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ARTIFICIAL INTELLIGENCE IN AUTONOMOUS VEHICLES

VII semester

Department of AIML

RV College of Engineering

Course Incharge: Dr. Viswavardhan Reddy Karna

2024-2025

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Course Contents

Semester: VII						
ARTIFICIAL INTELLIGENCE IN AUTONOMOUS VEHICLES **Category: Professional Core Elective** **(Theory)**						
Course Code	:	21AI73G1		CIE	:	100Marks
Credits: L: T: P	:	3:0:0		SEE	:	100 Marks
Total Hours	:	40T		SEE Duration	:	3.00 Hours

Unit-I	**8 Hrs.**
Introduction to Autonomous Driving: Autonomous Driving Technologies Overview, Autonomous Driving Algorithms, Autonomous Driving Client System, Autonomous Driving Cloud Platform Autonomous Vehicle Localization: Localization with GNSS, Localization with LiDAR and High-Definition Maps, Visual Odometry, Dead Reckoning and Wheel Odometry, Sensor Fusion	
Unit – II	8 Hrs.
Perception in Autonomous Driving: Introduction, Datasets, Detection, Segmentation, Stereo, Optical Flow, and Scene Flow, Tracking Deep Learning in Autonomous Driving Perception: Convolutional Neural Networks., Detection, Semantic Segmentation, Stereo and Optical Flow	
Unit –III	8 Hrs.
Prediction and Routing: Planning and Control Overview, Traffic Prediction, Lane Level Routing Decision, Planning, and Control: Behavioral Decisions, Motion Planning, Feedback Control	

Course Contents with COs

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Unit –IV	8 Hrs.
Reinforcement Learning-Based Planning and Control: Introduction, Reinforcement Learning, Learning-Based Planning and Control in Autonomous Driving Client Systems for Autonomous Driving: Autonomous Driving: A Complex System, Operating System for Autonomous Driving, Computing Platform (Agent, Environment, State (position, velocity), Action (steering, acceleration and braking), and Reward(safety, comfort))	
Unit –V	8 Hrs
Cloud Platform for Autonomous Driving: Infrastructure, Simulation, Model Training, HD Map Generation Autonomous Last-Mile Delivery Vehicles in Complex Traffic Environments: Autonomous Delivery Technologies in Complex Traffic Conditions, Safety and Security Strategies, Production Deployments	

Course Outcomes: After completing the course, the students will be able to:-	
CO1	Analyse the various driving conditions for autonomous cars and apply AI techniques
CO2	Identify various problems involved in developing Autonomous Driving cars and suggest the appropriate solutions
CO3	Integration of advanced driver assistance system with cloud infrastructure for training and modelling
CO4	Development of Deep learning techniques to analyse the data for decision making.
CO5	Demonstrate the use of modern tools by exhibiting teamwork and effective communication skills

Course Contents – Reference Books

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Reference Books	
1.	Creating Autonomous Vehicle Systems, Second Edition Shaoshan Liu, Liyun Li, Jie Tang, Shuang Wu, and Jean-Luc Gaudiot ,2nd Edition, September 2020, ISBN: ISBN: 9781681739366
2.	George Dimitrakopoulos, Aggelos Tsakanikas, Elias Panagiotopoulos, Autonomous Vehicles Technologies, Regulations, and Societal Impacts, 1st Edition,Elsevier Publications, 2021 , ISBN-10 1681730073
3.	Hanky Sjafrie, “Introduction to Self-Driving Vehicle Technology”, 1st Edition, Published December 11, 2019 by Chapman and Hall/CRC, ISBN: 978-0-323-90137-6
4	Creating Autonomous Vehicle Systems Shaoshan Liu, Liyun Li, Jie Tang, Shuang Wu, and Jean-Luc Gaudiot October 2017, ISBN-10 1681730073

Course Contents – CIE

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#	COMPONENTS	MARKS
	RUBRIC FOR THE CONTINUOUS INTERNAL EVALUATION (THEORY)	
1.	QUIZZES: Quizzes will be conducted in online/offline mode. TWO QUIZZES will be conducted & Each Quiz will be evaluated for 10 Marks. THE SUM OF TWO QUIZZES WILL BE THE FINAL QUIZ MARKS.	20
2.	TESTS: Students will be evaluated in test, descriptive questions with different complexity levels (Revised Bloom's Taxonomy Levels: Remembering, Understanding, Applying, Analyzing, Evaluating, and Creating). THREE tests will be conducted. Each test will be evaluated for 50 Marks, adding upto 150 Marks. FINAL TEST MARKS WILL BE REDUCED TO 40 MARKS.	40
3.	EXPERIENTIAL LEARNING: Students will be evaluated for their creativity and practical implementation of the problem. Case study-based teaching learning (10), Program specific requirements (10), Video based seminar/presentation/demonstration (20) ADDING UPTO 40 MARKS.	40
	MAXIMUM MARKS FOR THE CIE THEORY	100

Course Contents – SEE

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RUBRIC FOR SEMESTER END EXAMINATION (THEORY)		
Q.NO.	CONTENTS	MARKS
PART A		
1	Objective type of questions covering entire syllabus	20
PART B (Maximum of THREE Sub-divisions only)		
2	Unit 1 : (Compulsory)	16
3 & 4	Unit 2 : Question 3 or 4	16
5 & 6	Unit 3 : Question 5 or 6	16
7 & 8	Unit 4 : Question 7 or 8	16
9 & 10	Unit 5: Question 9 or 10	16
	TOTAL	100

Course Contents – Unit - I

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Introduction to Autonomous Driving:

- Autonomous Driving Technologies Overview
- Autonomous Driving Algorithms
- Autonomous Driving Client System
- Autonomous Driving Cloud Platform

Autonomous Vehicle Localization:

- Localization with GNSS
- Localization with LiDAR and High-Definition Maps
- Visual Odometry
- Dead Reckoning and Wheel Odometry
- Sensor Fusion

Introduction to Autonomous Driving

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Introduction to Autonomous Driving: Autonomous Driving Technologies Overview

- Autonomous Driving Systems – popular in research topic and industry
- Problem: talent is limited and stems from several key factors:
  - Technical Complexity : Expertise in fields of ML, DL, CV, robotics, sensor fusion.
  - Growing Demand Across Industries: Demand for AI & robotics – healthcare, finance, manufacturing etc (increases complexity and pool of experts scarcity)
  - Emerging Field: New domain – universities and training programs to produce enough graduates with relevant expertise.

Introduction to Autonomous Driving

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- Regional Disparities: Other regions may lack the infrastructure, resources, or institutions to develop and retain talent.

- Cross-Disciplinary Requirements: Software with hardware integration, automative engineering, safety regulations and standards, etc.

The Dawn of Autonomous Driving – Learning from History

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Historical Layers of Information Technology

1960s: The Birth of IT

1. Introduction of **microprocessors** that boosted productivity -With **Intel** and **Fairchild**

1980s: Personal Computing Revolution

2. **Microsoft** and **Apple** introduced the **Graphic User Interface (GUI)**. Realized the vision of "a **PC/Mac** in every home.“

2000s: The Internet Era

3. **Google** connected people with **information** - Enabled indirect connections between information providers and consumers.

2010s: The Social Network Revolution

4. **Facebook** and **LinkedIn** moved **human society online** - direct connections between individuals.

Mid-2010s: Internet-Based Commerce

5. **Uber** and **Airbnb** created an **internet-based service economy** - Provided efficient access to services but still human-driven.

AUTONOMOUS DRIVING TECHNOLOGIES OVERVIEW

Three major components

- Algorithms: extracts meaningful information from sensors (raw data).
- Client system: real time processing
- Cloud platform: Computing and storage capabilities.

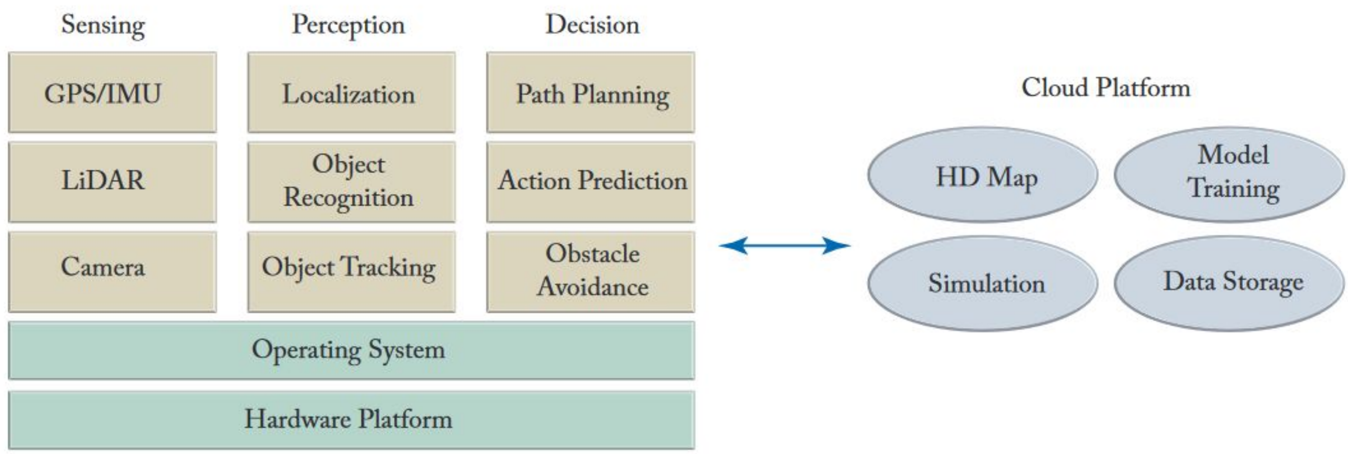

Figure 1.1: Autonomous driving system architecture overview.

AUTONOMOUS DRIVING Algorithms

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SENSING

Extracting the meaningful information from sensor raw data

1. Camera Systems

- **Purpose:** Capture high-resolution images for object recognition and object tracking tasks such as: lane detection, traffic light detection, and pedestrian detection, etc. (1080p)

- **Advantages:** Cost-effective and detailed visual information.

- **Limitations:** Performance can be impacted by low light or adverse weather conditions.

- 1.8 GB data is being generated per sec with cameras usually run at 60 Hz.

2. Lidar (Light Detection and Ranging)

- **Purpose: A** remote sensing technology that uses laser pulses to create 3D models of the Earth's surface - measuring distance by illuminating a target with laser light and analyzing the reflected light.

1. Emission of Laser Pulses

- A LiDAR sensor emits rapid pulses of laser light, typically in the infrared spectrum. (700 nanometers (nm) to 1 millimeter (mm)) – with frequency range 300 GHz to 429 THz.
- These laser beams are sent in multiple directions to cover the surrounding area.

2. Reflection of Laser Pulses

- The laser pulses hit objects (e.g., vehicles, pedestrians, buildings) in the environment.
- Light is reflected back to the LiDAR sensor.

AUTONOMOUS DRIVING Algorithms

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2. Lidar (Light Detection and Ranging)

Time-of-Flight Measurement

- The sensor measures the time it takes for each laser pulse to return.
- Using the formula **Distance = (Speed of Light × Time) / 2**, the system calculates the distance to each object.

Scanning and 3D Mapping

- A rotating mirror or solid-state scanning mechanism allows LiDAR to sweep across the environment.
- This process generates a detailed **3D point cloud**—a collection of points representing objects and surfaces in the scene.

2. Lidar (Light Detection and Ranging)

Data Processing

- The raw point cloud data is processed to identify objects, measure dimensions, and detect movement.

- Algorithms classify the data into meaningful categories, such as vehicles, pedestrians, or obstacles.

Key Features of LiDAR:

- **High Precision:** Accurate distance measurement within a few centimeters.

- **Wide Field of View (FoV):** Can scan up to 360 degrees, depending on the design.

- **All-Day Functionality:** Works in both daylight and nighttime conditions.

2. Lidar (Light Detection and Ranging)

Advantages:

- Generates highly detailed 3D maps and reliable for detecting small or distant objects.
- Effective in differentiating between overlapping objects.

Limitations:

- High cost compared to other sensors and performance affected by adverse weather (e.g., heavy rain or snow).
- Larger size and power consumption in some models.

Applications in Autonomous Vehicles:

- **Obstacle Detection:** Identifies objects like pedestrians, vehicles, and barriers.
- **Mapping and Localization:** Creates real-time 3D maps for navigation.
- **Safety Systems:** Supports advanced driver-assistance systems (ADAS) by detecting potential hazards.

3. Radar (Radio Detection and Ranging)

It is a technology that uses radio waves to detect, locate, and track objects.

