3D Perception. 50% better.

Point Cloud Library.

Radu Bogdan RUSU

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Outline

1. Introduction
2. Motivation
3. Acquisition
4. Data representation
5. Storage
6. PCL
7. PCL Examples
What are Point Clouds?

- Point Cloud = a "cloud" (i.e., collection) of \( n \)-D points (usually \( n = 3 \))

\[
p_i = \{x_i, y_i, z_i\} \rightarrow \mathcal{P} = \{p_1, p_2, \ldots, p_i, \ldots, p_n\}
\]

- used to represent 3D information about the world
Introduction (2/3)

What are Point Clouds?

- besides XYZ data, each point $p$ can hold additional information
- examples include: RGB colors, intensity values, distances, segmentation results, etc
What are **Point Clouds**?
What are Point Clouds?
What are Point Clouds?
Introduction

Motivation

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Why are Point Clouds important?

Point Clouds are important for a lot of reasons (!). Besides representing geometry, they can complement and supersede images when data has a high dimensionality.
Motivation (2/5)

Why are **Point Clouds** important?

Concrete example 1: get the **cup** from the **drawer**.
Motivation (3/5)

Why are Point Clouds important?

Concrete example 2: find the door and its handle, and open it.
Motivation (4/5)

Why are Point Clouds important?

Concrete example 3: safe motion planning/manipulation.
Motivation (5/5)

Why are **Point Clouds** important?

False positives!!!
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Acquisition (1/3)

How are Point Clouds acquired? Where do they come from?

There are many different sensors that can generate 3D information. Examples:

- laser/lidar sensors (2D/3D)
- stereo cameras
- time-of-flight (TOF) cameras
- etc...
Acquisition (2/3)

How are Point Clouds acquired? Where do they come from?

The PR2 sensor head:

- two pairs of stereo cameras (narrow + wide)
- tilting laser sensor
How are Point Clouds acquired? Where do they come from?

Simulation (!):

- raytracing + stereo imagery fed into the same algorithmic modules that are used to process real data
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Representing Point Clouds

As previously presented:

- a point \( p \) is represented as an n-tuple, e.g.,
  \[ p_i = \{ x_i, y_i, z_i, r_i, g_i, b_i, \text{dist}_i, \cdots \} \]
- a Point Cloud \( \mathcal{P} \) is represented as a collection of points \( p_i \),
  e.g., \( \mathcal{P} = \{ p_1, p_2, \cdots, p_i, \cdots, p_n \} \)
In terms of data structures:

- an XYZ point can be represented as:
  ```
  float32 x
  float32 y
  float32 z
  ```

- a n-dimensional point can be represented as:
  ```
  float32[] point
  ```
  which is nothing else but a:
  ```
  std::vector<float32> point
  ```
  in C++

- **potential problem**: everything is represented as floats (!)
Data representation (3/7)

Point Cloud Data structures

In terms of data structures:

- therefore a point cloud $\mathcal{P}$ is:

  ```
  Point[] points
  ```

  or:

  ```
  std::vector<Point> points
  ```

  in C++, where `Point` is the structure/data type representing a single point $p$
Because Point Clouds are big:

- operations on them are typically slower (more data, more computations)
- they are expensive to store, especially if all data is represented as floats/doubles

Solutions:
Because Point Clouds are big:

- operations on them are typically slower (more data, more computations)
- they are expensive to store, especially if all data is represented as floats/doubles

Solutions:

- store each dimension data in different (the most appropriate) formats, e.g., rgb - 24bits, instead of $3 \times 4$ (sizeof float)
- group data together, and try to keep it aligned (e.g., 16bit for SSE) to speed up computations
The ROS PointCloud(2) data format (sensor_msgs/PointCloud2.msg):

```markdown
#This message holds a collection of nD points, as a binary blob.
Header header

#2D structure of the point cloud. If the cloud is unordered,
#height is 1 and width is the length of the point cloud.
uint32 height
uint32 width

#Describes the channels and their layout in the binary data blob
PointField[] fields

bool is_bigendian  #Is this data bigendian?
uint32 point_step  #Length of a point in bytes
uint32 row_step    #Length of a row in bytes
uint8[] data       #Actual point data, size is (row_step*height)
bool is_dense      #True if there are no invalid points
```
ROS representations for Point Cloud Data

where PointField (sensor_msgs/PointField.msg) is:

```
# This message holds the description of one point entry in the # PointCloud2 message format.
uint8 INT8 = 1
uint8 UINT8 = 2
uint8 INT16 = 3
uint8 UINT16 = 4
uint8 INT32 = 5
uint8 UINT32 = 6
uint8 FLOAT32 = 7
uint8 FLOAT64 = 8
string name # Name of field
uint32 offset # Offset from start of point struct
uint8 datatype # Datatype enumeration see above
uint32 count # How many elements in field
```

