Robotics
Theory

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Academic Year 2023-2024

Abstract

The course is composed by a set of lectures on autonomous robotics, ranging from the main architectural patterns in mobile robots and autonomous vehicles to the description of sensing and planning algorithms for autonomous navigation. The course outline is:

- Mobile robots' kinematics.
- Sensors and perception.
- Robot localization and map building.
- Simultaneous Localization and Mapping (SLAM).
- Path planning and collision avoidance.
- Robot development via ROS.

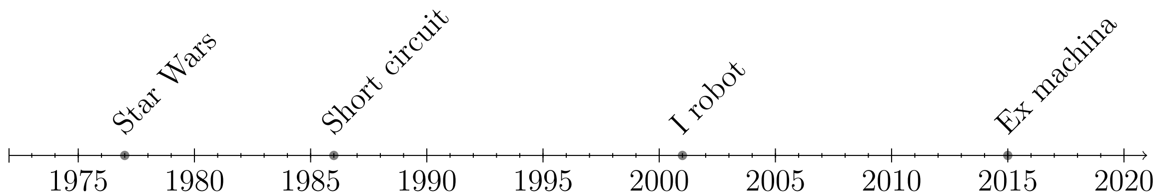
Contents

CHAPTER 1

Introduction

1.1 History

Filmography In the play "Rossum Universal Robots" from 1920, the term "robota" was introduced to refer to the first automatic robots. Several years later, Isaac Asimov penned the renowned science fiction series "I, Robot". Additionally, notable instances of robots in film include:



Robots evolution The mechanical era commenced in 1700 with the advent of the first automata, initially devised as specialized dolls for specific purposes. Transitioning from this era, the dawn of the 1920s saw a resurgence of interest in universal-purpose robots within the realm of fiction.

By 1940, the cybernetics era took root with the creation of the first turtles and telerobots. Grey Walters pioneered a significant development in this era by crafting a robotic tortoise that exhibited mechanical animal tropism (movement directed by stimuli).

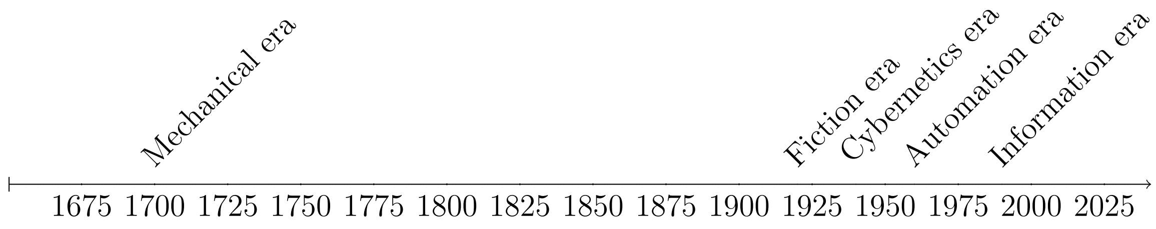
Two decades later, the automation era commenced with the inception of the first industrial robots, marking a shift towards mechanized processes. In 1961, UNIMATE, the inaugural industrial robot, initiated operations at General Motors, executing programmed tasks with precision and efficiency. In 1968, Marvin Minsky introduced the Tentacle Arm, a groundbreaking innovation resembling the movements of an octopus. This hydraulic-powered arm, controlled by a PDP-6 computer, featured twelve flexible joints facilitating maneuverability around obstacles.

In 1972, Shakey pioneered mobility in robotics with the creation of the Stanford cart, heralding advancements in mobile robotics.

The year 1980 witnessed the establishment of the first comprehensive definition of a robot as a reprogrammable, multifunctional manipulator designed for diverse tasks involving material, parts, tools, or specialized devices.

The onset of the information era in 1990 saw robots evolving to possess autonomy, cooperation, and intelligence, marking a significant leap in their capabilities.

Finally, in 2012, the International Organization for Standardization (ISO) established the standard definition for robots, consolidating their diverse functionalities and characteristics into a unified framework.



1.2 ISO definitions

Definition (*Robot*)**.** A robot is an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks. Autonomy in this context means the ability to perform intended tasks based on current state and sensing, without human intervention.

Definition (*Service robot*)**.** A service robot is a robot that performs useful tasks for humans or equipment excluding industrial automation application.

Definition (*Personal service robot*)**.** A personal service robot or a service robot for personal use is a service robot used for a noncommercial task, usually by lay persons.

