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Speaker: Daniel Piro

- Software engineer in the Intel® Realsense™ Group
- Researching and developing new technologies and capabilities in the Realsense CTO team
- With Intel since 2004
- Worked on Networking, Servers, Mobile CPUs and Realsense™ products
Agenda

• Depth review
• Realsense D400 Series depth cameras
• Tuning for best depth
• Software Components
• Realsense T265 Tracking camera
• Q&A
• Coding example - Python
WHAT IS DEPTH?
APPLICATIONS IN COMPUTER VISION

Navigation & Mapping
Where am I? How do I move around?

Collision Avoidance
Don’t hit walls and objects (dynamic or static)

Scene Understanding
What are the objects in the scene?

Object Measurement
What are the physical attributes of an object?

Manipulation
Perform a task (grasp, drill, mow, clean)

HMI
How to communicate with the machine?
APPLICATIONS IN COMPUTER VISION
3D Depth cameras provides information 2D cameras are unable to – information that helps us understand shapes, sizes and distances, as well as allowing devices to move around in 3D space.

*Faux color represents range to object (red=far, blue=near)*
STEREOSCOPIC DEPTH SENSING

Depth = \frac{\text{Baseline} \times \text{Focal Length}}{\text{Disparity}}
D400 REALSENSE DEPTH CAMERA

☑️ Outdoor / Indoor Operation
☑️ Up to 10m depth range
☑️ <2% Z-error @ 2 meters
☑️ No Multi-camera Interference
☑️ Low Power
Before we go in-**Depth** into the details...
# RealSense™ Depth Cameras

<table>
<thead>
<tr>
<th></th>
<th>D415</th>
<th>D435</th>
<th>D435i</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Image Sensor</strong></td>
<td>OV2740</td>
<td>OV9282</td>
<td>OV9282</td>
</tr>
<tr>
<td><strong>Active Pixels</strong></td>
<td>1920 × 1080</td>
<td>1280 × 800</td>
<td>1280 × 800</td>
</tr>
<tr>
<td><strong>Color</strong></td>
<td>Monochrome</td>
<td>Monochrome</td>
<td>Monochrome</td>
</tr>
<tr>
<td><strong>Sensor Aspect Ratio</strong></td>
<td>16:9</td>
<td>8:5</td>
<td>8:5</td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
<td>55mm</td>
<td>50mm</td>
<td>50mm</td>
</tr>
<tr>
<td><strong>F Number</strong></td>
<td>f/2.0</td>
<td>f/2.0</td>
<td>f/2.0</td>
</tr>
<tr>
<td><strong>Focal Length</strong></td>
<td>1.88mm</td>
<td>1.93mm</td>
<td>1.93mm</td>
</tr>
<tr>
<td><strong>Filter Type</strong></td>
<td>IR Cut – D400, None – D410</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Focus</strong></td>
<td>Fixed</td>
<td>Fixed</td>
<td>Fixed</td>
</tr>
<tr>
<td><strong>Shutter Type</strong></td>
<td>Rolling Shutter</td>
<td>Global Shutter</td>
<td>Global Shutter</td>
</tr>
<tr>
<td><strong>Signal Interface</strong></td>
<td>MIPI CSI-2, 2X Lanes</td>
<td>MIPI CSI-2, 2X Lanes</td>
<td>MIPI CSI-2, 2X Lanes</td>
</tr>
<tr>
<td><strong>Horizontal Field of View</strong></td>
<td>69.4</td>
<td>91.2</td>
<td>91.2</td>
</tr>
<tr>
<td><strong>Vertical Field of View</strong></td>
<td>42.5</td>
<td>65.5</td>
<td>65.5</td>
</tr>
<tr>
<td><strong>Diagonal Field of View</strong></td>
<td>77</td>
<td>100.6</td>
<td>100.6</td>
</tr>
<tr>
<td><strong>Distortion</strong></td>
<td>&lt;=1.5%</td>
<td>&lt;=1.5%</td>
<td>&lt;=1.5%</td>
</tr>
<tr>
<td><strong>IMU</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>BMI055</td>
</tr>
</tbody>
</table>

