ROS 2 on Autonomous Vehicles

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Apex.AI® Tier IV

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Autonomous vehicles will...

...give hours back to commuters,
...change the way the world is connected,
...disrupt industries, and
...generate lots of value.

Autonomous vehicles are big robots with...

...sensors,
...actuation, and
...lots of algorithms,
...and they can cause a lot of damage.
Can we make an autonomous vehicle\(^1\) using ROS 2?

Yes\(^2\)

\(^1\) a large robotic system in a safety critical application.
\(^2\) with caveats.
Our Autonomous Driving Setup

- GPS for reference
- 2x Lidar for object detection and localization
- Camera for object detection and traffic light state detection
- Power distribution and battery
- Network and display
- ROS running on x86 PC
- Apex.OS and Apex.Autonomy running on Drive PX2

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Our ROS 2 - ROS 1 Setup

Nvidia DrivePX2
Apex.OS ~ ROS 2

VLP-16
Ground Plane Segmentation
Drivers
Fusion
Downsampling
Clustering
Hull Formation
/points_no_ground
Waypoint Following
/localization
/filtered_points
/pointcloud
/pointcloud_no_ground
/bounding_boxes
Prediction
Vehicle Drive by Wire Interface
Decision Making
Traffic Light Detection

Intel Nuvo
ROS 1

Tracking

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Recap: ROS 2 vs. ROS 1

ROS 2 has all the core features needed to build a large robot
• Node API, topics, services
• Parameter server
• Command line introspection
• Composition
• TF

In addition to extra features missing from ROS 1
• Deterministic roslaunch
• Rclcpp_lifecycle
• DDS (best effort and reliable QoS)
• Data Security
• Layered architecture

Why we still need ROS 1
• Legacy Algorithms
• Rviz
• Rosbag
• Rqt_graph
• Rqt_plot
• Gazebo
• Console Logging (to file, rosout topic)
Limitations of ROS 2 for Autonomous Driving

ROS 2 is missing features needed for safety-critical applications

1. Hard Real-Time
   - OS Primitives (memory, synchronization)
   - Real Time Logging
   - Waitsets
   - Large Memory Support

2. Robustness and Security
   - Managed System
   - OS Security

3. Testing and Certification

Apex.OS is an automotive ROS 2 for safety-critical applications
Deterministic resource usage and runtime is necessary for a safety critical system

- Memory
- Threads
- Blocking calls

ROS 2 is still too dynamic for hard real-time

1. Memory
   - Allocation on subscription
   - `std::string`
   - `std::vector`
   - `std::exception`

2. Blocking calls
   - `fprintf`
   - `fwrite`

3. Non-RT DDS Implementation

To bridge the gap to hard real-time

- No resource allocation during runtime
- All operations are finite and bounded
- All potentially blocking calls have timeouts
Automotive ROS 2: Real Time Logging

Printing console is a nondeterministic blocking call

A purpose-built real-time logger was built instead

- Logging call uses deterministic atomic operations
- Writes to a self-healing, fail-resistant ring-buffer in shared memory
- Buffer can be flushed with minimal overhead

```c
// Trace of RCLCPP_INFO call:
RCLCPP_INFO(logger, "foo");
RCUTILS_LOG_INFO_NAMED(logger, get_name(), "foo");
RCUTILS_LOG_COND_NAMED(...);
// ...
rcutils_log(...);
"output_handler"
(location, severity, name ? name : ":", now, format, &args);
output_handler = g_rcutils_logging_output_handler;
g_rcutils_logging_output_handler =
rcutils_logging_console_output_handler(...);
// Calls
fprintf(...);
```

```
#define APEX_PRINT(...) \
apex::console::print(\ 
 static_cast<uint32_t>(__LINE__), \ 
 __FILE__, \ 
 __VA_ARGS__)
APEX_PRINT("Debug float value", 32.23);
```

14941| apex_console_logging | 2018-08-30 17:15:54.319515| Version: 0.0.0
14942| apex_console_logging | 2018-08-30 17:15:54.319520| Formal build: No
14943| apex_console_logging | 2018-08-30 17:15:54.319521| Debug float value: +32.23
14944| apex_console_logging | 2018-08-30 17:15:55.319628| Debug integer value: -32
14945| apex_console_logging | 2018-08-30 17:15:56.319741| This is a debug message
Automotive ROS 2: Waitsets