Examples of personal service robots include domestic servant robots, automated wheelchairs, personal mobility assist robots, and pet exercising robots.

Definition (*Professional service robot*)**.** A professional service robot or a service robot for professional use is a service robot used for a commercial task, usually operated by a properly trained operator.

Examples of professional service robots encompass cleaning robots for public spaces, delivery robots in offices or hospitals, fire-fighting robots, rehabilitation robots, and surgical robots in hospitals. In this context, an operator is an individual designated to initiate, oversee, and terminate the intended operation of a robot or robot system.

Notes A robot system is defined as a system comprising robots, end-effectors, and any machinery, equipment, or sensors that support the robot in performing its tasks.

According to this definition, service robots require a degree of autonomy, which can range from partial autonomy involving human-robot interaction to full autonomy without active human intervention. Human-robot interaction involves information and action exchanges between humans and robots via a user interface to accomplish tasks.

Industrial robots, whether fixed or mobile, can also be considered service robots if they are utilized in non-manufacturing operations. Service robots may or may not feature an arm structure, which is common in industrial robots. Additionally, service robots are often mobile, but this is not always the case.

Some service robots consist of a mobile platform with one or several arms attached, controlled similarly to industrial robot arms. Unlike their industrial counterparts, service robots do not necessarily need to be fully automatic or autonomous. Many of these machines may assist a human user or operate via teleoperation.

1.3 Robot architecture

A machine gathers information from a set of sensors and utilizes this data to autonomously execute tasks by controlling its body parts.

One commonly employed model in robotics is the sense plan act paradigm, which forms the foundation of cognitive robotics. In this model, the sensing phase involves collecting data from sensors, the planning phase utilizes algorithms to process this data, and the action phase involves executing commands through actuators. This architecture is illustrated in the following diagram.

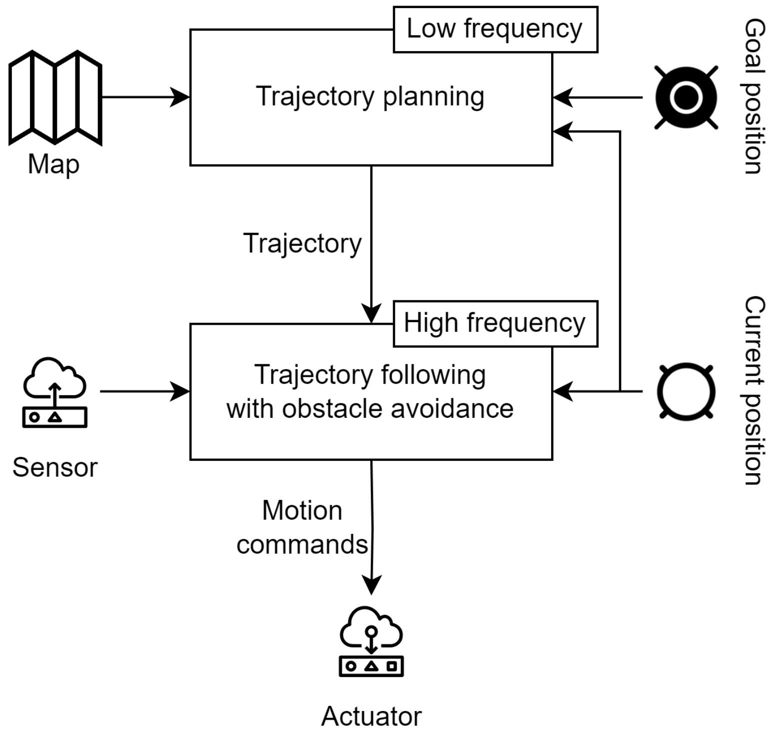


Figure 1.1: Sense plan act architecture

CHAPTER 2

Sensors and actuators

2.1 Sensors

Sensors serve to detect both the internal condition of the robot (proprioceptive sensors) and the external state of the environment (exteroceptive sensors). Another classification for sensors can be based on whether they are passive, which measure physical properties, or active, which involve an emitter and a detector.

2.1.1 Encoder

An encoder translates rotary motion or position of a motor/joint into electronic pulses. Encoders come in two primary types:

- *Linear encoder*: comprising a lengthy linear read track and a compact read head, linear encoders are designed for linear motion measurement.
- *Rotary encoder*: suitable for both rotary and linear motion, rotary encoders convert rotary motion into electrical signals. They are further categorized as incremental or absolute.