**D415**
- Rolling shutter
- 2MP COLOR stereo.
- Narrower FOV (65HFOV)
- Offers higher depth resolution (~2.5x)

**D435**
- Global image shutter
- 1MP MONOCHROME stereo
- Wider field of view (90HFOV)
- Great for high speed motion
- More photosensitive (~4x)

**D435i**
- Same as D435
- IMU Included
**What is image rectification and why is it needed?**
- Stereo is based on comparing left and right images. They have to be perfectly aligned (rotated, scaled) and undistorted (rectified) so that you can do “epipolar” scanline comparisons and find matches and count disparity shifts for each pixel.

**What is done in our hardware?**
- The D4 ASIC performs a proprietary version of a stereo matching algorithm.

**RGB image not rectified – what does it mean?**
- The RGB Camera is NOT passed through the same hardware rectification pipeline. This means that to do good UV mapping (Match RGB pixels to depth pixels) you need to ideally rectify the RGB image as well.
D435i Infrared Images

D435i Left and Right infrared imagers (Infrared projector on)
D435i Color & Depth

Color image
RGB888
1280x720

Depth image – With depth colorization (red=far, blue=near)
uint16_t -> RGB888
848x480
Camera Calibration Information

- Camera intrinsic and extrinsic calibration information is available through the Realsense SDK.
- In D435i the left imager and the depth streams are pixel aligned.
- Extrinsic information between different sensor (e.g. depth to color) is available through the SDK.
Pointcloud

• A point cloud is a set of data points in 3D space.
• Point-clouds are created by projecting the 2D depth map to 3D world coordinates \((X,Y,Z)\)
• UV Map - maps each valid depth pixel to a coordinate in the color or infrared image
• For more information check [Projection in RealSense SDK 2.0](#)
3D Reconstruction

- **3D reconstruction** is the process of capturing the shape and appearance of real objects.
- Mesh or Volumetric representations
- There are multiple open-source 3DR libraries with Realsense SDK capture support:
  - Open3D
  - Infinitam V3

3D reconstruction using open-source library and the D400 camera
INERTIAL MEASUREMENT UNIT - D435I

Accelerometer \( m/sec^2 \)

Gyroscope \( rad/sec \)
INERTIAL MEASUREMENT UNIT
Tuning for best Depth
The Realsense SDK supports several predefined depth presets that can be selected according to the user's usage.

The predefined presets are listed in the table.
• Poor exposure is the number one reason for bad performance.

• Check whether auto-exposure works well, or switch to manual exposure to make sure you have good color or monochrome left and right images.

• Adjust EXPOSURE first for best results, with GAIN constant

• Make sure that the Laser Power is set correctly

• Best-Known-Methods for Tuning Intel® RealSense™ D400 Depth Cameras for Best Performance whitepaper
UNDERSTAND THEORETICAL LIMIT

• **Understand theoretical limit**: The RMS error represents the depth noise for a localized plane fit to the depth values.
  
  • On passive textured target, expect you ~30% better RMS with the laser turned OFF (due to residual laser speckle).

• **The depth noise**:
  
  • Tends to manifest itself as “bumps” on a plane, looking a bit like an egg carton. This is expected.

The graph is obtained using subpixel=0.08:
D415 with HFOV=65deg, Xres=1280, and baseline=55mm,
D435 with HFOV=90deg, Xres=848, and baseline=50mm

\[
\text{Depth RMS error (mm)} = \frac{\text{Distance (mm)}^2 \times \text{Subpixel focal length (pixels)} \times \text{Baseline (mm)}}{\text{focal length (pixels)}}
\]

where focal length (pixels) = \( \frac{1}{2} \frac{\text{Xres (pixels)}}{\tan\left(\frac{\text{HFOV}}{2}\right)} \)
**UNDERSTAND MIN-Z**

\[
\text{MinZ}(\text{mm}) = \text{focal length(pixels)} \times \text{Baseline(\text{mm})} / 126
\]

where focal length(pixels) = \[
\frac{1 \times \text{Xres(pixels)}}{\frac{2}{\tan\left(\frac{\text{HFOV}}{2}\right)}}
\]

