May mobility

Practical Data Science in Robotics using DataFusion

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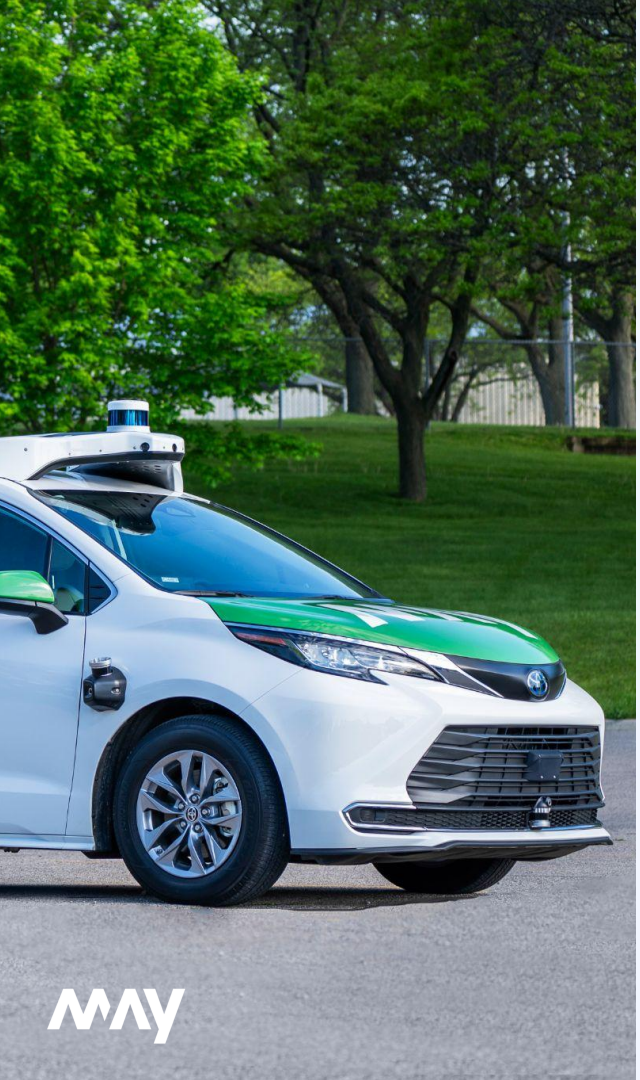
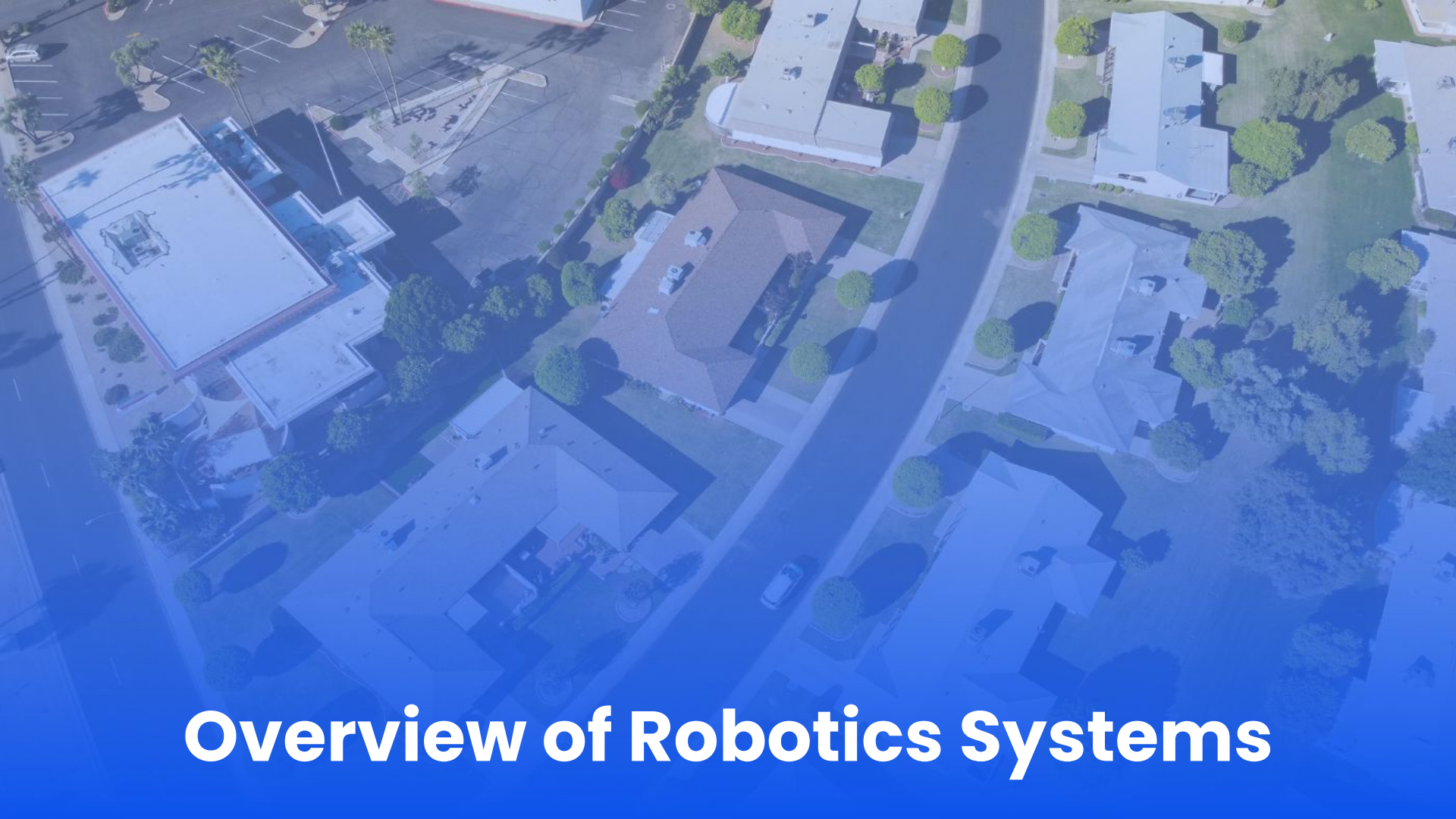