Their operation proceeds as follows:

1. A light-emitting diode (LED) projects a light beam onto a tape striped with red and black segments.
2. The reflected light is captured by a photodetector.
3. The photodetector generates a periodic wave whose frequency varies based on the speed of the tape.

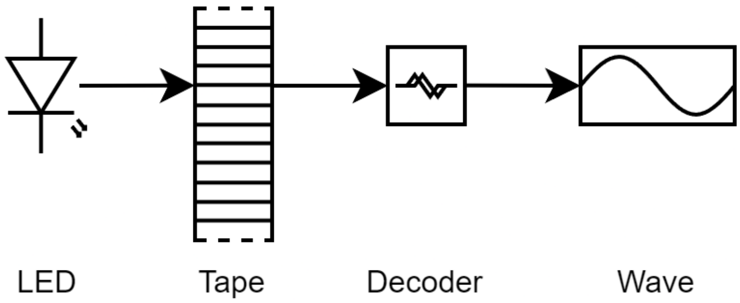


Figure 2.1: Linear encoder structure

Incremental rotary encoders Incremental rotary encoders operate based on the photoelectric principle, employing a disk with alternating transparent and opaque zones containing two traces or sensors. These traces facilitate the identification of rotation direction and enhance resolution through quadrature.

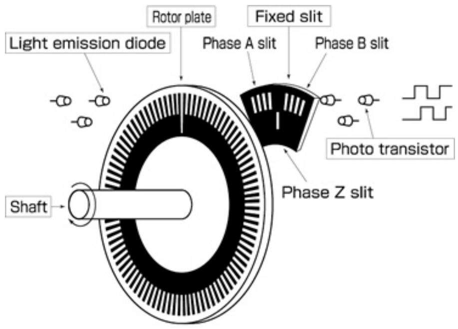


Figure 2.2: Incremental rotary encoder

To determine speed and direction, the quadrature technique is employed, where the two signals are shifted by $\frac{1}{4}$ step. Denoting N as the number of steps of light/dark zones per turn, the resolution is given by:

$$\text{resolution} = \frac{360°}{4N}$$

Using this technique:

- If a transition from 11 to 10 occurs, it indicates a counterclockwise rotation.
- Conversely, if a transition from 11 to 01 occurs, it indicates a clockwise rotation.

The encoders' limitation lies in their inability to determine the actual position relative to the starting point. The only feasible solution involves resetting to the starting position and then incrementally counting until reaching the desired position.

Absolute rotary encoder The absolute rotary encoder addresses the limitation of determining absolute position by encoding it directly on the disk.

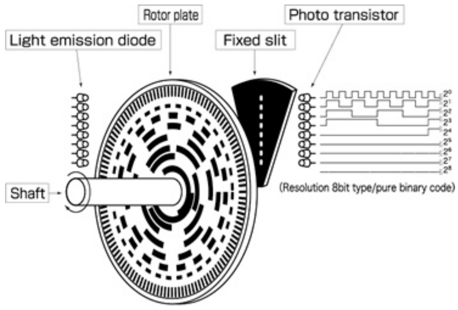


Figure 2.3: Incremental rotary encoder

The disk features transparent and opaque areas arranged in concentric rings. Each bit of position data is represented by a corresponding ring, offering an absolute resolution of:

$$\text{resolution} = \frac{360°}{2^N}$$

In robotic applications, a minimum of 12 rings are typically employed. To prevent ambiguities, binary codes with single variations, such as Gray code, are utilized.

2.1.2 Time of flight telemeter

The time-of-flight telemeter records the duration between when the emitter generates a signal and when the detector detects its reflection. The signal travels a distance of $2d$, and the time of flight is given by:

$$\Delta t = \frac{2d}{c}$$

The initial type of sensor utilizing this principle in robotics was the sonar, which relies on sound waves. Sound waves, with their slower speed of approximately 340 m/s, and their relatively broad directionality ranging from 20° to 40°, offer an advantage in measuring shorter distances.