Callbacks are the primary mechanism by which ROS handles the receipt of interprocess communication.

```
const auto subscriber1_ptr = node_ptr->create_subscriber<std_msgs::msg::String>("Topic1", bar);
const auto subscriber2_ptr = node_ptr->create_subscriber<geometry_msgs::msg::PointStamped>("aTopic2");
rcppl::Waitset<2> ws({sub1, sub2});
```

Waitsets better lend themselves to a deterministic execution order and error handling.

```
rcppl::Node node("Node");
auto sub1 = node.create_subscriber<std_msgs::msg::String>("Topic1");
auto sub2 = node.create_subscriber<geometry_msgs::msg::PointStamped>("aTopic2");
rcppl::Waitset<2> ws({sub1, sub2});

// Wait for 5 seconds.
ws.wait(5s);
```

```
auto msgs1 = sub1->take();
if (msgs1) {
    // always update to latest msgs2 if available
    // before acting on msg1
    auto msgs2 = sub2->take();
    if (msgs2) {
        handle_sample(msg2.data());
    } else {
        // react to not receiving msgs1 in time
    }
```

```
handle_sample(msg1.data());
```
Automotive ROS 2: Large Memory Support

The maximum size of a UDP packet is 64kB

• Messages larger than 64kB require fragmentation
• Large messages are slower to transmit
• Exchanging pointers (8 B) to memory locations in shared memory is significantly faster for large data

```cpp
/* SHM Publish */
// Initialize
apex::shared_memory::ShmArray<BigMsg> shm_pub(num_frames, topic.c_str());
const auto pub_ptr = node_ptr->create_publisher<std_msgs::msg::Uint64>(topic);

// publish: write message to shared memory
BigMsg big_msg;
const uint64_t frame_num = 0U;
shm_pub[frame_num] = big_msg;
// publish: send frame number via DDS
std_msgs::msg::Uint64 msg;
msg.data = frame_num;
pub_ptr->publish(msg);

/* SHM Subscribe */
// Initialize
const apex::shared_memory::ShmArray<BigMsg> shm_sub(num_frames, topic.c_str());

auto cb = [&](const std_msgs::msg::Uint64::SharedPtr msg) {
    // copy large message to local context
    // could also manipulate in shared memory for zero copy
    local_big_msg = shm_sub[msg->data];
};

const auto sub_ptr = node_ptr->create_publisher<std_msgs::msg::Uint64>(topic, cb);
```
Automotive ROS 2: Managed System

Deterministic startup order of nodes is important for large systems
• ROS 2 launch (Python) provides this capability
• ROS 2’s managed nodes allow individual nodes to react to failures

ROS 2 lacks mechanisms for the whole system to react to node failures
• Heartbeat (detect silent failures)
• Lifecycle Manager (coordinate system level responses)
• Shadow nodes (instant failure response for critical systems)
• Consensus
ROS 2 exposes three kinds of security from DDS
- Message encryption
- Authentication
- Access Control
- Data Tagging
- Logging

This is insufficient to guard against corrupted or malicious binaries
- Memory hoggers
- CPU stressors
- Tailor-made DDS participants

ROS 2 also lacks key mechanisms such as
- Secure over-the-air (OTA) updates
- Secure key storage
- Integration with existing security infrastructure
Automotive ROS 2: Testing and Certification

How do you prove code is safe?

Follow a functional safety standard (ISO 26262):

1. Analyze your use case
   - Write requirements

2. Follow a process
   - Document everything
   - Follow a coding standard
   - Analyze your code
   - Do code reviews

3. Write tests
   - Unit, integration, full stack, stress, fault, injection, requirements
   - SIL, HIL (every supported ECU, sensor)
   - Line, branch, MC/DC coverage
## Giving Back

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Building Algorithms for Safety Critical Applications
Case Study: ROS 1 Velodyne Driver

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Conclusion

ROS 1 is great
• Lots of tools and algorithms
• Community
• But can never be automotive grade

ROS 2 is even greater
• Enough features for serious development
• API is stable enough
• Can work with ROS 1
• Can be automotive grade

Apex.AI® is automotive grade ROS 2
• Real-time
• Secure
• ISO 26262 certified

Apex.AI® is hiring!
We are actively recruiting developers and engineers:
• Framework
• Embedded
• Security
• Certification
• Algorithms
If you are interested to learn more, talk to us at ROSCon or apply at www.apex.ai
ROS 1 PubSub vs. Apex.OS PubSub

Rate & Latency between nodes under stress (Run-1)

Rate & Latency between nodes under stress (Run-2)