**PointField examples:**

```
"x", 0, 7, 1
"y", 4, 7, 1
"z", 8, 7, 1
"rgba", 12, 6, 1
"normal_x", 16, 8, 1
"normal_y", 20, 8, 1
"normal_z", 24, 8, 1
"fpfh", 32, 7, 33
```
Data representation (7/7)

ROS representations for Point Cloud Data

- binary blobs are hard to work with
- we provide a custom converter, Publisher/Subscriber, transport tools, filters, etc, similar to images
- templated types: `PointCloud2` → `PointCloud<PointT>`
- examples of `PointT`:

```cpp
struct PointXYZ
{
    float x;
    float y;
    float z;
}

struct Normal
{
    float normal[3];
    float curvature;
}
```
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Point Cloud Data storage (1/2)

ROS input/output

- **PointCloud2**.msg and **PointField**.msg are ROS messages
- they can be published on the network, saved/loaded to/from BAG files (ROS message logs)
- usage example:

```
$ rostopic find sensor_msgs/PointCloud2 | xargs rosrecord -F foo
[ INFO] [1271297447.656414502]: Recording to foo.bag.
^C
[ INFO] [1271297450.723504983]: Closing foo.bag.
$ rosplay -c foo.bag
bag: foo.bag
version: 1.2
start_time: 1271297447974280542
end_time: 1271297449983577462
length: 2009296920
topics:
  - name: /narrow_stereo_textured/points2
count: 3
datatype: sensor_msgs/PointCloud2
md5sum: 1158d486dd51d683ce2f1be655c3c181
```
In addition, point clouds can be stored to disk as files, into the PCD format.

```
# Point Cloud Data (PCD) file format v.5
FIELDS x y z rgba
SIZE 4 4 4 4
TYPE F F F U
WIDTH 307200
HEIGHT 1
POINTS 307200
DATA binary
...
```

**DATA** can be either **ascii** or **binary**. If **ascii**, then

```
DATA ascii
0.0054216 0.11349 0.040749
-0.0017447 0.11425 0.041273
-0.010661 0.11338 0.040916
0.026422 0.11499 0.032623
...
```
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Point Cloud Library (1/10)

http://pcl.ros.org/

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What is PCL (Point Cloud Library)?

PCL is:

- fully templated modern C++ library for 3D point cloud processing
- uses SSE optimizations (Eigen backend) for fast computations on modern CPUs
- uses OpenMP and Intel TBB for parallelization
- passes data between modules (e.g., algorithms) using Boost shared pointers

PCL deprecates older ROS packages such as point_cloud_mapping and replaces sensor_msgs/PointCloud.msg with the modern sensor_msgs/PointCloud2.msg format (!)
PCL (Point Cloud Library) structure

- collection of smaller, modular C++ libraries:
  - **libpcl_features**: many 3D features (e.g., normals and curvatures, boundary points, moment invariants, principal curvatures, Point Feature Histograms (PFH), Fast PFH, ...)
  - **libpcl_surface**: surface reconstruction techniques (e.g., meshing, convex hulls, Moving Least Squares, ...)
  - **libpcl_filters**: point cloud data filters (e.g., downsampling, outlier removal, indices extraction, projections, ...)
  - **libpcl_io**: I/O operations (e.g., writing to/reading from PCD (Point Cloud Data) and BAG files)
  - **libpcl_segmentation**: segmentation operations (e.g., cluster extraction, Sample Consensus model fitting, polygonal prism extraction, ...)
  - **libpcl_registration**: point cloud registration methods (e.g., Iterative Closest Point (ICP), non linear optimizations, ...)