Agenda

1. Overview of robotics systems
2. Use Case Example
3. Common Problems and Approaches
4. Where DataFusion fits in

My background (briefly)

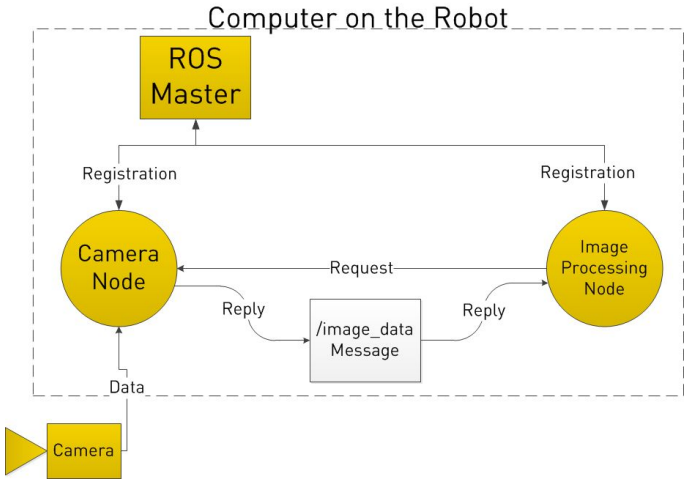
- May Mobility
  - Currently director for simulation and infrastructure
  - Heavily work in data engineering of features
  - Current main focus of using data to validate safety case
  - Prior: Autonomy engineer in decision making engine
- Soar Technology
  - Mostly worked on robotics projects for DARPA
  - Developed rust wrapper for cognitive architecture (soar)
- Dassault Systemes
  - Industrial robotics software (such as 6 DOF arms in an automotive plant)
- Ph.D. Physics - University of Michigan
  - Thesis used nature inspired search algorithms to optimize solutions in high dimensional parameter space
- US Navy - irrelevant, but some people say it's interesting