How Radar Works:

- **Transmission**: A radar system emits a burst of radio waves (pulses) via an antenna.
- **Propagation**: These radio waves travel through the atmosphere, potentially interacting with objects.
- **Reflection**: When the waves hit an object, some are reflected back toward the radar system.
- **Reception**: The radar system's antenna detects the reflected waves.
- **Processing**: The radar analyzes the time delay between transmission and reception, the frequency shift (Doppler effect), and the strength of the reflected signal to gather information about the object.

AUTONOMOUS DRIVING Algorithms

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3. Radar (Radio Detection and Ranging)

Key Components:

- **Transmitter**: Generates radio waves. **Antenna**: Transmits radio waves and receives reflections. **Receiver**: Detects and amplifies the reflected signals.
- **Processor**: Interprets the data and produces useful information like range, velocity, and angle.

Applications:

- **Aviation**: For air traffic control, weather detection, and collision avoidance.
- **Maritime**: For navigation and avoiding obstacles at sea.
- **Military and Defense**: For detecting enemy aircraft, ships, and missiles.
- **Weather Monitoring**: To track storms and precipitation.
- **Automotive**: In advanced driver-assistance systems (ADAS) like adaptive cruise control.

3. Radar (Radio Detection and Ranging)

Advantages:

- Operates in all weather conditions, day or night.
- Can detect objects at long distances.
- Provides precise measurements of speed and direction.

Limitations:

- Susceptible to interference from other signals.
- Performance can be affected by terrain, buildings, or other obstacles.
- Expensive and complex to maintain.

AUTONOMOUS DRIVING Algorithms
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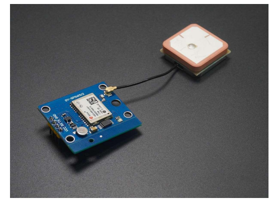
Key Applications of Radar in Cars:

1. **Adaptive Cruise Control (ACC)**:
   - Maintains a safe distance from the vehicle ahead by adjusting speed automatically.
2. **Collision Avoidance**:
   - Detects potential obstacles and warns the driver or applies emergency braking to prevent accidents.
3. **Blind-Spot Detection**:
   - Alerts drivers to vehicles in adjacent lanes that may not be visible in mirrors.
4. **Parking Assistance**:
   - Guides drivers when parking in tight spaces by detecting nearby objects.
5. **Cross-Traffic Alert**:
   - Warns of vehicles approaching from the side when reversing.
6. **Autonomous Driving**:
   - Radar is a key sensor for self-driving systems, providing data about the environment to make driving decisions.

GPS/IMU: Global Positioning System: vital technology for navigation and location-based services.

GPS uses satellite signals to determine the exact location of a vehicle and provide real-time information about its position, speed, and direction.



How GPS Works in Cars:

- **Satellite Signals**: GPS receivers in cars connect with at least four satellites from a global network of satellites orbiting Earth.
- **Triangulation**: The receiver calculates the car's position by measuring the time it takes for signals from multiple satellites to reach it.
- **Data Interpretation**: The system converts latitude, longitude, and altitude data into usable formats, such as a map display or directions.

AUTONOMOUS DRIVING Algorithms

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Applications of GPS in Cars:

1.Navigation:
1. Provides turn-by-turn directions and helps drivers reach their destination efficiently.
2. Displays real-time traffic updates and suggests alternate routes to avoid congestion.

2.Location Tracking

3.Emergency Assistance:
1. Systems like **eCall** automatically send the vehicle's location to emergency services in case of a collision.

4.Stolen Vehicle Recovery: Helps law enforcement locate stolen vehicles using GPS data.

5.Geofencing:
1. Triggers alerts when the vehicle enters or exits a predefined area, useful for fleet management or parental controls.

6.Route Optimization:
1. Ideal for delivery vehicles or ride-sharing services to plan the most efficient routes.

Advantages of GPS in Cars:

- **Convenience**: Eliminates the need for physical maps and simplifies navigation.
- **Real-Time Updates**: Provides live traffic information, road closures, and detour suggestions.
- **Enhanced Safety**: Enables emergency assistance and precise tracking.
- **Efficiency**: Saves time and fuel by optimizing routes.

Limitations of GPS in Cars:

- **Signal Issues**: Can struggle in tunnels, dense forests, urban areas with tall buildings, or during bad weather.
- **Accuracy Variations**: Standard GPS may have an error margin of a few meters.
- **Dependence on Maps**: Outdated maps can lead to inaccurate directions.
- **Privacy Concerns**: Tracking and data sharing can raise concerns about user privacy.

Future Trends in Automotive GPS:

- **Integration with ADAS**: Enhancing advanced driver-assistance systems with precise location data.
- **Augmented Reality (AR) Navigation**: Displaying directions on the windshield or in the driver's line of sight.
- **Satellite-Based Augmentation Systems (SBAS)**: Improving accuracy to centimeters for autonomous driving.
- **V2X Communication**: Allowing GPS to interact with other vehicles and infrastructure for safer driving.

AUTONOMOUS DRIVING Algorithms
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Ultrasonic Sensors

- **Purpose:** Used for short-range detection, such as parking and obstacle avoidance.
- **Advantages:** Inexpensive and highly reliable at close distances.
- **Limitations:** Limited range and lower resolution.

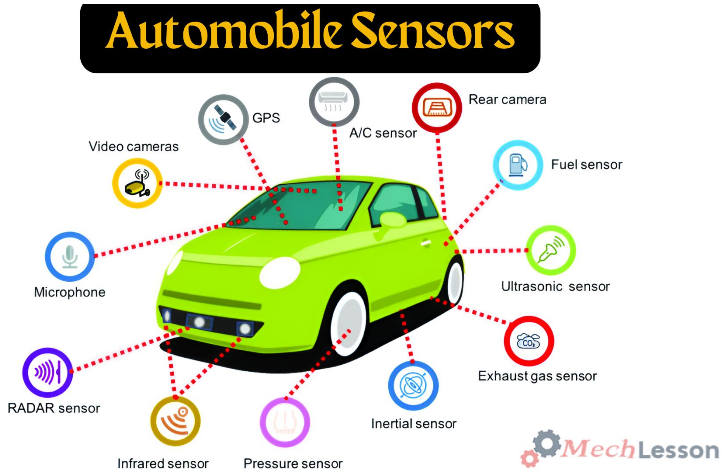
Figure 6. Ultrasonic surround sensor from Bosch [126].

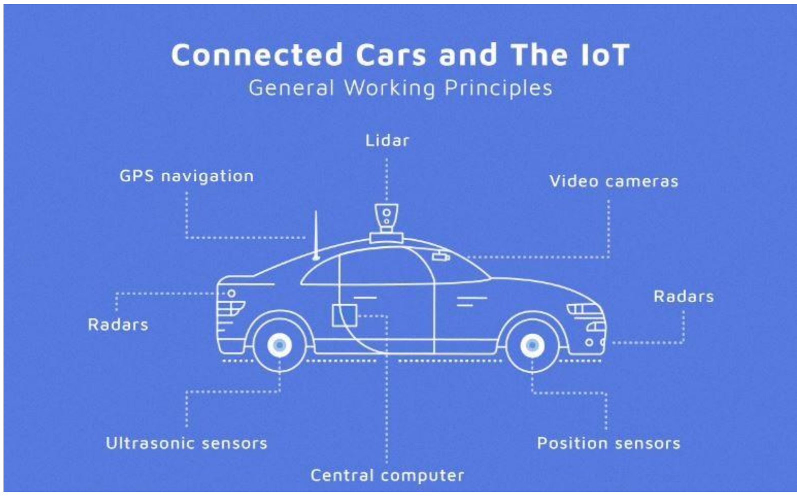
An **Inertial Measurement Unit (IMU)** is a sensor system that measures a vehicle's motion and orientation using accelerometers, and gyroscopes. It is widely used in automotive applications, robotics, aerospace, and mobile devices for navigation, control, and stabilization.

Components of an IMU:

- **Accelerometer**:
  - Detects movement such as speeding up, slowing down, or changes in direction.
- **Gyroscope**:
  1. Detects rotational motion and helps determine orientation.

AUTONOMOUS DRIVING Algorithms





Introduction to Perception in Autonomous Driving

Perception in Autonomous Vehicles:

- The perception stage interprets sensor data to understand the environment: Three key tasks:
  - Localization
  - Object detection and
  - Object tracking

Role of GPS and IMU in Localization

GPS:

- Provides accurate results (~1m precision).
- Low update rate (~100 ms).

IMU:

- Fast updates (~5 ms).
- Errors accumulate over time.

Combining GPS and IMU with Kalman Filters

- Sensor Fusion with Kalman Filters
  - Combines GPS accuracy with IMU speed.
- Process:
  - IMU updates position every 5 ms.
  - GPS corrects accumulated IMU errors every 100 ms.

Result: Fast and accurate localization.

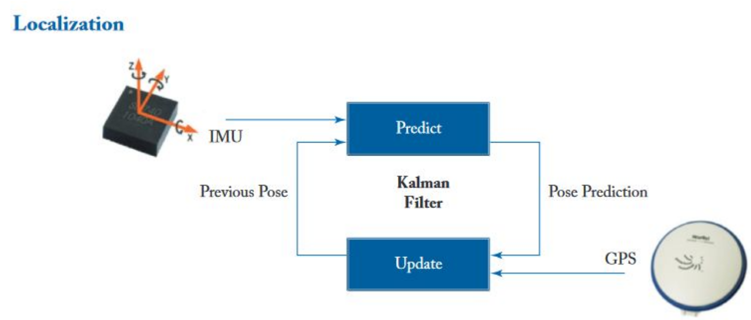
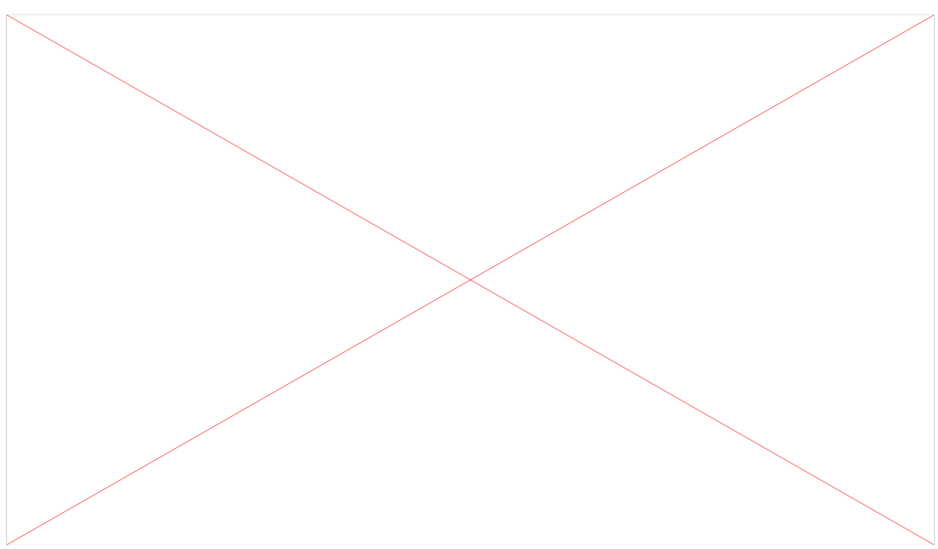


Figure 1.2: GPS/IMU localization.

Challenges of GPS/IMU Localization

- Accuracy limited to ~1 meter.
- GPS multipath issues (e.g., signal bouncing off buildings).
- Requires an unobstructed sky view; fails in tunnels.

the visual representation of the scenarios highlighting the challenges for autonomous vehicles in urban settings, tunnels, and suburban areas.



Cameras in Localization

- Vision-based localization leverages stereo cameras.
- Generates depth and positional data from image analysis.

Pipeline for Vision-Based Localization

- **Disparity Map & Depth Estimation**:
  - Derived from triangulating stereo image pairs.
- **Motion Estimation**:
  - Match salient features between successive frames. (corners or edges)
    - Helps in estimating motion by calculating transformations like translation, rotation, or scaling.
  - Estimate motion from feature point correlations.
- **Position Derivation**:
  - Compare features with a known map to determine position.