- unit tests, examples, tutorials (some are work in progress)

- C++ classes are templated building blocks (nodelets!)
Philosophy: *write once, parameterize everywhere*

PPG: **Perception Processing Graphs**

Diagram:
- Clusters (1..N) (PointIndices)
- Indices (rest) (PointIndices)
- Projected inliers (PointCloud)
- Inliers (PointIndices)
- Input (PointCloud)
- Normals (PointCloud)
- Model (ModelCoefficients)
Point Cloud Library (5/10)

PPG: Perception Processing Graphs

Why PPG?

▶ Algorithmically:
  door detection = table detection = wall detection = ...

▶ the only thing that changes is: parameters (constraints)!
Inheritance simplifies development and testing:

```cpp
pcl::Feature<PointT> feat;
feat = pcl::Normal<PointT> (input);
feat = pcl::FPFH<PointT> (input);
feat = pcl::BoundaryPoint<PointT> (input);
...
feat.compute (&output);
...```
Point Cloud Library (7/10)

PCL 0.5 statistics

Misc, stats:

▶ 30 releases already (0.1.x → 0.5.x)
▶ over 100 classes
▶ over 60k lines of code (PCL, ROS interface, Visualization) – in contrast, OpenCV trunk has 300k
▶ young library: only 10 months of development so far, but the algorithms and code bits have been around for 3-5 years
▶ external dependencies (for now) on eigen, cminpack, ANN, FLANN, TBB
▶ internal dependencies for PCL_ROS: dynamic_reconfigure, message_filters, TF
Nodelets

▶ write once, parameterize everywhere $\Rightarrow$ modular code
▶ ideally, each algorithm is a “building block” that consumes input(s) and produces some output(s)
▶ in ROS, this is what we call a node. inter-process data passing however is inefficient. ideally we need shared memory.

Solution:
nodelets = “nodes in nodes” = single-process, multi-threading
Nodelets

- **write once, parameterize everywhere** → modular code
- ideally, each algorithm is a “building block” that consumes input(s) and produces some output(s)
- in ROS, this is what we call a node. inter-process data passing however is inefficient. ideally we need shared memory.

**Solution:**

nodelets = “nodes in nodes” = single-process, multi-threading

- same ROS API as nodes (subscribe, advertise, publish)
- dynamically (un)loadable
- optimizations for zero-copy Boost shared_ptr passing
- PCL nodelets use **dynamic_reconfigure** for on-the-fly parameter setting
Point Cloud Library (9/10)

Downsample and filtering example with nodelets

```xml
<launch>
  <node pkg="nodelet" type="standalone_nodelet"
        name="pcl_manager" output="screen"/>
  <node pkg="nodelet" type="nodelet" name="foo"
        args="voxel_grid VoxelGrid pcl_manager">
    <remap from="/voxel_grid/input" to="/narrow_stereo_textured/points"/>
    <rosparam>
      # -[ Mandatory parameters
      leaf_size: [0.015, 0.015, 0.015]
      # -[ Optional parameters
      # field containing distance values (for filtering)
      filter_field_name: "z"
      # filtering points outside of <0.8,5.0>
      filter_limit_min: 0.8
      filter_limit_max: 5.0
      use_indices: false # false by default
    </rosparam>
  </node>
  ...
</launch>
```
<launch>
  <node pkg="nodelet" type="standalone_nodelet"
        name="pcl_manager" output="screen" />

  <node pkg="nodelet" type="nodelet" name="foo"
        args="normal_estimation_NormalEstimation,pcl_manager">
    <remap from="/normal_estimation/input"
           to="/voxel_grid/output" />
    <remap from="/normal_estimation/surface"
           to="/narrow_stereo_textured/points" />
    <rosparam>
      # - [Mandatory parameters
      # Set either 'k_search' or 'radius_search'
      k_search: 0
      radius_search: 0.1
      # Set the spatial locator. Possible values are:
      # 0 (ANN), 1 (FLANN), 2 (organized)
      spatial_locator: 0
    </rosparam>
  </node>
</launch>

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PCL - Table Object Detector

How to extract a table plane and the objects lying on it

PointCloud2 → VoxelGrid → NormalEstimation → SACSegmentationFromNormals (planar segmentation) → ExtractInliers

ExtractPolygonalPrismData (get all points lying on the table) → ConvexHull2D → EuclideanClusterExtraction (split the points into N object clusters)

ProjectInliers → TablePlane → ObjectClusters
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Filters :: Examples (1/4)

```cpp
pcl::PassThrough<T> p;

p.setInputCloud (data);
p.setFilterLimits (0.0, 0.5);
p.setFilterFieldName ("z");
```