Overview of Robotics Systems

Robotics Systems

- Talk is focused on modern robotic systems
  - Industrial robots (like 6 DOF manufacturing arms) don't usually operate like this
- Typically consist of 1+ CPUs, 1+ GPUs, and multiple sensors
- Frequently a mixture of ethernet enabled devices and some connected to a single CPU
- All processes operating asynchronously, some with additional threading
- Communication is typically done through message passing infrastructure, such as ROS defined by:
  - Communication Layer
  - Message Definitions
  - Serialization Protocols
- Some processes work on a pub/sub approach, others on a request/response, and some a mixture

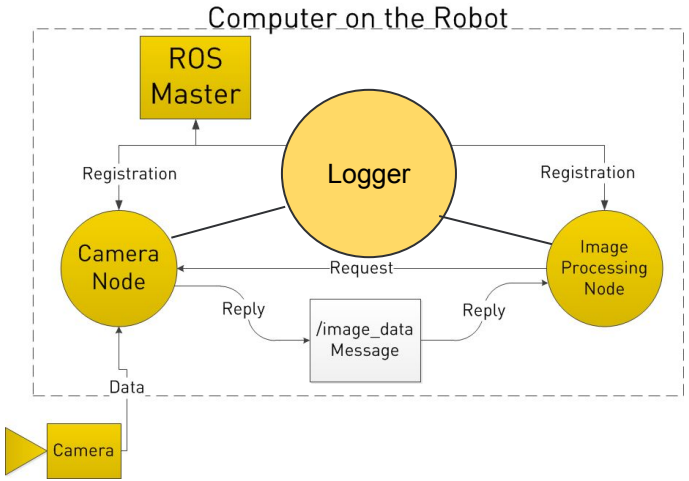


Typical node structure within a single CPU. Realistic systems often have multiple computers, each with tens to a hundred nodes.

Image courtesy Clearpath Robotics.

Data Offload

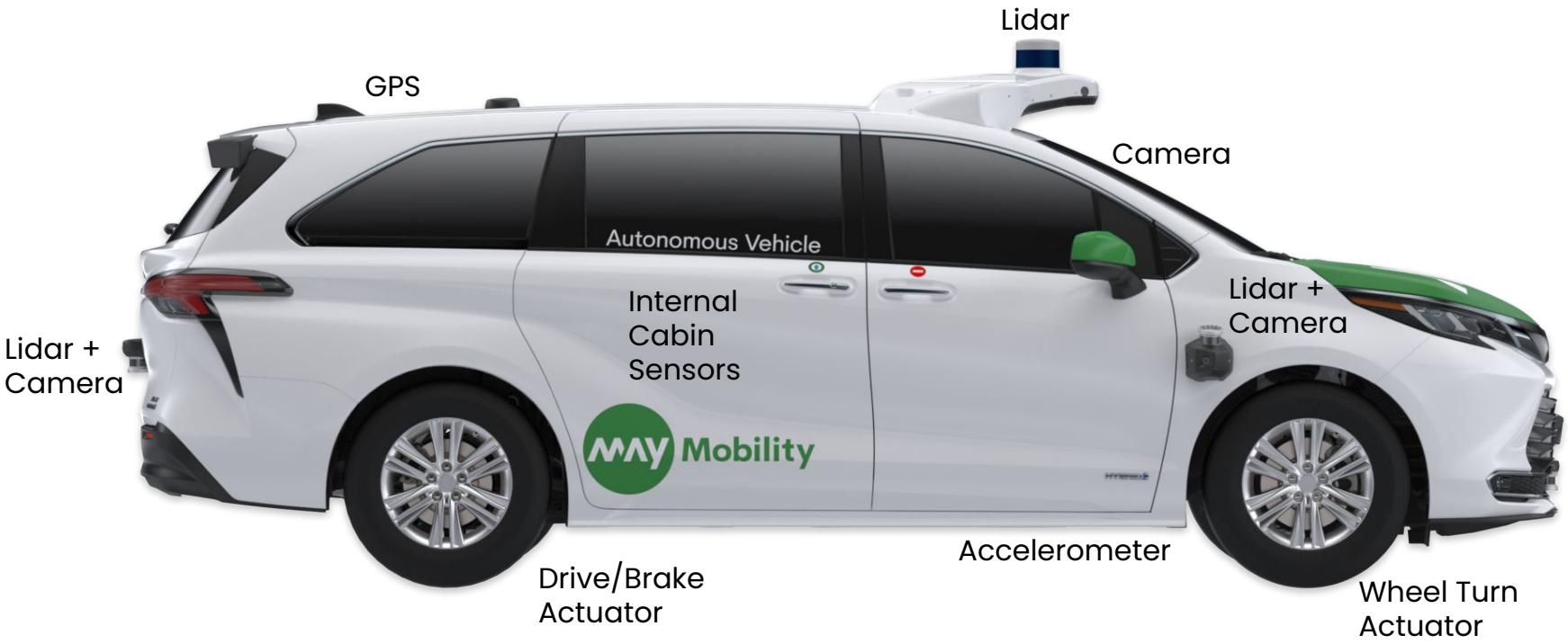
- Typically attach one or more nodes as loggers
  - This is a process that listens only and attempts to write the serialized data as fast as possible to a file(s)
- There *may* be no guarantees about the timing of messages
  - The current time for a process maybe:
    - A “trigger” based on a message received and it assumes that is the current time
    - An internal clock mechanism
    - A timing signal from an external source
- In the end you frequently have one or more log files that require some form of ingestion into your data analysis suite
  - Common log sizes are ~300-500 Gb/Hr of data