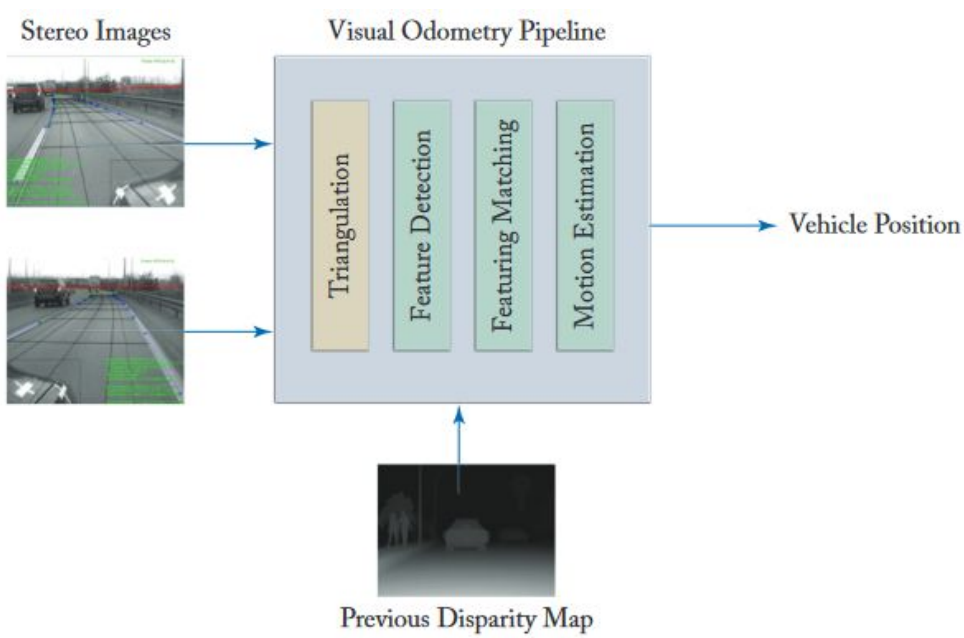


Figure 1.3: Stereo visual odometry.

Introduction to Perception in Autonomous Driving – Stereo Images

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1. Capturing Images:
   - Two cameras capture the same scene from slightly different angles.
   - Cameras are mounted with a fixed baseline.

2. Disparity Map:
   - Compares the two images to identify corresponding points.
   - Difference in position is called disparity.

3. Depth Calculation:
   - Depth is calculated using triangulation:
   Depth = (Focal Length × Baseline) / Disparity.

Introduction to Perception in Autonomous Driving – Stereo Images

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Applications of Stereo Images

• Autonomous Driving:
 - Detect obstacles, measure distances, generate 3D maps.

• Robotics:
 - Navigate and interact with 3D environments.

• Medical Imaging:
 - Create detailed 3D reconstructions for surgeries.

• Virtual Reality (VR):
 - Generate immersive 3D environments.

Introduction to Perception in Autonomous Driving – Visual Odometry

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Advantages of Vision-Based Localization

- Provides rich environmental detail. Enables localization in areas with poor GPS signal.
- Works well with maps containing visual data.

Limitations of Vision-Based Localization

- Highly sensitive to lighting conditions (e.g., shadows, nighttime). Computationally expensive.
- Challenging in feature-poor environments (e.g., deserts, blank walls).

Understanding LiDAR and Particle Filter Techniques for Localization

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Why Use Particle Filters?

- Compares observed shapes with known maps
- Reduces uncertainty in localization

Application: Localizing moving vehicles

- Achieves **real-time localization with 10-cm accuracy**

LiDAR Limitations

Major Drawbacks:

- Noisy measurements in the presence of: Rain, Dust, Other suspended particles

Impact: Reduced reliability in harsh environments

Importance of Sensor Fusion

Solution:

- Combine data from multiple sensors for: Greater reliability and Improved accuracy

•**Key Insight:**

- LiDAR + Sensor Fusion = Robust Localization

Sensor-Fusion Localization Pipeline

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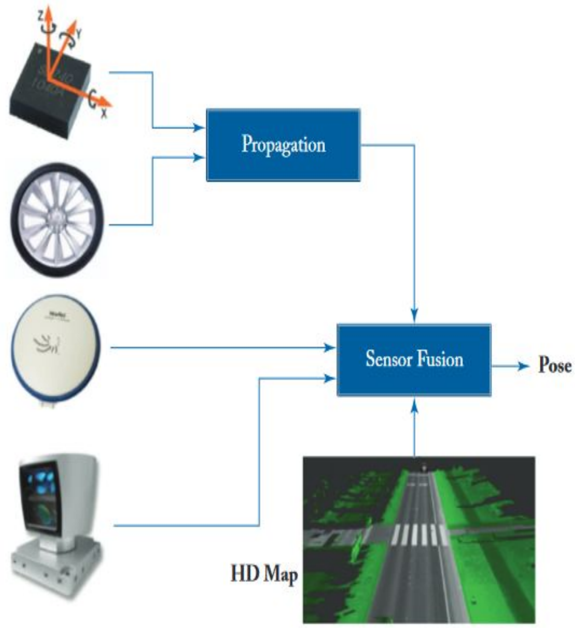

Figure 1.4: Sensor-fusion localization pipeline.

Wheel Encoder:

- Measures wheel rotations to calculate the vehicle's traveled distance.
- Useful for odometry but can also suffer from errors like wheel slip.

GNSS (Global Navigation Satellite System):

- Provides global position data (latitude, longitude, altitude).
- Accurate but may face challenges in urban areas (e.g., signal blockage or multipath reflections).

OBJECT RECOGNITION AND TRACKING

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Role of Deep Learning in Object detection and Tracking

- **Convolutional Neural Networks (CNN)**
  - **Convolution Layer**: Extracts features using learnable filters.
  - **Activation Layer**: Activates target neurons.
  - **Pooling Layer**: Reduces spatial size and computational requirements.
  - **Fully Connected Layer**: Links neurons to prior layers' activations.
- **Deep learning surpasses traditional vision methods in accuracy and robustness.**

Object Tracking Technology

- Tracks **object trajectories** (e.g., vehicles, pedestrians).

Deep Learning Advances

- Uses **stacked Auto-Encoders** to learn robust features.

Applications

- Enhancing safety by avoiding collisions with **moving vehicles** and **pedestrians**.

OBJECT RECOGNITION AND TRACKING

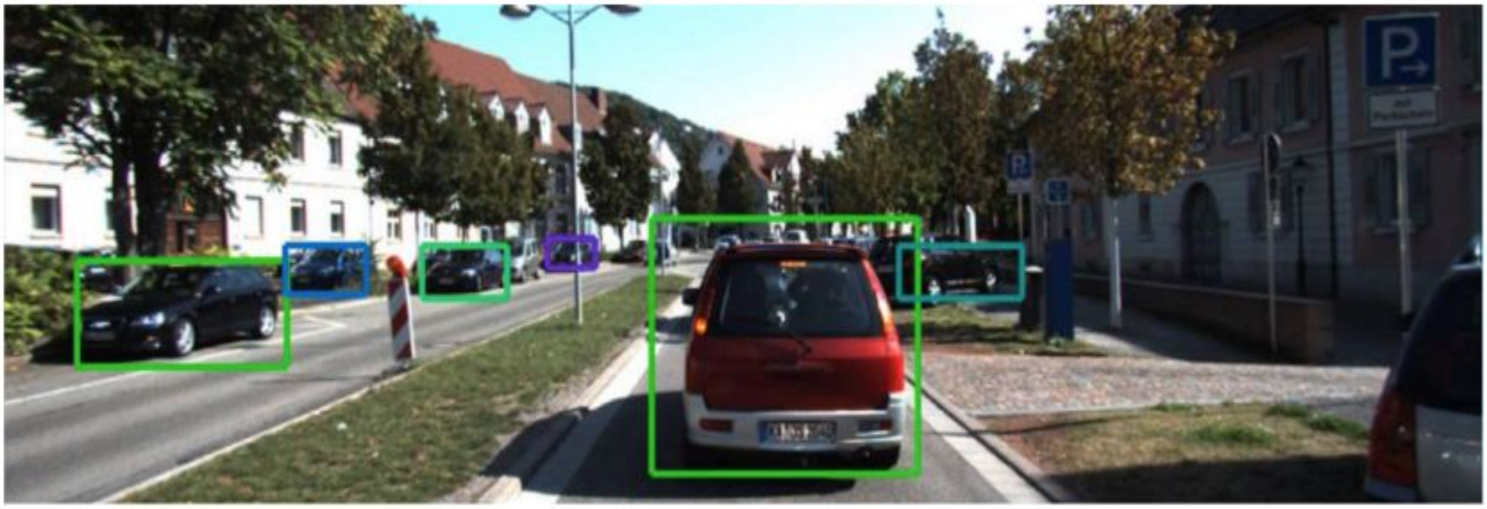

Figure 1.5: Object recognition and tracking [34], used with permission.

ACTION

Challenges for Human Drivers

- Navigating unpredictable actions of other drivers.
- **Complex scenarios** like multi-lane roads or traffic change points.

Role of Decision Units in Autonomous Vehicles

- **Action Prediction**
  - Generates predictions of nearby vehicles' behaviors.
- **Action Planning**
  - Develops a safe strategy based on predicted actions.

Stochastic Modeling for Prediction

- Creates **reachable position sets** for other vehicles.
- Associates **probability distributions** with these reachable sets.

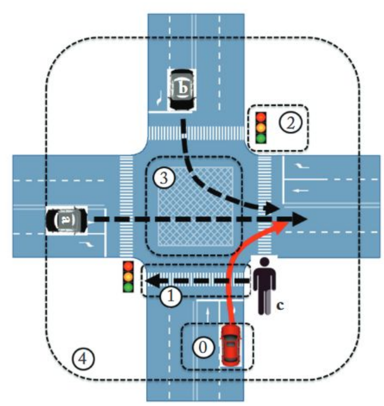

Figure 1.6: Action prediction.

Objective

Ensure safe travel by accurately predicting and responding to surrounding traffic dynamics.

Path Planning and Obstacle Avoidance in Autonomous Vehicles

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Path Planning

- **Challenge**:
  - Planning agile vehicle paths in dynamic environments is highly complex.
  - Brute force methods require excessive computation and fail to provide real-time solutions.

- **Solution:**
  - Utilize **probabilistic planners** for efficient and real-time path planning.

Obstacle Avoidance

Safety Mechanisms:

- **Proactive Mechanism**:
  - Uses traffic predictions to calculate metrics like **time to collision** and **minimum distance**.
  - Performs **local path re-planning** to avoid obstacles.

- **Reactive Mechanism:** Activates when proactive measures fail. Relies on **radar data** to detect obstacles and override controls for immediate avoidance.

Objective:

Ensure collision-free navigation using advanced predictive and reactive strategies.

AUTONOMOUS DRIVING CLIENT SYSTEM

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Challenges in Integrating Autonomous Driving Systems

- **System Integration Goals:**
  - Combine algorithms to ensure **real-time performance** and **high reliability**.

- **Key Challenges:**

  1.Processing Speed:
  - Handle the vast amount of sensor data within a fast processing pipeline.

  2.System Robustness:
  - Recover seamlessly from potential system failures.

  3.Energy and Resource Efficiency:
  - Operate under strict energy and resource constraints.

ROBOT OPERATING SYSTEM (ROS)

- A **distributed computing framework** designed for robotics applications.

Key Features:

- Tasks (e.g., localization) hosted in **ROS nodes**. Communication via **topics** and **services**.

- **Challenges with ROS:**

  1.Reliability:
  - Single master with no recovery for failed nodes.

  2.Performance:
  - Duplicate messages during broadcasts cause degradation.

  3.Security:
  - Lacks authentication and encryption mechanisms.

- **ROS 2.0:**
  - Promises to address these challenges but is **not fully tested** and lacks complete features.

- **Action Plan:**
  - Resolve **reliability, performance, and security issues** for effective use in autonomous driving.

AUTONOMOUS DRIVING CLIENT SYSTEM

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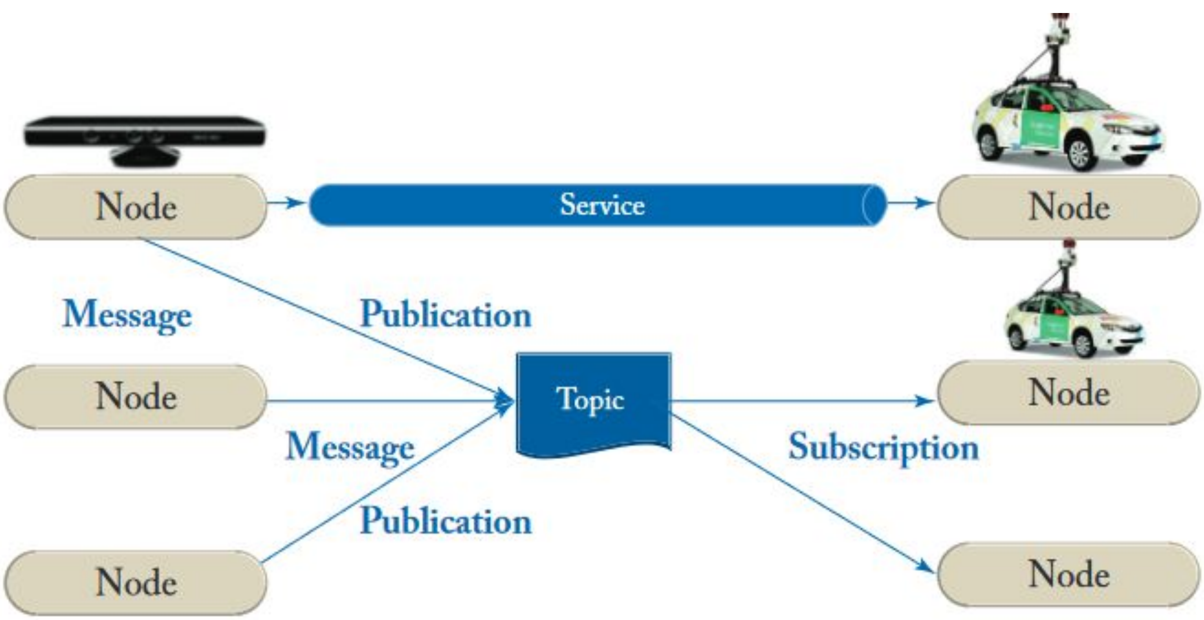

Figure 1.7: Robot operating system (ROS).