```
filter_field_name = "x";  // or filter_field_name = "xz";
```
**Filters :: Examples (2/4)**

```cpp
pcl::VoxelGrid<T> p;

p.setInputCloud (data);
p.FilterLimits (0.0, 0.5);
p.SetFilterFieldName ("z");
p.setLeafSize (0.01, 0.01, 0.01);
```
Filters :: Examples (3/4)

```cpp
pcl::StatisticalOutlierRemoval<T> p;
p.setInputCloud (data);
p.setMeanK (50);
p.setStddevMulThresh (1.0);
```
Filters :: Examples (4/4)

$pcl::MovingLeastSquares<T> p;$ (note: more of a surface reconstruction)

- $p.setInputCloud (data);$  
  $p.setPolynomialOrder (3);$  
  $p.setSearchRadius (0.02);$
Features :: Examples (1/9)

```cpp
pcl::NormalEstimation<T> p;

p.setInputCloud (data);
p.SetRadiusSearch (0.01);
```
Surface Normal Estimation Theory

▶ Given a point cloud with x,y,z 3D point coordinates
Features :: Examples (2/9)

Surface Normal Estimation Theory

- Given a point cloud with x, y, z 3D point coordinates
- Select each point’s $k$-nearest neighbors, fit a local plane, and compute the plane normal
Features :: Examples (3/9)

Surface Normal Estimation Theory

bad scale (too small)  good scale

Selecting the right scale ($k$-neighborhood) is problematic:

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Features :: Examples (4-5/9)

Consistent Normal Orientation

Before

- Extended Gaussian Image
- Orientation consistent for:
  1. registration
  2. feature estimation
  3. surface representation

- normals on the Gaussian sphere
- should be in the same half-space
Features :: Examples (4-5/9)

Consistent Normal Orientation

Before

After

$(\text{viewpoint} - p_i) \cdot n_{p_i} \geq 0$

or:

propagate consistency through an EMST

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Features :: Examples (6/9)

```cpp
pcl::NormalEstimation<T> p;

p.setInputCloud (data);
p.SetRadiusSearch (0.01);
```
Features :: Examples (7/9)

```cpp
pcl::BoundaryEstimation<T,N> p;

p.setInputCloud (data);
p.setInputNormals (normals);
p.SetRadiusSearch (0.01);
```
Features :: Examples (8/9)

```cpp
pcl::PrincipalCurvaturesEstimation<T,N> p;

p.setInputCloud (data);
p.setInputNormals (normals);
p.SetRadiusSearch (0.01);
```
Features :: Examples (9/9)

Other features

- RIFT (Rotation Invariant Feature Transform)
- occlusion/natural border extraction (range images)
- intensity gradients
- moment invariants
- spin images
- PFH (Point Feature Histogram)
- FPFH (Fast Point Feature Histogram)
- VFH (Viewpoint Feature Histogram) - cluster descriptor
- soon: RSD (Radial Signature Descriptor), etc

All use the same API:

```cpp
p.setInputCloud (cloud);
p.setInputNormals (normals); // where needed
p.setParameterX (...);
```
Segmentation :: Examples (1/5)

```cpp
pcl::SACSegmentation<T> p;

// Set input cloud
p.setInputCloud (data);

// Set model type
p.setModelType (pcl::SACMODEL_PLANE);

// Set method type
p.setMethodType (pcl::SAC_RANSAC);

// Set distance threshold
p.setDistanceThreshold (0.01);
```
Segmentation :: Examples (2/5)

```cpp
cpcl::ConvexHull2D<T> p;

p.setInputCloud (data);
```

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Segmentation :: Examples (3/5)

```cpp
cpcl::ExtractPolygonalPrismData<T> p;

p.setInputCloud (data);
p.setInputPlanarHull (hull);
p.setHeightLimits (0.0, 0.2);
```
p::EuclideanClusterExtraction<T> p;

p.setInputCloud (data);
p.setClusterTolerance (0.05);
p.setMinClusterSize (1);
Segmentation :: Examples (5/5)

```cpp
pcl::SegmentDifferences<T> p;

p.setInputCloud (source);
p.setTargetCloud (target);
p.setDistanceThreshold (0.001);
```
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Questions?

[http://pcl.ros.org/](http://pcl.ros.org/)

Point Cloud Library

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