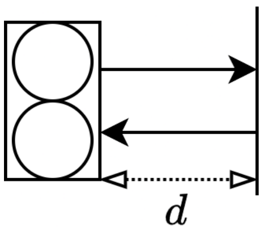


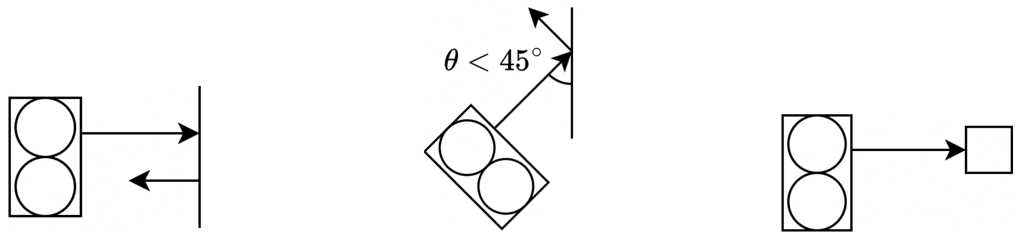
Figure 2.4: Sonar sensor

Sonar	
Range (m)	0.3 up to 10
Accuracy (m)	0.025
Cone opening (°)	30
Frequency (Hz)	50000

The primary limitation is the susceptibility of the signal-to-noise, particularly from significant reflections. Selecting an appropriate range is crucial depending on the specific application. However, these sensors may not function optimally in all scenarios, due to factors such as:

- Balancing sampling frequency.
- Dealing with reflections off walls.
- Detecting small or soft objects.

Additionally, it's worth noting that room dimensions may appear distorted, especially around corners.



(a) Distance (b) Inclination (c) Dimension

Figure 2.5: Possible problems for sonar sensors

2.1.3 Reflective optosensors

Reflective optosensors are active sensors where the emitter is a source of light and the detector is a light detector. This type of sensors uses triangulation to compute distance:

1. Emitter casts a beam of light on the surface.
2. The detector measures the angle corresponding to the maximum intensity of returned light.
3. Being s the distance between the emitter and the detector we have:

$$d = s \cdot \tan \alpha$$

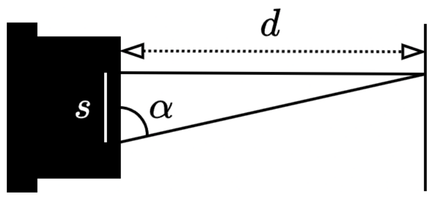


Figure 2.6: Reflective optosensor

Infrared sensors are relatively inexpensive and sturdy, but they have their drawbacks. They exhibit nonlinear characteristics that require calibration. Additionally, there can be ambiguity when used at short ranges, necessitating precise placement within the robot. Their fixed ranges and opening angles mean that careful selection is needed for optimal performance in various applications. Moreover, they may encounter issues with reflections under certain conditions.

An instance of such technology is the Kinect, an input device designed by Microsoft (originally by Primesense) for Xbox 360. This device functions as a three-dimensional scanner and is equipped with an infrared projector, an infrared camera, and an RGB camera.

Kinect	
Range (m)	0.7 up to 6
Horizontal cone opening (°)	57
Vertical cone opening (°)	43
Infrared camera	11-bit 640×480
RGB camera	30 Hz 8-bit 640×480

In this device, the distance from the camera Z_k is calculated as:

$$Z_k = \frac{Z_0}{1 + \frac{d}{fb} Z_0}$$

Time of flight camera Three-dimensional time-of-flight (TOF) cameras illuminate the scene using a modulated light source and capture the reflected light. The phase shift between illumination and reflection is then translated into distance information.

These sensors encounter challenges such as utilizing illumination from a solid-state laser or a near-infrared ($\sim$ 850 nm) LED, where an imaging sensor converts captured light into electrical current. Additionally, distance information is encoded within the reflected component. Consequently, a high ambient component diminishes the signal-to-noise ratio (SNR).

2.1.4 Light detection and ranging (LIDAR)

Laser sensors offer superior accuracy with the following capabilities:

- Providing 180 ranges across a 180° field of view (expandable to 360°).
- Scanning 1 to 64 planes.
- Delivering scan rates of 10-75 scans per second.
- Achieving range resolutions of less than 1 cm.
- Offering a maximum range of up to 50-80 meters.
- Facing challenges only with mirrors, glass, and matte black surfaces.

2.1.5 Position sensor

Positioning outdoors can be determined using a Global Navigation Satellite System (GNSS), with multiple constellations available including GPS, GLONASS, Beidou, Galileo, and more.

The Global Positioning System (GPS) comprises 24 satellites circling the Earth twice daily. These satellites emit synchronized signals containing location and time data. Receivers compare the transmitted and received signal times to determine position. At least four satellite signals are needed for accurate positioning. The typical accuracy of GPS is approximately 2.5 m at a 2 Hz refresh rate, with the potential for even greater precision of around 20 cm with Differential GPS (DGPS).

