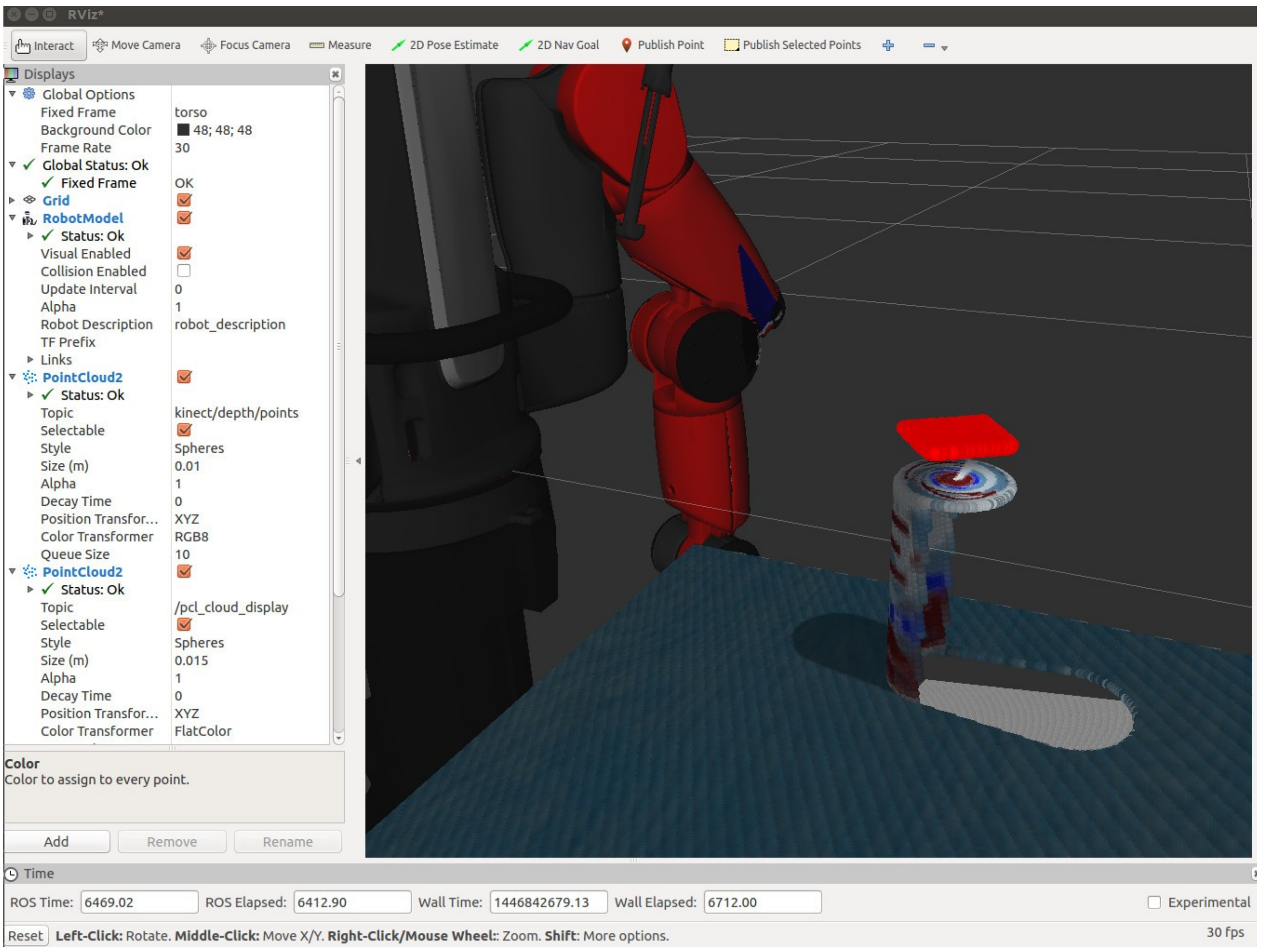
```
ros::Publisher pubCloud = nh.advertise<sensor_msgs::PointCloud2> ("/pcl_cloud_display", 1);
```

This publisher is used to publish the processed pointCloud, with:

```
//convert datatype to compatible ROS message type for publication
      pcl::toROSMsg(display_cloud, pcl2_display_cloud);
//update the time stamp, so rviz does not complain
      pcl2_display_cloud.header.stamp = ros::Time::now();
//publish a point cloud that can be viewed in rviz (under topic pcl_cloud_display)
      pubCloud.publish(pcl2_display_cloud);
```

As a result, one can view the processed pointCloud via Rviz. Within Rviz, add a second PointCloud2 item, and set the topic to “pcl_cloud_display.” Rviz will then display the processed pointCloud, as illustrated below. In this example, a patch of points was selected from the top of the can. These points were transformed to the torso frame, then elevated by 5cm. In Rviz, the pcl_cloud_display topic is displayed as red spheres. As shown, a rectangular patch of points (corresponding to the click-drag region selected) is displayed 5cm above the top of the can.

The ability to display processed pointClouds is useful for visual interpretation of internal computations, both for debugging and for operation under supervisory control.



Global Options	
Fixed Frame	torso
Background Color	■ 48; 48; 48
Frame Rate	30
✓ Global Status: Ok	
✓ Fixed Frame	OK
Grid	✓
RobotModel	✓
✓ Status: Ok	
Visual Enabled	✓
Collision Enabled	☐
Update Interval	0
Alpha	1
Robot Description	robot_description
TF Prefix	
Links	
PointCloud2	✓
✓ Status: Ok	
Topic	kinect/depth/points
Selectable	✓
Style	Spheres
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transfor...	XYZ
Color Transformer	RGB8
Queue Size	10
PointCloud2	✓
✓ Status: Ok	
Topic	/pcl_cloud_display
Selectable	✓
Style	Spheres
Size (m)	0.015
Alpha	1
Decay Time	0
Position Transfor...	XYZ
Color Transformer	FlatColor

Color
Color to assign to every point.

ROS Time: 6469.02 ROS Elapsed: 6412.90 Wall Time: 1446842679.13 Wall Elapsed: 6712.00

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

30 fps