The logging node typically sits on one or more CPUs within the robotics system.

Image courtesy Clearpath Robotics.

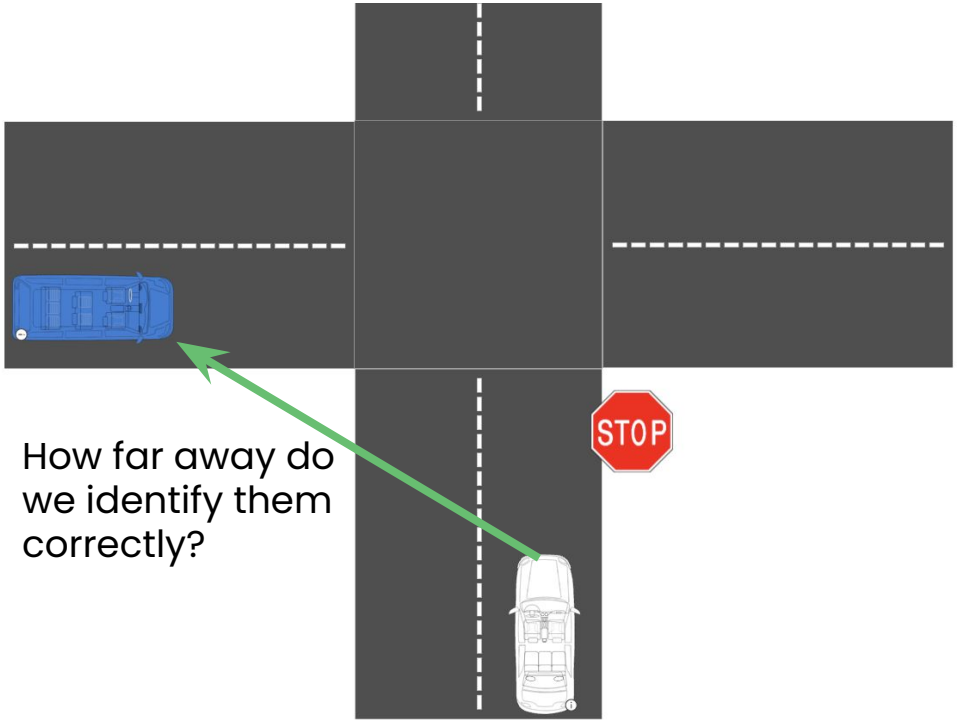
Example Robotic System



Use Case Example

Use Case: Cross Traffic Identification

- Define cross traffic identification as: For vehicles that are on the cross streets from ours, how far away they are from our vehicle when we get our first positive identification.
- Two useful, related metrics:
  - Distance from our vehicle to the entrance of the intersection when we get a positive ID X meters away.
  - When we are at the entrance to the intersection, the maximum distance away at which we get a positive ID.
- You may want to predicate these results on the type of vehicle (car, truck, bus, etc)
- Also useful is the distance of the first identification compared to the distance of the first positive ID
  - Far away tracks are hard to recognize