Enhancing ROS Reliability with ZooKeeper Mechanism

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Problem in Current ROS Implementation:

Single Master Node:
- If the master node crashes, the entire system fails, thus not meeting **safety requirements** for autonomous driving.

Proposed Solution:

•Implement a **Zookeeper-like mechanism** to enhance reliability:
- **Main Master and Backup Master Nodes**:
  - The **Backup Master** takes over if the **Main Master** fails.
  - Ensures continuous system operation without interruptions.
- **Node Monitoring and Recovery**:
  - Detects and **restarts failed nodes** automatically.
  - Improves system robustness and reliability.

Enhancing ROS Reliability with ZooKeeper Mechanism

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ZooKeeper Local Cluster: Acts as a coordination service and Ensures high availability and fault tolerance through **leader election**.

Master and Follower: Nodes in the ZooKeeper cluster participate in **leader election** to choose a master. The **Master** coordinates tasks, while the **Follower** serves as backup or secondary nodes.

Node Publisher: Responsible for **publishing topics** (data streams or messages). Examples: sensor data or localization updates.

Node Subscriber: Subscribes to the topics published by the **Node Publisher** to receive and process data. Examples: path planning or obstacle avoidance modules.

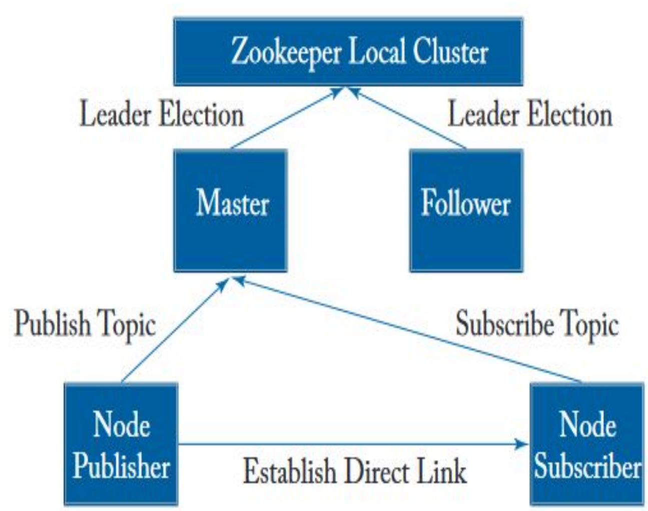

Figure 1.8: Zookeeper for ROS.

Enhancing ROS Reliability with ZooKeeper Mechanism

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Performance:

- **ROS node broadcasts a message, the message gets copied multiple times, consuming significant bandwidth in the system**

- **Sol: Switching to multicast**

Security:

- **kidnapping of other node – draining its battery – making whole system down**
- **Eavesdropping as msgs are not encrypted.**

Autonomous driving cloud platform

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• Two main functions:

- Distributed computing – Spark, OpenCL for heterogeneous computing, and Alluxio for in-memory storage.
- Distributed storage

Simulation:

- Development of new algorithms for autonomous systems, testing is essential before deploying them in real-world scenarios, such as on cars.
- Testing directly on vehicles is costly and time-consuming, so simulations are used instead.

- To address challenges like long testing durations and insufficient test coverage on a single machine, a **distributed simulation platform** has to be developed..

- The platform leverages **Apache Spark** to manage distributed computing nodes, with each node running a **ROS (Robot Operating System) replay instance** to simulate data.

Autonomous driving cloud platform

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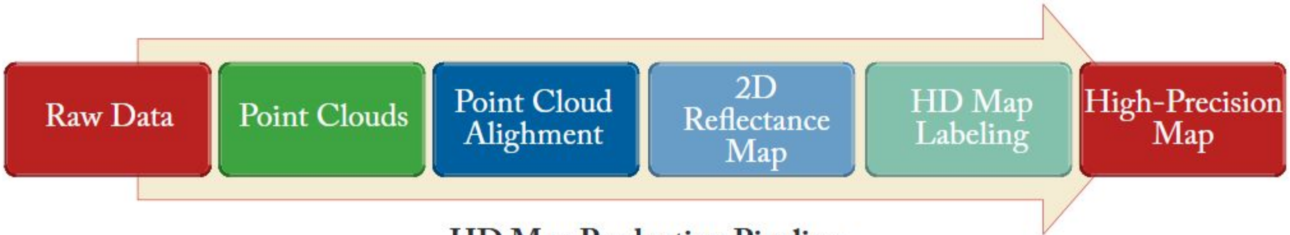
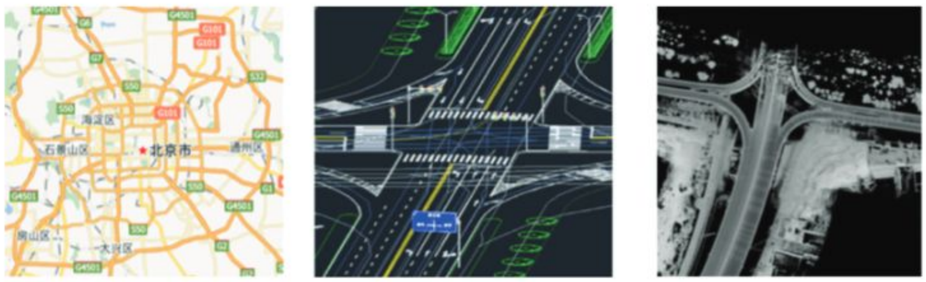
•HD Map Production Pipeline: Creates high-precision maps essential for applications like autonomous driving



HD Map Production Pipeline



Course Contents – Unit - I

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Autonomous Vehicle Localization:

- Localization with GNSS
- Localization with LiDAR and High-Definition Maps
- Visual Odometry
- Dead Reckoning and Wheel Odometry
- Sensor Fusion

Autonomous Vehicle Localization

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Localization with GNSS

1. Global Navigation Satellite Systems (GNSS):

- GPS (Global Positioning System)
- GLONASS (Russia)
- Galileo (Europe)
- BeiDou (China)
- Indian Regional Navigation Satellite System (IRNSS) Due to Kargil in 1999, US denied access to India. So decided to develop and finished by 2006.

2. GPS Overview:

- Signals: Provides coded satellite signals processed by receivers to estimate position, velocity, and time.
- Satellite Constellation: 7 satellites - 4, 29° inclination. Covers 1500 kms
  - ~36,000 km altitude, ~23 hrs 56 mins and 4 secs - orbital period.

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Localization with GNSS

3. GNSS Reference Systems:
   - Space-Fixed Inertial System: Describes satellite motion.
   - Earth-Fixed Terrestrial System: For observer positions.

4. Benefits of Multi-Constellation GNSS:
   - Increased Availability: Better performance in obstructed areas.
   - Higher Accuracy: More satellites = improved precision.
   - Enhanced Robustness: Harder to spoof signals.

Autonomous Vehicle Localization

GNSS Error Analysis

Ideally, GNSS provides perfect localization, but errors can arise due to several factors:

1. **Satellite Clocks:**
   - Atomic clock inaccuracies can cause significant errors.
   - Example: 10 ns clock error = ~3 m position error.

2. **Orbit Errors:**
   - Orbits are precise but subject to minor variations.
   - Even with corrections, errors can reach up to ±2.5 m.

3. **Ionospheric Delay:**
   - Caused by electrically charged particles in the ionosphere.
   - Typical error: ±5 m, varying by solar activity, time, and location.

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GNSS Error Analysis

4. **Tropospheric Delay:**
   - Caused by humidity, temperature, and atmospheric pressure.
   - Real Time Kinematics GNSS compensates for this within local areas.

5. **Multipath:**
   - Reflected signals (e.g., off buildings) delay signal reception.
   - Results in incorrect position calculations.

Contributing Source	Error Range
Satellite Clocks	±2 m
Orbit Errors	±2.5 m
Inospheric Delays	±5 m
Tropospheric Delays	±0.5 m
Receiver Noise	±0.3 m
Multipath	±1 m

GNSS system errors (based on [3]).

Satellite-Based Augmentation Systems (SBAS) complement GNSS to enhance accuracy, integrity, continuity, and availability:

1. **How SBAS Works:**
   - GNSS errors are measured by accurately located reference stations across a continent.
   - Corrections and integrity messages are computed and broadcast via geostationary satellites.
   - Covers vast areas with augmented GNSS messages.

2. **Regional SBAS Implementations:**
   - **Europe:** European Geostationary Navigation Overlay Service (EGNOS).
   - **U.S.:** Wide Area Augmentation System (WAAS).
   - **China:** BeiDou System (BDS).
   - **Japan:** Multi-functional Satellite Augmentation System (MSAS).
   - **India:** GPS and GEO Augmented Navigation (GAGAN).
   - All systems comply with global standards, ensuring compatibility and interoperability.

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REAL-TIME KINEMATIC AND DIFFERENTIAL GPS

3. **SBAS Performance:**
   - Most commercial GNSS receivers support SBAS.
   - Example: WAAS provides position accuracy better than 1.0 m laterally and 1.5 m vertically throughout most of the U.S.

Autonomous Vehicle Localization

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Understanding RTK and Differential GNSS

- Most GNSS systems provide 2-meter accuracy, insufficient for autonomous vehicles. (as 2m is sufficient for human drivers – to find where road is, and lane is)
- Real-Time Kinematic (RTK) GNSS and Differential GNSS achieve decimeter-level accuracy.
- A base station calculates GNSS errors and sends corrections to the vehicle.
- RTK uses carrier-based ranging, which is more precise than code-based positioning.
- Accuracy depends on the base station location, satellite observations, and receiver quality.
- Base station with a known position identifies GNSS errors (clock, orbit, atmospheric).
- Errors are communicated to the vehicle for real-time corrections.
- Carrier-based ranging calculates precise positions by determining carrier cycles.

- RTK achieves sub-meter accuracy by addressing differential corrections and ambiguity resolution.

Autonomous Vehicle Localization

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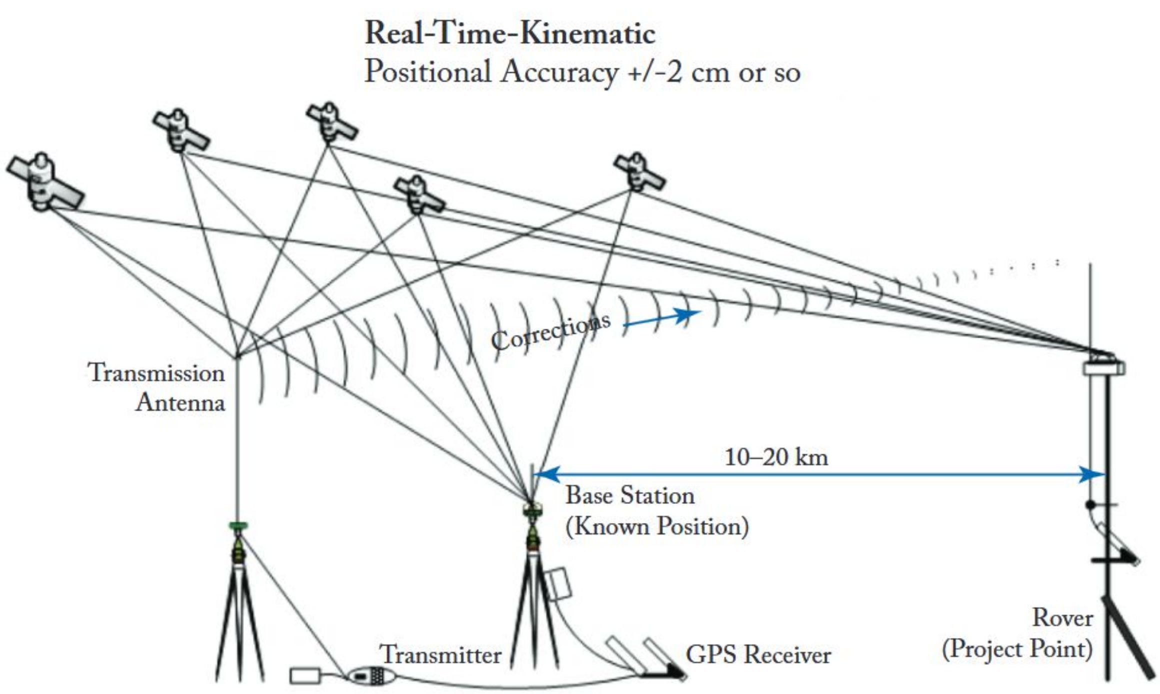
Understanding RTK and Differential GNSS