1. **Minimum Operating Distance (MinZ) changes with resolutions**
   - It scales linearly with the output Xres
2. **Shorter than MinZ there is depth noise**
   - This can be mitigated with different depth settings
3. **MinZ can be shifted using “Disparity Shift”:**
   - Increasing Disparity shift above 0, will create a MaxZ

---

D415 at 1280x720 → MinZ is ~44cm  
D435i at 848x480 → MinZ is ~17cm

"MinZ Noise" can be reduced using depth settings. Above = "High Density", Bottom = "High Accuracy" preset.
INFRARED PROJECTOR

• Infrared image (left imager) with projector turned on
• Dark surfaces are harder to illuminate
• Some surfaces reflect better than others
• More textures == Better depth
Infrared Projector (another example)
Librealsense implementation includes post-processing filters to enhance the quality of depth data and reduce noise levels.

- Decimation filter
- Spatial Edge-Preserving filter
- Temporal filter
- Holes Filling filter

* - more information in this whitepaper

Post-processing filters can be tested using the Intel Realsense Viewer
• Realsense Cameras include an Active infrared projector to illuminate objects to enhance the depth data. Setting it correctly can improve depth
SOFTWARE COMPONENTS
Intel® RealSense™ SDK 2.0

- Library designed for accessing depth & tracking cameras
- Open-source
- Cross-platform
- Supports Intel® RealSense™ products:
  - D400 series and the SR300 Depth cameras
  - T265 tracking camera
- https://github.com/IntelRealSense/librealsense
Intel® RealSense™ Viewer

- RealSense Viewer is the flagship tool providing access to most camera functionality through simple, cross-platform UI.
- The tool offers:
  - Streaming from RealSense devices
  - Testing different configurations
  - Recording / Playback RealSense
  - Access to most camera specific controls
- The tool is included with the Realsense SDK
Robotic operating system (ROS)

Framework for Robots

- Tools
- Libraries
- Conventions/Standards
- Collaborative
packages for using Intel RealSense cameras (D400, SR30 and T265) with ROS

ROS Wrapper for Intel® RealSense™ Devices

*- More information and installation instructions: https://github.com/IntelRealSense/realsense-ros
VISUAL ODOMETRY

- Google Cartographer
- GMapping
- Hector SLAM
- RTabMap
- ORB SLAM
- Rovio
## Odometry Methods with ROS

<table>
<thead>
<tr>
<th></th>
<th>Visual Odometry</th>
<th>IMU Odometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROS package</td>
<td>rtabmap</td>
<td>imu_filter_madgwick</td>
</tr>
<tr>
<td>Update Frequency</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Stability over Time</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Scene Dependent</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>CPU Utilization</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

The two methods are complementary – We can use both!
PUTTING EVERYTHING TOGETHER

Follow the guide at github.com/intel-ros/realsense/wiki/SLAM-with-D435i
PUTTING EVERYTHING TOGETHER
LIMITATIONS AND WAYS TO IMPROVE IT

**Problem:** Trade-offs between localization and mapping:

<table>
<thead>
<tr>
<th>Field of View</th>
<th>Tracking</th>
<th>Depth Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Spectrum</td>
<td>Visible Light</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>Wide</td>
<td>Narrow</td>
</tr>
</tbody>
</table>

**Improvement:**
- Introduce wide-FOV sensor with IR-cut filter

**Problem:** Consuming too much system resources

**Improvement:**
- Offload tracking to a dedicated hardware accelerator
REALSENSE T265 TRACKING CAMERA
Intel® RealSense™ Tracking Camera T265

- 170-degree field of view (FOV)
- 6-DOF Visual Odometry
- SLAM Compute On-Board
- Loop-Closure
- Low Power
Intel T265 + D435i RTabMap
Video - Tracking using RealSense Viewer
T265 + D435i for Robotics