Cross Traffic - Technical Approach

- Identify distance from ego vehicle to the intersection
  - Combine GPS data with map data
    - Requires identification of what is defined as the “entry” of the intersection
- Identify the “real” classification of the other agent
  - Since you are not trying to process in real time, search for the agent’s maximum likelihood classification
    - **All robotics data are noisy**
- Identify the time range for which the classification is stable and the same as the maximum likelihood
- Compute summary statistics predicated on things like
  - Type of agent based on maximum likelihood
  - Differentiability (how certain can you be you got it right)
  - Particular intersection
    - Bonus points to identify intersections that are significantly different from the norm

when it comes to robotics data

Common Problems and Approaches

Common Robotics Challenges

- Noisy data - Loss of signal - process crash, buffer full, weak connection, etc
- Getting the data into a data store
  - This is basically “just” a traditional computer science problem of converting bits of type X into bits of type Y
  - Naive approaches are typically to hand encode these
  - In practice, often requires building generators to enable scalability
- Transforms!
  - Sensors are “dumb” and put out what they see
  - Define a transform to go from the reference point of the robot to the sensor
    - You may have multiple reference transforms between one and the other and these may change dynamically
      - Example: distance sensor on the end of a long arm with two joints along it
- Noisy data
- Spatial Analysis
  - This problem is more related to database approaches, not robotics in general
- Time Synchronization
  - Making sense of when the messages come in, and how to consistently apply timing information
- No, seriously, the data are noisy

Getting robotics data into a data store

- Robotics data are **highly** structured
- Two general approaches - sending messages via publish/subscribe or query/response
- Most difficult issue: How to convert the data into a usable format?
  - Should you try to ingest “raw”?
  - Can we automate the message translation process?
  - Where in your pipeline can/should you make the data more friendly to data analysis?
  - Trivial example: cartesian position (x, y, z) stored as a float[] in a message
    - We know *a priori* this is always a 3 element float, should we store this as a fixed length array element or should we store three columns pos_x, pos_y, pos_z?
- Real Time ingestion
  - Requires all messages to have an agreement about how timing information is stored (example: timestamp in std_msgs/Header)
- After the Fact ingestion
  - Usually you can use embeddings within the log file
  - Log file computer may be distant from the source, so you may need to account for this as well

sensor_msgs/Image

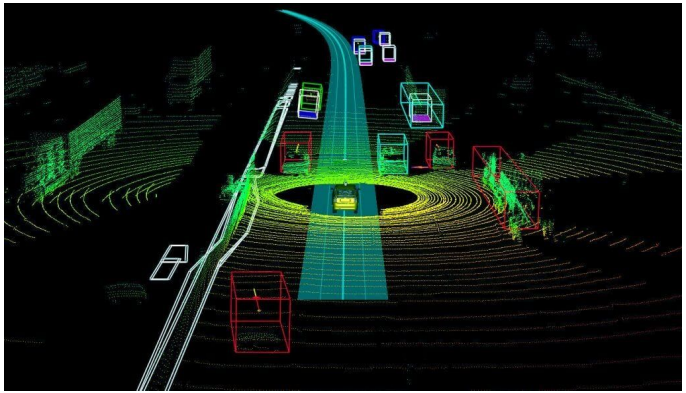
```
std_msgs/Header header
uint32 height
uint32 width
string encoding
uint8 is_bigendian
uint32 step
uint8[] data
```

gps_common/GPSFix

```
std_msgs/Header header
gps_common/GPSStatus status
float64 latitude
float64 longitude
float64 altitude
float64 track
...
```