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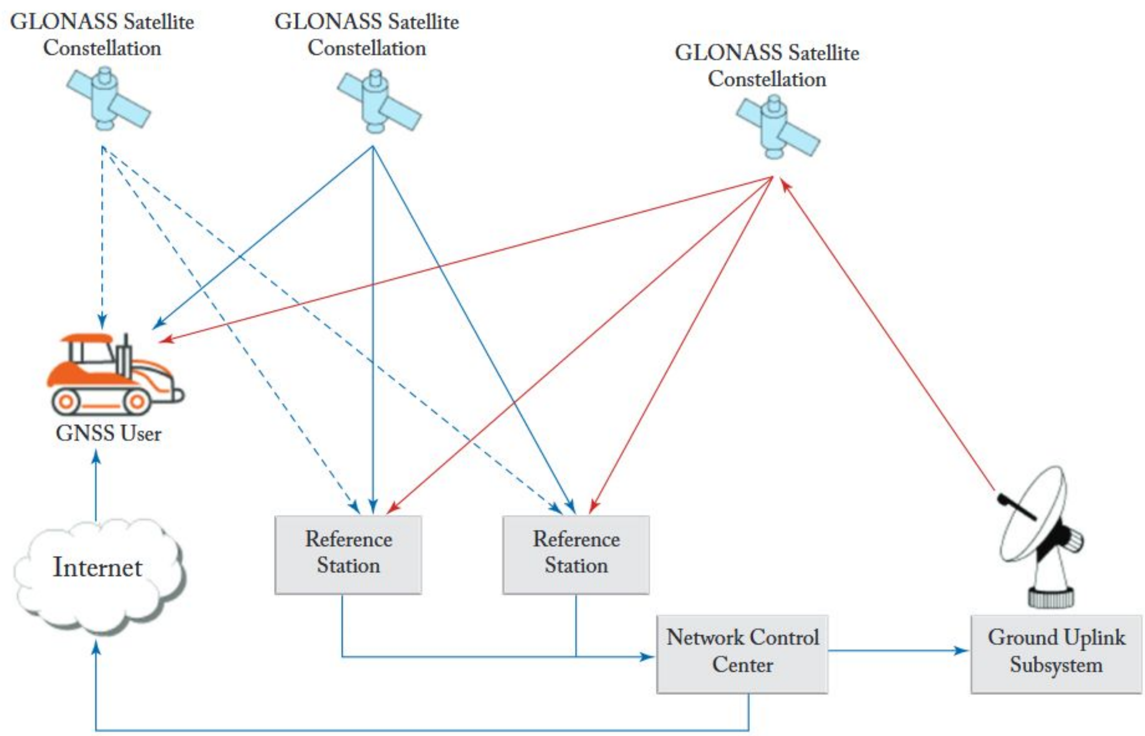
Precise Point Positioning



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Precise Point Positioning

- Provides high-accuracy positioning using corrections from global reference stations.
- Eliminates the need for expensive local base stations required by RTK GNSS.
- Achieves decimeter-to-centimeter level accuracy for various applications.

How PPP works

- Reference stations calculate satellite orbit and clock corrections in real-time.
- Corrections are delivered to users via satellite or internet.
- Dual-frequency GNSS receivers eliminate ionospheric delays.
- Tropospheric delays are corrected using the UNB model.
- Extended Kalman Filter (EKF) processes data for precise positioning.

Advantages of PPP GNSS

- Provides **absolute positioning** (global reference frame) rather than relative positioning.
- Requires **only one GNSS receiver**—no nearby reference station needed.
- Achieves centimeter-level accuracy, exceeding the meter-level accuracy of SBAS.

Comparison with RTK GNSS

- **RTK**: Requires local base stations for corrections; provides relative positioning.
- **PPP**: Eliminates local base station needs; absolute positioning with global consistency.
- RTK has faster initialization but limited by base station range (~20 km).
- PPP has slower convergence time (~30 min) but is global in scope.

Challenges with PPP

- **Slow Convergence**: Requires ~30 minutes to achieve decimeter accuracy.
- **Local Biases**: Affected by atmospheric conditions, multipath, and satellite geometry.
- Real-time PPP systems are still in early development stages.

Autonomous Vehicle Localization

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Localization with LiDAR and High-Definition Maps

Types of LiDAR Detection Methods

•**Categories:**

- **Incoherent Detection:** Direct energy detection, spreads in all directions.

- **Coherent Detection:** Optical heterodyne detection for Doppler or phase-sensitive measurements. (generates energy near or at optical spectrum - low power consumption)

Pulse Models

•**Types:**

- **High-Energy Systems:** Used in atmospheric research; potentially harmful to eyes.

- **Micro-Pulse Systems:** Eye-safe, used in autonomous driving and other safe applications.

Autonomous Vehicle Localization

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Localization with LiDAR and High-Definition Maps

Laser Wavelengths

- **Key Wavelengths and Applications:**
  - **600–1000 nm:** Commonly used, category one safety.
  - **1,550 nm:** Military and long-range uses.
  - **1,064 nm & 532 nm:** Airborne and Bathymetric systems.

Components of a LiDAR System

- **Main Components:**
  - **Laser Scanners:** Various scanning methods affect range and resolution.
  - **Laser Receivers:** Silicon avalanche photodiodes and photomultipliers.

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Velodyne HDL-64 LiDAR - used in autonomous vehicles. It utilizes 64 LiDAR channels aligned from +2.0° to -24.9° for a vertical field of view of 26.9° and delivers a real-time 360° horizontal field of view with its rotating head design. The rotation rate is user-selectable from 5–20 Hz to tells the user with how many data points generated by the LiDAR sensor.

It generates laser with 905 nm wavelength and 5 ns pulse, which captures a point cloud of up to 2,200,000 points/s with a range of up to 120 m and a typical accuracy of ±2 cm. The upper part of the device consists of the laser emitters (4 groups of 16 each), and the lower part of the device consists of laser receivers (2 groups of 32 each).

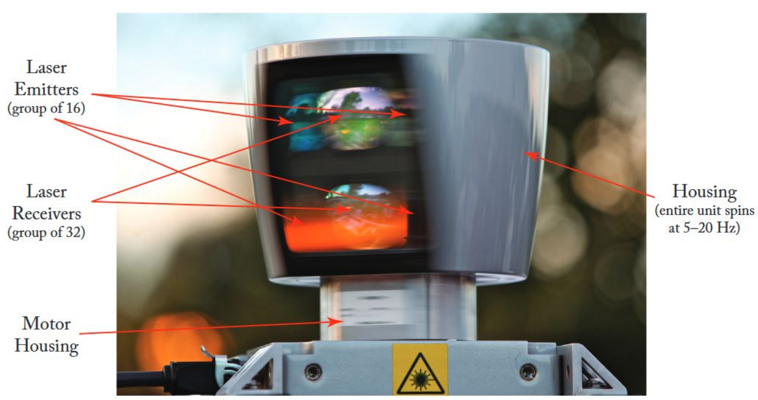

Figure 2.5: Velodyne HDL-64 LiDAR [45].

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Localization with LiDAR and High-Definition Maps

In practice, one major problem faced by LiDAR manufacturers as well as users is calibration

The calibration process is an optimization process that involves many parameters: **Calibration Challenges**

- **Importance:** Calibration ensures precision in 3D data processing.
- **Steps in Calibration:**
  - **Parameterization:** Define 5–7 parameters per laser beam.
  - **Objective Function:** Quantify differences between acquired data and ground truth.
  - **Data Segmentation:** Extract data corresponding to the calibration object

Autonomous Vehicle Localization

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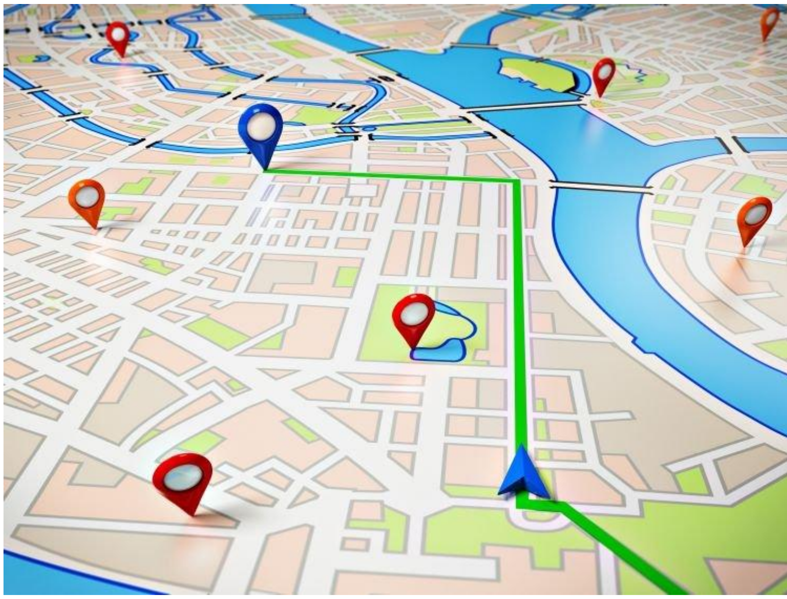
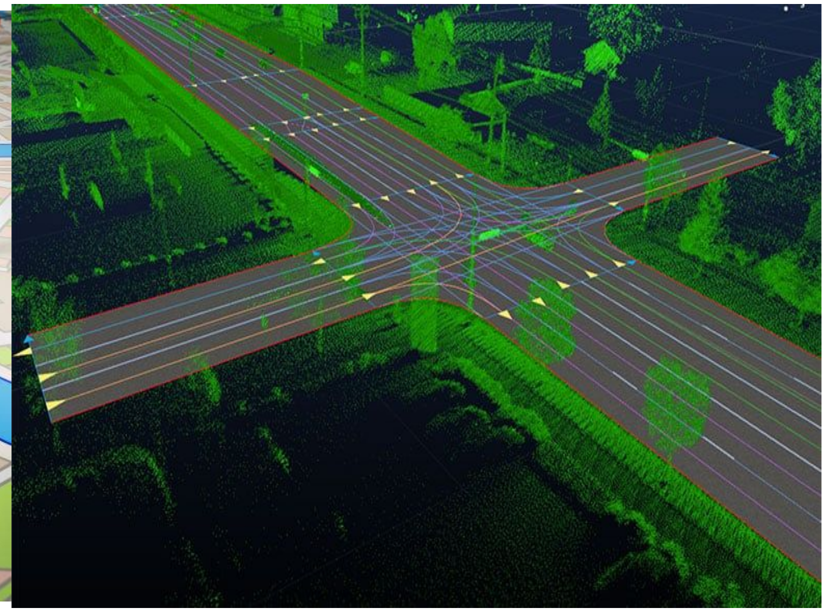
The Making of HD Maps for Autonomous Driving

- **Why HD Maps?**
  - Provides familiarity to autonomous vehicles, similar to mental maps for humans.
  - Enables anticipation of changes in the driving environment (e.g., blocked signs, potholes).
- **Why not Digital Maps?**
  - Low resolution (meter-level precision).
  - Not updated frequently. Suitable for human navigation.
  - Insufficient for real-time localization and lane-specific navigation
  - Focuses on user-friendly data like road names, traffic conditions, and distances.

Difference between Digital Map and HD Map





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Challenges in HD Map Making

- **Key Challenges:**
  - **Precision:** Centimeter-level accuracy required.
  - **Freshness:** Weekly updates needed for real-time changes.
  - **Performance:** Seamless integration with autonomous driving systems.
- **Solutions:**
  - LiDAR and sensor fusion for data capture.
  - Crowd-sourcing vs. survey fleets for updates.
  - High-performance cloud infrastructure.

Autonomous Vehicle Localization

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HD Map Construction Process

•**Core Idea:** Augment GNSS/INS navigation with detailed LiDAR-based maps.

•**Steps:**

- GNSS/INS provides rough location data – with timestamped and synchronized data.
- LiDAR Point clouds are converted into 3D models of the environment, including road surfaces, curbs, and infrastructure.
- Sensor fusion minimizes errors in grid cells.

Anatomy of HD Maps

•**Data Structure:** Hierarchical with a 5x5 cm resolution foundation layer.