Intel® Realsense™ Tracking Camera T265

Intel® Realsense™ Depth Camera D435

Kobuki robot base

Intel® NUC Mini PC
System diagram

- Depth camera D435
  - Depth image
- Tracking camera T265: SLAM/ Sensorfusion
  - 6DOF
  - Wheel odometry
- NUC
  - Occupancy mapping
  - Path planning
  - Motion control
- Wheel encoders (Kobuki)
- Kobuki robot base
- Motor controller (Kobuki)
- Wheel odometry
- Velocity commands
Video – Robot with T265 & D435
Occupancy Map from depth ROS package

ROS Realsense Occupancy Map
(occupancy map libraries branch)

This ROS package can be used to generate a 2D occupancy map based on depth images, from the D435 or D415 depth camera and T265 tracking camera.
Online presentations:
- Open-source SLAM with Intel RealSense depth cameras by Sergey Dorodnicov
- Visual Navigation for Wheeled Autonomous Robots by Phillip Schmidt

Intel Realsense products:
- Intel® RealSense™ Tracking Camera T265
- Intel® RealSense™ depth camera D435i
- Intel® RealSense™ depth camera D415

Additional Information:
- The basics of stereo depth vision
- Intel RealSense Stereoscopic Depth Cameras
Backup
Video – Getting Started ROS T265
<table>
<thead>
<tr>
<th>API</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tracking</strong></td>
<td></td>
</tr>
<tr>
<td>Start / Stop 6DoF Tracking</td>
<td>Start/Stop streaming of all streams configured on a profile Video and IMU streaming can be enabled (USB3 required)</td>
</tr>
<tr>
<td>On Pose Frame</td>
<td>Callback providing the 6DOF pose of the camera relative to its initial position</td>
</tr>
<tr>
<td>On Video Frame</td>
<td></td>
</tr>
<tr>
<td>On Accelerometer Frame</td>
<td></td>
</tr>
<tr>
<td>On Gyro Frame</td>
<td>Callbacks providing the latest raw video and IMU data over USB3</td>
</tr>
<tr>
<td>Append Calibration</td>
<td>Updates calibration data for the wheel odometry</td>
</tr>
<tr>
<td>Send Frame (VelocimeterData)</td>
<td>Send wheel odometry data to the tracking algorithm</td>
</tr>
<tr>
<td><strong>Re-localization</strong></td>
<td></td>
</tr>
<tr>
<td>Enable / Disable Re-localization</td>
<td>Flag that is part of the profile used when configuring tracking</td>
</tr>
<tr>
<td>Set/Get Localization Data</td>
<td>Save or load the re-localization map to or from the host</td>
</tr>
</tbody>
</table>
Intel® RealSense™ Tracking Camera T265

- Stand-alone inside/out 6DoF tracking sensor with **Mapping & Re-localization**
- VPU/CV engine offload from host provides **low latency and power**
- Integrates wheel odometer for greater robustness in robotics
- Appearance-based relocalization (kidnapped robot)

Platform agnostic standalone tracking sensor

- **200Hz**
- **USB 2.0 support**
- **6DoF, SLAM algorithms run here**

**Components:**
- **Left fisheye camera**
- **Right fisheye camera**
- **IMU**
T265 SLAM (Simultaneous Localization And Mapping)

• SLAM provides inside out 6 Degree of Freedom tracking (orientation and position) with no limitation of range

• SLAM lets a robot or drone know where it is and helps plan where it is going

• SLAM provides area learning and re-localization with a relatively small data footprint

• SLAM lets a HMD understand how to align a virtual camera with the real world, so that virtual objects stay registered to the world in AR displays
Camera-Odometry Calibration

In order to fuse camera and odometry measurements, their relative transformation has to be estimated.

Common hand-eye calibration methods are not applicable.

[1] proposes an two-step analytical least-square solution.

1 DOF of translation is unobservable.

In practice, mount in known orientation (e.g. parallel), measure translation with cm accuracy, possibly refine.