Transforms

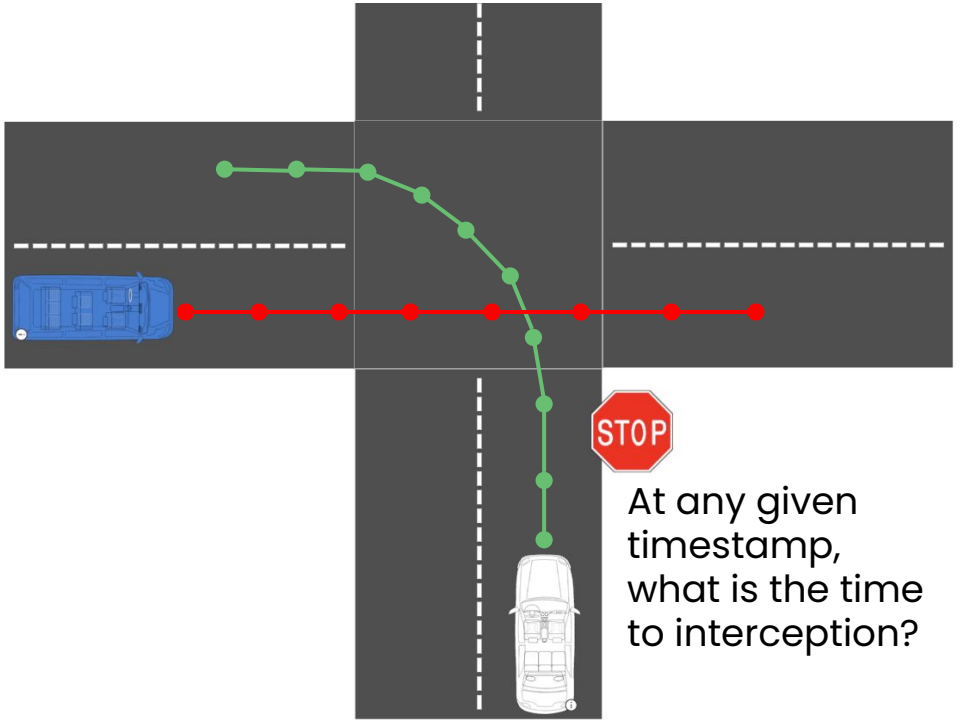
- Frequently your data comes “nearly” raw from the sensors
- Example: LiDAR
  - A spinning device that sends out laser beams and measures the time of flight for the returned signal.
  - This generates a “point cloud” of all of the returned signals
  - These are measured relative to where the LiDAR is mounted
- Transforms are *typically* defined as a rotation and translation to get from one coordinate frame to another
  - Do you translate first or rotate first? It matters.
  - Not everyone does it the same.
  - There are *conventions*, but not strictly followed
  - You must also track which frame is transformed from and to (some publish the inverse of what you need)
- Transform operations are not easily handled by things like DataFrame libraries or SQL
  - Minimum 7 entries to compute a transform: 3 for translation and 4 for rotation
  - The math is not trivial
  - Frequently you have multiple transforms to apply
    - Robotics tooling does this “built in”



"Your data cannot remain as it is. You must convert it—only then can you achieve greatness."

Spatial Analysis

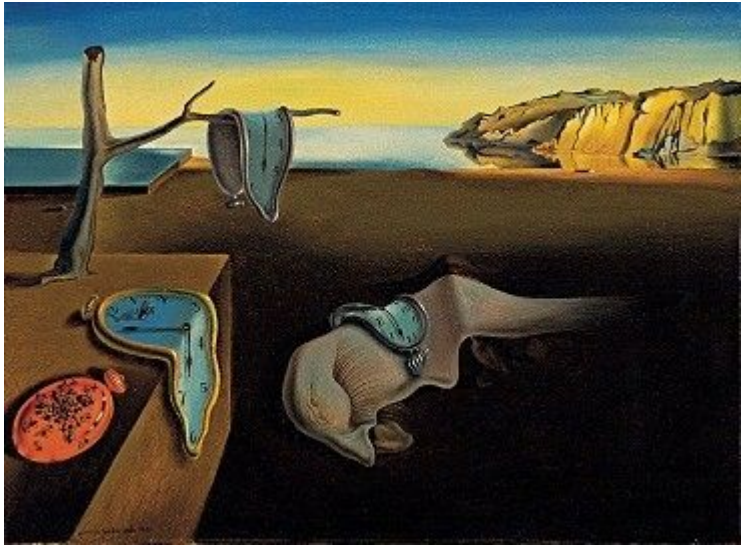
- Spatio-Temporal Analysis is one of the most common tools roboticists need to use
- Examples:
  - Path intersection (in picture)
  - Projection onto a curved route
  - Time to intersection
    - Made more fun by varying acceleration profiles
- Robotics engineers have *many* tools to handle these, but they don't always map well to database approaches
- Existing packages:
  - geopandas - by far the most used
  - Sedona - geo on PySpark, essentially
  - geoarrow-rs : newcomer and a member of the DataFusion community
- There is no native storage structure for geo data
  - Usually encoded as text (WKT) or binary (WKB)