- **Foundation Layer:** Infrared reflectivity data for identifying road surfaces and obstacles.
- **Usage:** Real-time comparison of vehicle LiDAR scans against stored grid cell data.

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HD Map Construction Process

Data Acquisition

•**Infrared Reflectivity Mapping:**

- LiDAR sensors mounted on vehicles capture road surface reflectivity.
- Vertical objects are discarded to focus on flat ground.
- Independent of ambient lighting conditions (e.g., night driving).

Example

- Imagine a car driving past a row of trees on the roadside. LiDAR can isolate the road surface while "removing" the tree data points, whereas a camera would struggle to differentiate between the tree shadows and the road.

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HD Map Construction Process

Addressing Non-Stationary Objects

•**Challenge:** Non-stationary objects (e.g., vehicles, pedestrians, bicycles, or animals.) affect mapping accuracy.

•**Solution:** Fit a ground plane to each laser scan and retain only coincident measurements.

•**Benefit:** Ensures only stationary ground data is used for mapping.

Real-Time Localization

•**Process:**

- Autonomous vehicles compare current LiDAR scans to HD map reflectance data.
- Achieves centimeter-level precision for safe navigation.

•**Key Advantage:** Works effectively in varying lighting conditions.

Example:

•Imagine an autonomous car mapping a street while a truck is moving in front of a building. If the system doesn't correctly account for the moving truck, it might add it to the map as a permanent obstacle, leading to confusion during navigation.

Autonomous Vehicle Localization

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Generate a large-scale HD map from LiDAR scans.

•**Key Challenge**: Stitching local LiDAR scans into a global map using **map matching**.

•**Applications**: Autonomous vehicles require HD maps for accurate navigation, lane detection, and traffic signal interpretation.

Local and Global Maps

•**Local Map**: Each LiDAR scan represents a snapshot of the environment.

•**Global Map**: Created by stitching multiple local maps.

•**Map Matching**:

- Identifies overlapping regions between local scans.
- Uses overlaps as anchors to align and stitch maps together.

Autonomous Vehicle Localization

Generate a large-scale HD map from LiDAR scans.

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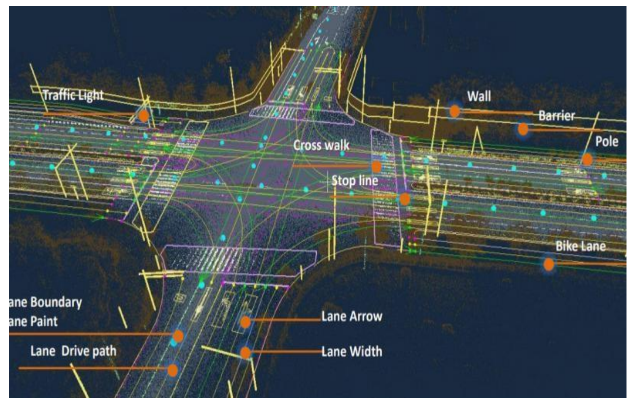
Map Matching Process

- **Input**:
  - Two disjoint sequences of time indices: “a1, a2, …” and “b1, b2, …”.
  - Overlap threshold **T**.

- **Steps**:
  - Compare infrared reflectivity maps of overlapping regions.
  - Compute a linear correlation field for different x-y offsets.
  - Identify a single peak in the correlation field for optimal alignment.

- **Pose Information**: <x, y, θ>, where:
  - x, y: Precise Vehicle’s location when sensor scan is taken.
  - θ: Vehicle’s heading direction.

- **Usage**:
  - Bounds errors during map matching.
  - Improves correlation coefficient calculations.



Autonomous Vehicle Localization

Generate a large-scale HD map from LiDAR scans.

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HD Map Layers

- **Foundation Layer**:
  - Basic road structure from LiDAR data.

- **Semantic Layers**:
  - **Road Markings**:
    - Locations and characteristics of lane markings.
    - Lane safety identification.
  - **Road Signs and Traffic Signals**:
    - Input to **Perception Stage**: Prepares the car to detect signs and speed limits.
    - Input to **Planning Stage**: Allows safe travel even without sensor detection.

Autonomous Vehicle Localization

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Generate a large-scale HD map from LiDAR scans.

Challenges in HD Maps: Storage Requirements

- **High Storage Needs**:
  - 5-cm resolution maps occupy significant memory.
  - Example: 1 TB can hold data for ~100,000 miles.

- **Methods to Optimize Storage**:
  - **Filter Irrelevant Data**:
    - Use a square grid to store data only in populated areas.
    - ~10 MB per mile at 5-cm resolution.

  - **Dynamic Memory Loading**:
    - Preload only the local HD map needed.
    - GNSS/INS data helps dynamically load relevant portions.

Autonomous Vehicle Localization

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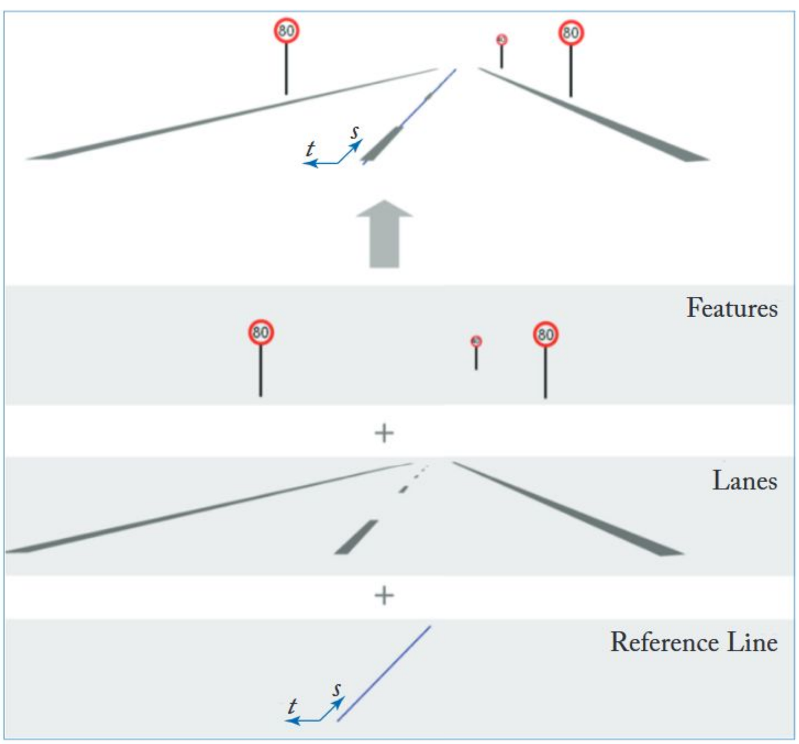
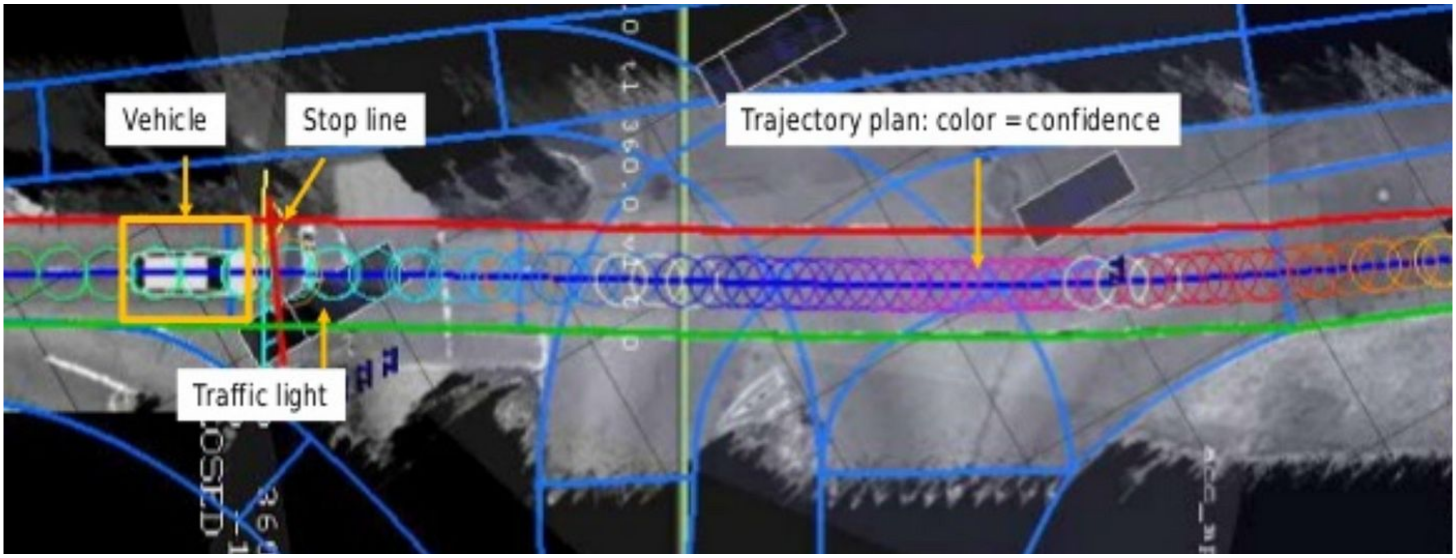


Semantic Layers of HD Maps



Introduction to Vehicle Localization

- **Definition:** Localization is the process of determining a vehicle's position and orientation on an HD map in real-time.

- **Importance:**
  - Enables precise navigation and safety in autonomous systems.
  - Essential for lane-accurate driving and obstacle avoidance.

Particle Filters vs. Kalman Filters

- **Key Concepts:**
  - **Kalman Filter:** Works for linear Gaussian systems; fails in non-linear and non-Gaussian scenarios.
  - **Particle Filter:** Handles non-linear and non-Gaussian models using simulation and importance sampling.

- **Comparison:**
  - Kalman filters are computationally efficient but limited.
  - Particle filters discretize possible states for more complex scenarios.

Autonomous Vehicle Localization

LOCALIZATION WITH LIDAR AND HD MAP

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Particle Filter Localization

•Process Overview:

- Generate particles representing potential vehicle states.
- Predict particle movements based on velocity and inertial data.
- Update particle weights using LiDAR scans and HD map correlation.
- Resample particles based on weights for convergence.

Problems in Basic Localization Approach

•Issues Identified:

- Binary matching of LiDAR scans often leads to high error rates.
- High cost of 3D LiDAR sensors limits commercial viability.
- Adverse weather conditions impact LiDAR reflectivity.

Autonomous Vehicle Localization

LOCALIZATION WITH LIDAR AND HD MAP

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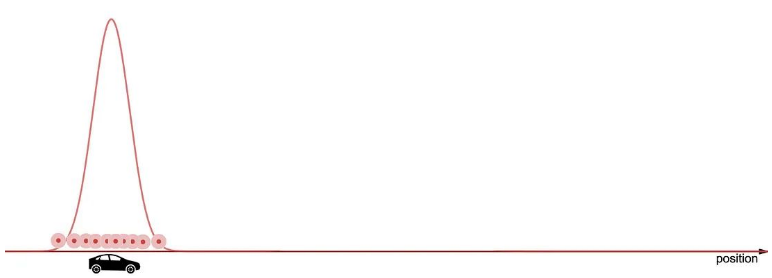
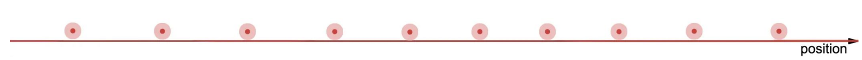


If GPS is not available, we can distribute the particles uniformly.
This is the same saying we do not know where the car is.



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LOCALIZATION WITH LIDAR AND HD MAP

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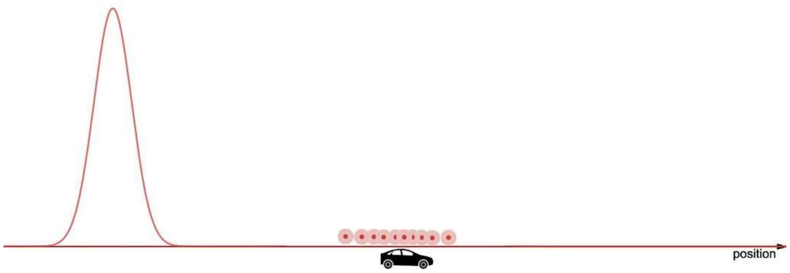
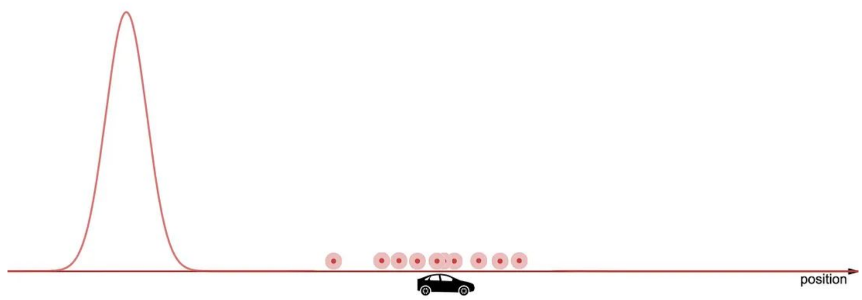
For each particle, we apply a dynamic model (like $x' = x + v\,\delta t$) to calculate the next position at time $t + \delta t$.