At any given timestamp, what is the time to interception?

Time Synchronization

- On a distributed robotics system, there is a fundamental question of what time means
- Some common approaches:
  - The local time of the computer for which the data were generated
  - The time embedded within a message that triggered a process to run
  - The time of receipt of a message according to a specified computer (such as the logger)
  - The time specified by a time server at which a message was published
- This is one of the most important features with the data from a robotics system. How we organize data along temporal dimension will impact nearly all analysis.
  - **You must get this right.**



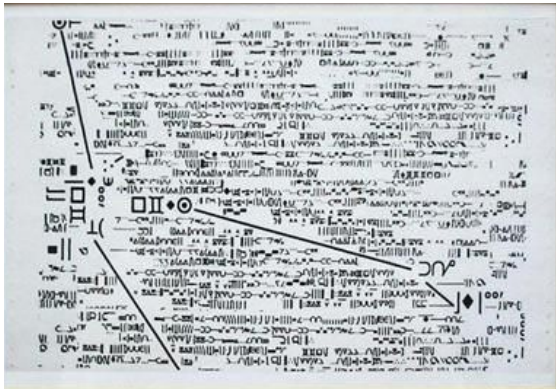
The Persistence of Memory by Salvador Dali

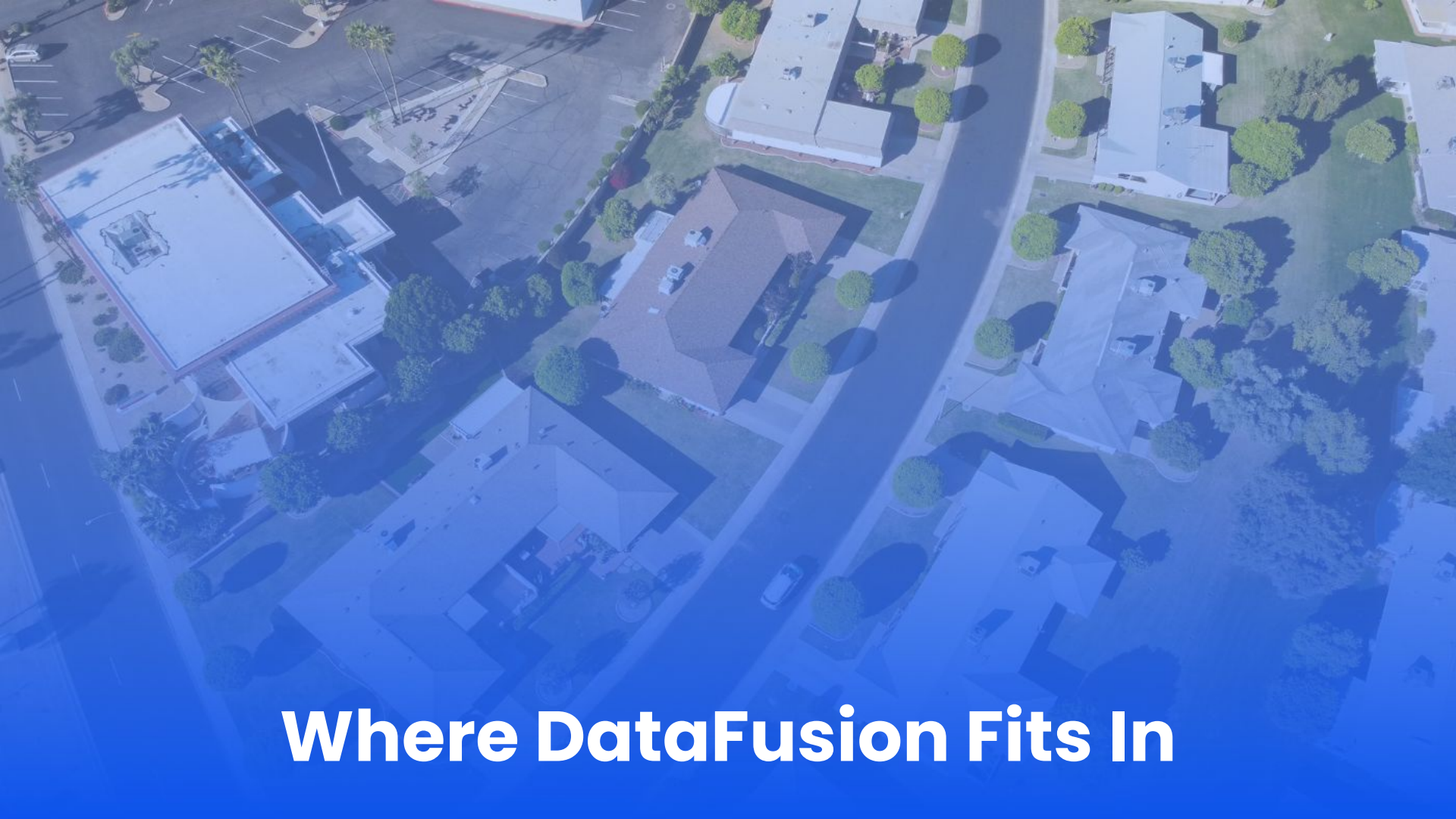
Noisy Data

Tim's opinionated view:

To be successful in robotics, you must cultivate an attitude of distrust of the data.

- Thresholding does not work due to boundary effects
  - Smoothing helps
  - Dynamic boundaries is a more robust solution
- Build in detections for known problems such as loss of data and duplicate data
  - Duplicate may not be exactly duplicate, so frequently need more nuance, such as some fields to ignore
- Build in outlier detections into all data analysis workflows
  - Don't tack it on at the end, make it part of your flow
  - Rust got a huge win from treating errors as part of the normal flow. Can we do the same in data?
- How to handle errors in the data is a top line problem, so make it front and center of your solution
  - When reviewing results, explain the reasoning for acceptance/rejection criteria





Where DataFusion Fits In

DataFusion for Robotics Data Science

- Python is the language for Data Science, almost exclusively with DataFrame APIs
  - Overwhelmingly: PySpark for scale, Pandas for single node
- For DataFusion to compete it must have comparable functionality and some clear advantage

Tim's Opinionated View:

Rust backed python UDFs is the killer feature for doing robotics data science in DataFusion.

Reasoning:

- Roboticists and Data Scientists have different skill sets
- Rust UDFs can be written in a way that Roboticists understand (ideally by Roboticists)
- Package up a set of reusable message oriented rust backed UDFs as an analytics toolkit
- Data Scientists can leverage this toolkit to get:
  - Highly performant functions that operate at native speed
  - Abstract away the portion of the problem that does not match their skill set

But to win, we need distribution. Under heavy development:

- ballista
- datafusion-ray

Abstraction will set you free.

How DataFusion might address...

- Getting the data into a data store
  - I don't think it impacts here, **but** my work on DataFusion led me to design an ingestion system that is saving so much money it pays my entire salary
- Transforms
  - Easy win here - These are trivially implemented in Rust
  - Good crates already exist - it's simply a matter of data agreements about struct/column layout
- Spatial Analysis
  - Geo-arrow is a top contender to win here
  - Ideally we can build in extension types, but this could break workflows
    - Suppose you want to read from a table which has these extension types but you aren't using those columns. Do you have to still load in the extensions to your workflow?
- Time Synchronization
  - Potentially a win by using a user defined async join?
  - We currently have a process to merge, sort on a time column, fill forward empty data
    - OOM problems on large data sets, so still needs work
  - Still needs more thought
- Noisy Data
  - User defined window functions!

Questions?