To simulate the **process noise** caused by factors like weather and the road conditions, we add independent random noise to each particle's location.



Autonomous Vehicle Localization

LOCALIZATION WITH LIDAR AND HD MAP

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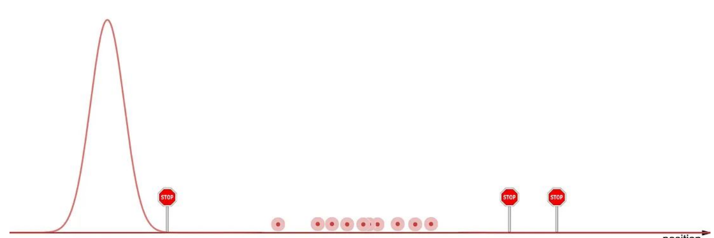
With a pre-determined map, we find all the surrounding landmarks.

But we remove all landmarks that are considered out-of-sight from our sensors (the left-most stop sign).

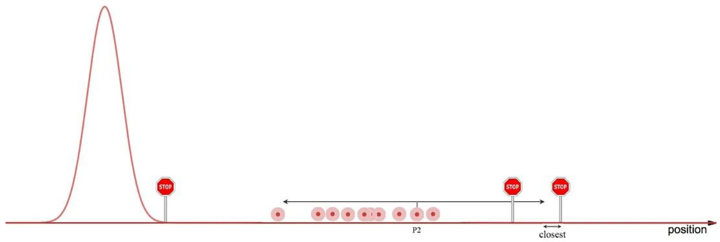


Each particle represents the suggested location of the car. We want to compute the likeliness using measurements from our sensors (like camera and LiDAR). Each reading contains a distance and an orientation from a landmark.

Autonomous Vehicle Localization

LOCALIZATION WITH LIDAR AND HD MAP

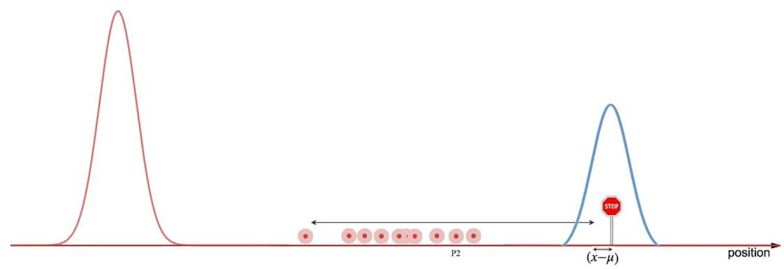
For example, in P2, we pick the right-most stop sign using our first sensor reading.



- We repeat the calculation (PDF) for every new measurement we received.
- Then the final likelihood for a particle is computed by multiplying all the corresponding PDFs together.
- We repeat the process for every particle. Then we normalize their probabilities such that the total probability is equal to one.
- This acts as the weight of our particles. The particle with the largest weight is where we estimate our car is.

We assume the measurement noise is Gaussian distributed, so the probability for P2 representing our current car location is:

$$PDF = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}$$



Autonomous Vehicle Localization

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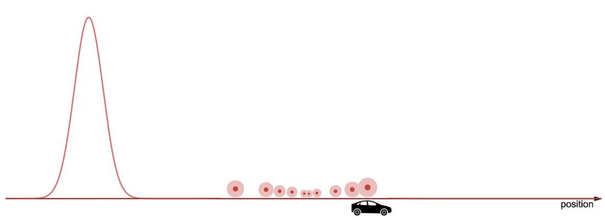
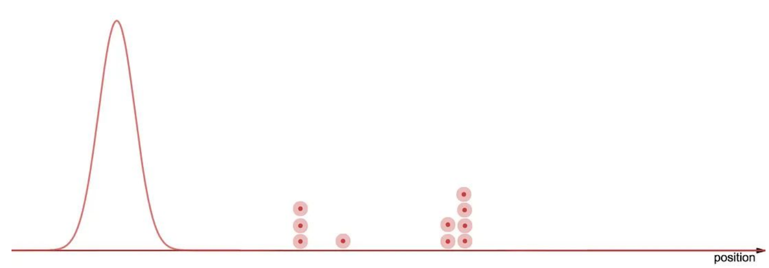
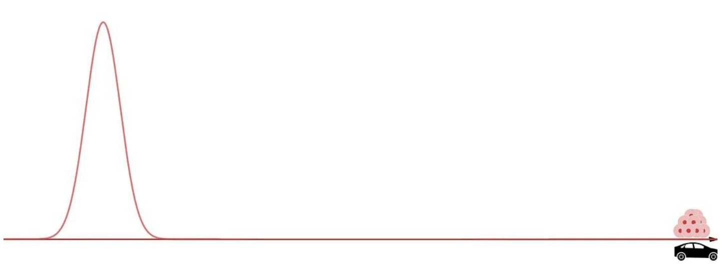
LOCALIZATION WITH LIDAR AND HD MAP



We resample another 10 particles based on the weights. For example, P2 will double the chance of being picked if it has twice the weight of P1. In our cases, we have 2 clusters of locations. This indicates our measurements show 2 possible locations for our car. This kind of ambiguity can be reduced by increasing the number of landmarks in the map or reduce the time (δt) between predictions.





Autonomous Vehicle Localization

LOCALIZATION WITH LIDAR AND HD MAP

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Handling Adverse Weather Conditions

- **Challenge:** Reflectivity issues in rain, snow, and mud.
- **Solution:** Use 3D structure (z-height) for scan matching.
- **Technique:** Gaussian mixture models for z-height distributions.
- **Visual:** Multi-resolution lookup table for weather-resistant localization.

Autonomous Vehicle Localization

VISUAL ODOMETRY

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- Visual Odometry is the process of estimating the egomotion of a vehicle using one or more cameras.
- **Key Task:** Compute relative transformations (Tx) from consecutive images (Ix, Ix-1) and use them to recover the vehicle's trajectory (V0:n).
- **Relative Transformations (Tx):** Estimate vehicle motion between two consecutive frames.
- In essence, localization is about knowing where you are, while ego motion is about understanding how you got there and how you are moving through the environment.

Autonomous Vehicle Localization

VISUAL ODOMETRY Pipeline

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1.Feature Extraction:

1. Identify key points in the current image (Ix).

2.Feature Matching:

1. Match key points between Ix and previous frames (Ix-1).

3.Motion Estimation:

1. Compute relative motion Tx between consecutive frames.

4.Trajectory Computation:

1. Concatenate Tx with previous poses to compute Vx.

5.Bundle Adjustment: Refine local trajectory for higher accuracy.

Autonomous Vehicle Localization

VISUAL ODOMETRY Pipeline

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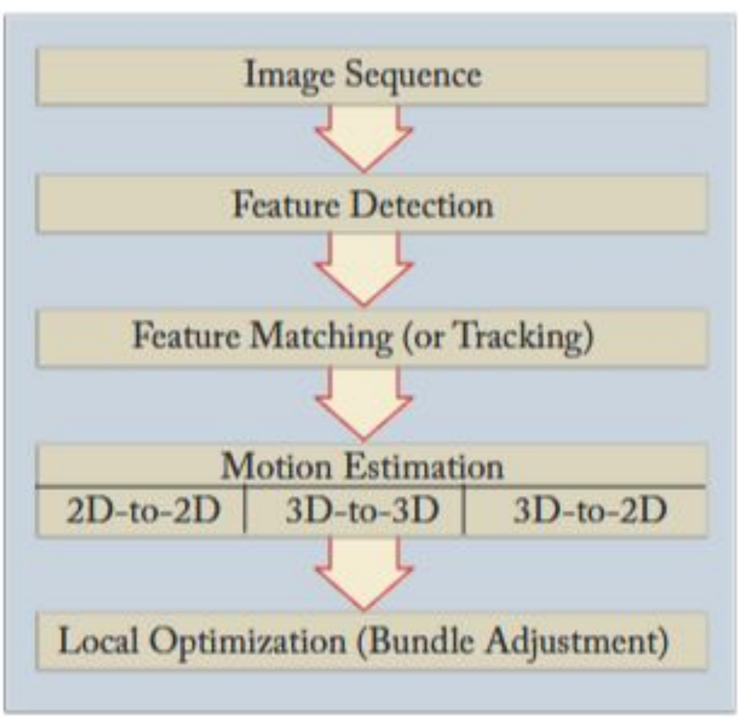

Motion Estimation Methods

- **Core Step in VO:** Compute vehicle motion from the current and previous images.

- **Methods:**
  - **2D-to-2D:**
    - Both fx-1 and fx specified in 2D image coordinates.
  - **3D-to-3D:**
    - fx-1 and fx specified in 3D after triangulation.
  - **3D-to-2D:**
    - fx-1 in 3D and fx as their 2D reprojections on Ix.

- **Monocular Case:** 3D structure triangulated from two adjacent frames (Ix-2, Ix-1) and matched with Ix.

Autonomous Vehicle Localization

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Motion Estimation & Trajectory Recovery

- **Process:** Combine all incremental motions (Tx) to recover the full trajectory of the vehicle.

- **Goal:** Accurate localization and mapping for autonomous navigation.

Benefits of Visual Odometry

- No reliance on external signals like GPS.

- Works in GPS-denied environments (e.g., tunnels, urban canyons).

- High precision in motion estimation and trajectory computation.

Autonomous Vehicle Localization

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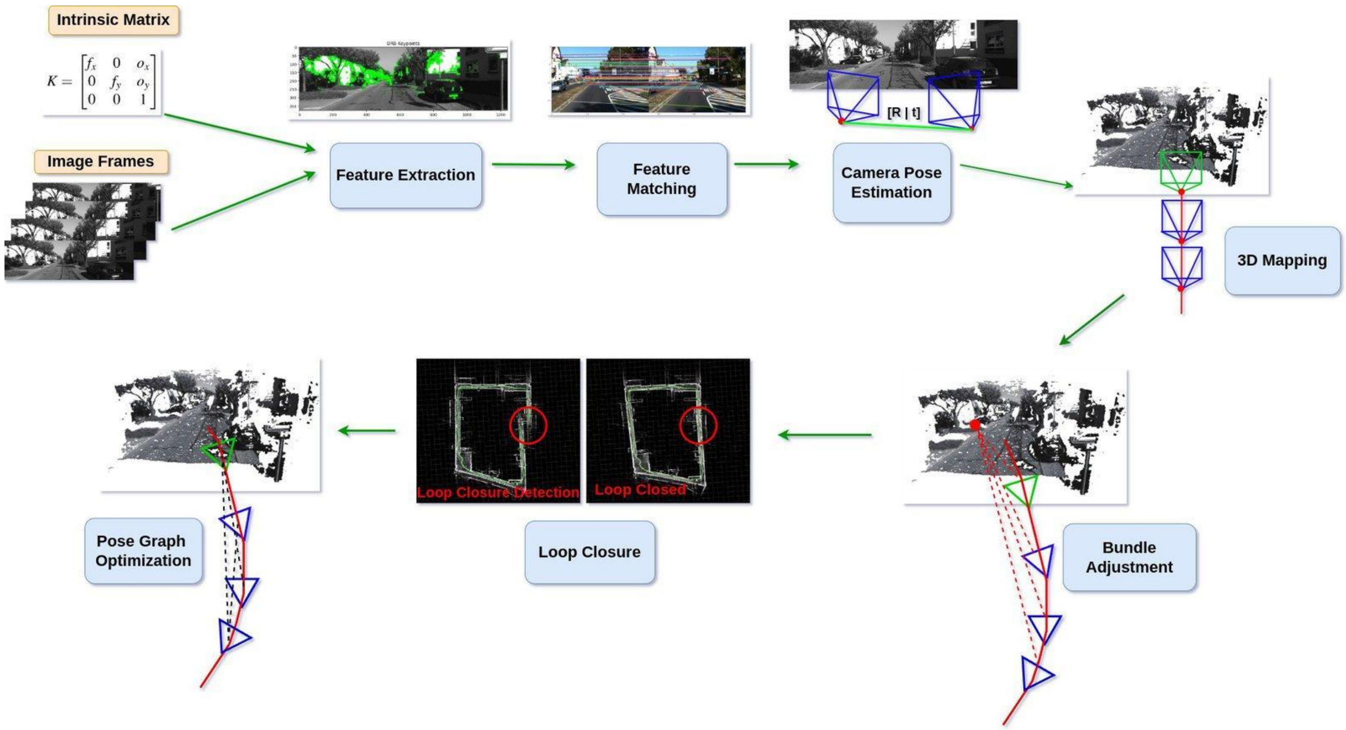
VISUAL ODOMETRY Pipeline



Autonomous Vehicle Localization

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Challenges in VO

- Sensitive to:
  - Camera calibration errors.
  - Environmental conditions (e.g., lighting, occlusions).
  - Dynamic objects in the scene.
- Computationally intensive.
- **Summary:** Visual Odometry is a powerful tool for estimating vehicle motion using camera inputs, enabling accurate trajectory recovery without external signals.

Key Concepts in Stereo Visual Odometry

- **Egomotion Estimation:** Calculate the motion of the vehicle between consecutive stereo frames.

- **Trajectory Recovery:** Incrementally compute the full trajectory by combining transformations (Tx).

- **Depth Perception:** Stereo cameras directly measure the disparity between image pairs to compute depth.

Autonomous Vehicle Localization
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Introduction to Monocular Visual Odometry

- **Definition:** Monocular Visual Odometry (MVO) estimates the egomotion of a vehicle using input from a single camera.

- **Key Characteristics:**
  - Uses 2D image features to infer 3D motion.
  - Relies on triangulation from consecutive frames to estimate depth.

- **Limitations:**
  - Scale ambiguity without external references.
  - Requires assumptions or additional methods to recover absolute scale.

VISUAL INERTIAL ODOMETRY

- **Definition:** Visual-Inertial Odometry (VIO) estimates the motion of a vehicle by fusing data from a camera and an Inertial Measurement Unit (IMU).

- **Key Advantages:**
  - Combines visual and inertial data for robust motion estimation.
  - Provides real-time pose and trajectory information.
  - Provides robust motion estimation in:
    - Low-texture environments.
    - Fast-moving scenarios.

- **Monocular VO:**
  - Relies only on a single camera; scale ambiguity remains.
- **Stereo VO:**
  - Uses stereo images for depth but lacks high-frequency motion updates.
- **VIO:**
  - Combines vision with IMU for better accuracy and robustness.

DEAD RECKONING AND WHEEL ODOMETRY

- **Odometry:** Odometry refers to the process of estimating the change in position of a robot based on sensor data.

- **Optical Encoders:** Optical encoders measure the angular position and velocity of the wheels.

- **Types of Wheel Encoders:**

- **Optical Encoders:** Detect motion via light interruptions.

- **Doppler Encoders:** Utilize the Doppler effect for velocity measurement.

- **Applications:** Used in mobile robots for accurate movement tracking.

DEAD RECKONING AND WHEEL ODOMETRY

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Wheel Encoder Mechanisms

- **Differential Drive:**
  - Two independently driven wheels for navigation.

- **Tricycle Drive:**
  - Single steering wheel, often with additional fixed wheels.

- **Omnidirectional Drive:**
  - Allows movement in any direction with multiple wheels.

- **Racked Vehicle:**
  - Utilizes tracks for better traction on uneven terrain.

Ackerman Steering (AS) Overview

•**Definition:** AS geometry ensures that wheels rotate at correct angles to avoid tire slippage.

•**Application:** Common in cars and some mobile robots for precise turns.

•**Key Feature:** The steering angles of the front wheels are calculated to ensure all wheels align tangentially to concentric arcs centered at the rotation point.

Ackerman Equation

•**Equation:** $\cot\theta_i = \cot\theta_o = \frac{d}{l}$

•**Terms:**

- θi: Steering angle of the inner wheel.
- θo: Steering angle of the outer wheel.
- d: Lateral wheel separation.
- l: Longitudinal wheel separation.

•**Explanation:** Ensures correct wheel alignment for accurate odometry and reduced tire wear.

DEAD RECKONING AND WHEEL ODOMETRY

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Advantages of Ackerman Steering

•**Benefits:**

- Reduces tire slippage and improves traction.
- Suitable for all-terrain vehicles.

•**Applications:**

- Preferred in outdoor autonomous systems.
- Typically involves a gasoline/diesel engine and a drivetrain with transmission, differential, and universal joints.

•Challenges in Wheel Encoder Odometry: **Issues:** Slippage on slippery or rough surfaces.
•Calibration needs for precise measurements.

•**Limitations:** Cannot overcome all environmental factors that impact movement.

Wheel Odometry: Principles and Challenges

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The Challenge of Error Accumulation:

- **Overview:** Continuous integration of motion leads to error accumulation, particularly in orientation.

- **Impact:** Errors increase proportionally with distance traveled.

- Accumulated orientation errors lead to significant position inaccuracies.

Data Fusion with Absolute Positioning

- **Integration:**
  - Odometry data can be fused with absolute position measurements.

- **Benefits:**
  - Provides more reliable position estimation.
  - Reduces the need for frequent updates with landmarks (e.g., visual odometry).

Wheel Odometry: Principles and Challenges

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Importance of Odometry in Navigation

- **Role:**
  - Used between absolute position updates with landmarks.

- **Application:**
  - Helps maintain position in environments where landmarks are sparse or non-existent.

- **Scenario:**
  - Odometry may be the only navigation information available when external references fail.

Limitations of Wheel Odometry

•Key Assumption:

- Wheel rotations translate to linear displacement relative to the ground.

•Example of Error:

- Wheel slippage (e.g., oil spill) causes encoder data to reflect motion not matching the actual displacement.

•Types of Errors:

- **Systematic Errors:** Consistent, predictable errors (e.g., wheel diameter differences, misalignment).

- **Non-Systematic Errors:** Random, unpredictable errors (e.g., wheel slippage, rough terrain).

Systematic Errors Explained

•Examples: Unequal wheel diameters.

- Encoder resolution and sampling rate limitations.
- Wheel misalignment.

•Impact:

- Accumulate over time, affecting odometry more than non-systematic errors on smooth surfaces.

Non-Systematic Errors Explained

•Examples: Travel over uneven surfaces.

- Sudden wheel slippage due to over-acceleration or external forces.

•Challenges:

- Can occur unexpectedly.
- Lead to large, sudden position errors.

Error Reduction Strategies

•Systematic Error Mitigation:

- Regular calibration of wheels and encoders.
- Using higher-resolution encoders and advanced alignment techniques.

•Non-Systematic Error Management:

- Employing more sophisticated algorithms for real-time error correction.
- Integrating additional sensor data (e.g., IMUs) for better movement tracking.

CMU BOSS FOR URBAN CHALLENGE

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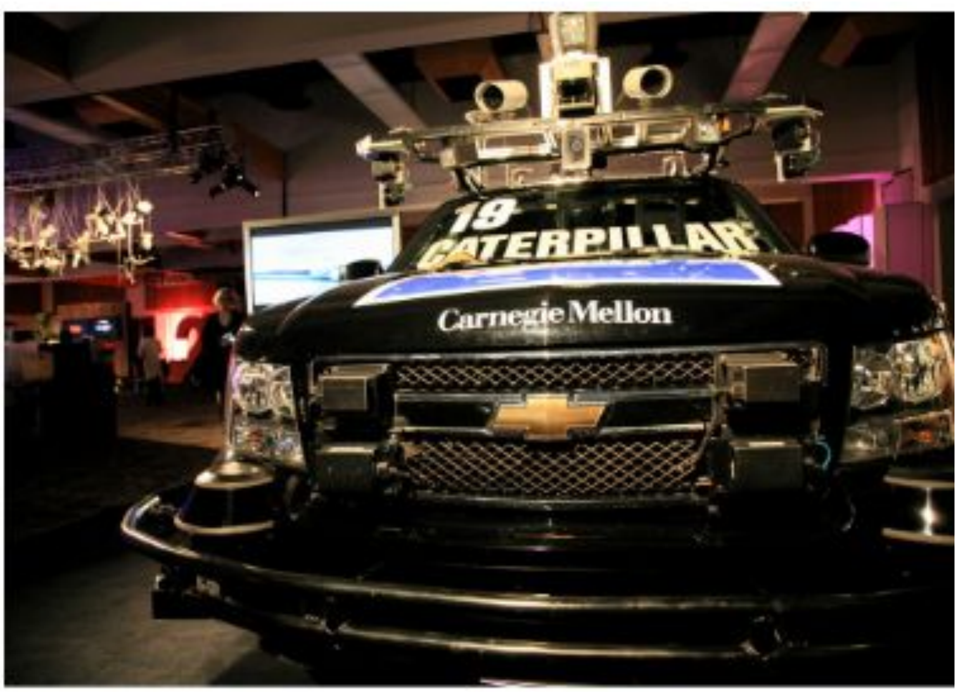

Sensor Fushion:**CMU BOSS FOR URBAN CHALLENGE**

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- Boss is an autonomous vehicle designed for safe operation in traffic at speeds up to 48 km/h.
- It uses multiple onboard sensors including GPS, LiDARs, radars, and cameras to detect vehicles, obstacles, and localize itself.
- Developed to meet the requirements of the DARPA Urban Challenge.
- The localization process starts with differential GPS-based pose estimation.
- Sensor fusion system combines GPS, IMU, and wheel encoder data for a 100-Hz position estimate.
- Accuracy is high, with error bounded to 0.3m under stable GPS, and 1m after 1 km without GPS signal.

Sensor Fushion: Stanford Junior for Urban Challenge

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Junior is Stanford's entry in the Urban Challenge, a modified 2006 Volkswagen Passat Wagon.

It is equipped with five LiDARs, a differential GPS-aided inertial navigation system, five radars, and two Intel quad-core computer systems.

Sensor Fushion: Stanford Junior for Urban Challenge

- The vehicle has an obstacle detection range of up to 120 m and a maximum speed of 48 km/h, as per the Urban Challenge rules.
- Localization in Junior begins with a differential GPS-aided inertial navigation system, integrating GPS, inertial measurements, and wheel odometry.
- Position and orientation errors are typically below 100 cm and 0.1°, respectively.
- LiDARs such as RIEGL LMS-Q120 and SICK LMS sensors measure road reflectivity and detect curbs.

Sensor Fushion: BERTHA FROM MERCEDES BENZ

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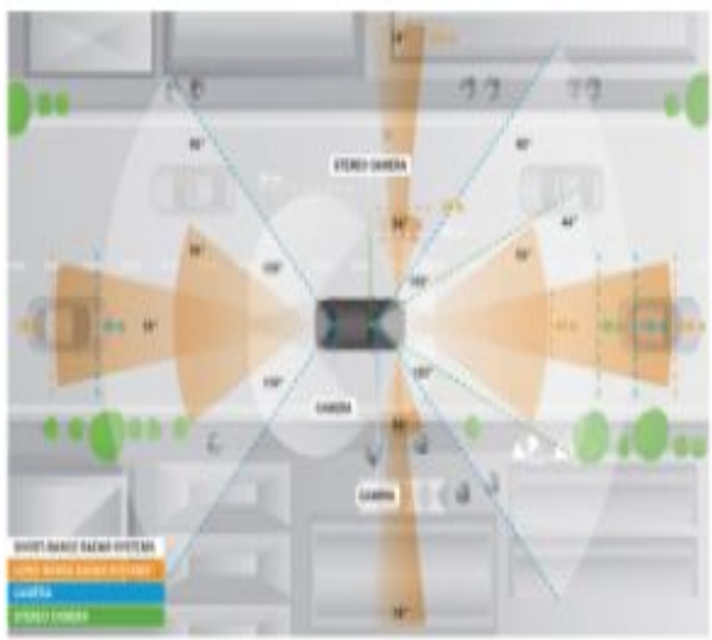

Sensors in the Bertha System

- **GPS module** for basic localization
- **Four 120° short-range radars** for intersection monitoring
- **Two long-range radars** for monitoring fast traffic at rural intersections
- **Stereo camera system** for depth information (60m range)
- **Wide-angle monocular camera** for traffic light and pedestrian recognition
- **Wide-angle backward camera** for self-localization

Digital Map and Mapping Process

- **Detailed digital map** containing:
  - Lane positions, topology, traffic regulation attributes (right-of-way, traffic lights, speed limits)
- **Map creation**:
  - Stereo camera imagery used to generate dense disparity images and 3D reconstructions
  - Refined using reference trajectories and RTK GNSS/INS data
- **Map maintenance**: Utilizes **OpenStreetMap tools**

Localization Techniques

- **GNSS/INS system** bounds localization error within 1 meter
- Two complementary map-relative localization algorithms:
  - **Feature-based localization** (urban areas): Detects point-shaped landmarks near the vehicle
  - **Lane-marking-based localization** (rural areas): Detects lane markings and curbs to estimate location
- Both techniques utilize **Visual Odometry**