There is also the RTKGPS that improves the time resolution with respect to the DGPS.

There are several limitations associated with GPS:

- It does not function indoors, underwater, or in urban canyons.

- Line of sight reception is required for optimal performance.
- GPS signals are susceptible to multiple paths and reflections, which can affect accuracy.

2.2 Inertial sensor

The inertial sensor can be divided into the following categories:

- *Gyroscopes*: measure angular velocities.
- *Accelerometers*: gauge linear accelerations with reference to the gravitational vector.
- *Magnetometers/compasses*: determine orientation based on the earth's magnetic field vector.

An Inertial Measurement Unit (IMU) integrates gyroscopes, accelerometers, and magnetometers to offer a complete six degrees of freedom pose estimate. However, integrating inertial measurements, such as for position computation, accumulates errors and drifts notably over time, particularly when using inexpensive MEMS (Micro-Electro-Mechanical Systems) technology.

2.2.1 Tactile sensor

Tactile sensors serve manipulation purposes and fall into two main categories:

- *Binary*: utilize switches placed on the fingers of a manipulator. Can be arranged in arrays (bumpers) on the external side to detect and avoid obstacles.
- *Analogical* (real valued): consist of soft devices producing a signal proportional to the local force. Utilize mechanisms like a spring coupled with a shaft or soft conductive material that changes resistance with compression. Capable of measuring movements tangential to the sensor surface.

2.2.2 Proximity sensor

Proximity sensors detect the presence of objects within a defined distance range, employed for grasping items and navigating around obstacles. Various technologies are utilized for this purpose:

- *Ultrasonic*: low cost.
- *Inductive*: detects ferromagnetic materials within a millimeters distance.
- *Hall effect*: detects ferromagnetic materials, small, robust, and inexpensive.
- *Capacitive*: detects any object, binary output, high accuracy when calibrated for a specific object.
- *Optical*: utilizes infrared light, offering binary or real-valued output.

2.3 Actuators

Effectors are responsible for altering the state of the environment, with actuators facilitating the actions of effectors. In robotics, we employ various types of actuators:

- *Electric motors*: these devices convert electrical energy into mechanical energy by leveraging the principles of electromagnetism. They produce rotational motion through the interaction between magnetic fields and electric currents.
- *Hydraulics*: this technology utilizes fluids to transmit force, employing the principles of fluid mechanics to generate, control, and transfer power via pressurized liquids.
- *Pneumatics*: a branch of engineering that employs compressed air or gas to transmit and regulate power, akin to hydraulics but using air or gas instead of liquids.
- *Photo-reactive materials*: these substances undergo a chemical change upon exposure to light.
- *Chemically reactive materials*: substances in this category undergo chemical reactions with other materials or their surroundings.
- *Thermally reactive materials*: these substances undergo changes in properties or behavior when subjected to variations in temperature.
- *Piezoelectric materials*: materials that generate electric charges in response to mechanical stress or pressure, while also displaying mechanical deformation under an electric field.

Originally, early robots were equipped with hydraulic and pneumatic actuators. Hydraulic actuators were costly, heavy, and required significant maintenance, making them suitable mainly for larger robots. Pneumatic actuators found use in stop-to-stop applications like pick-and-place tasks due to their swift actuation.

In modern times, electrical motors have become the prevalent choice for actuators. Typically, each joint incorporates its dedicated motor along with a controller. High-speed motors are often paired with elastic gearing to moderate their speed. These motors necessitate internal sensors for precise control. Stepper motors, on the other hand, don't require internal sensors; however, in case of an error, their exact position becomes unknown.

2.3.1 Direct current motor

Direct Current (DC) motors transform electrical energy into mechanical energy. They are compact, cost-effective, reasonably efficient, and straightforward to operate.

Electric current flows through coils of wire arranged on a rotating shaft. These wire loops create a magnetic field that interacts with the magnetic fields of permanent magnets positioned nearby. The resulting interaction between these magnetic fields causes them to repel each other, resulting in the rotation of the armature.

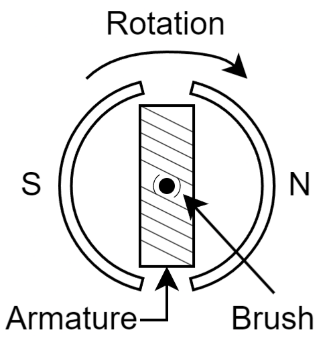


Figure 2.7: Brushed motor structure

Continuously adjusting the current causes the armature to keep rotating and generating motion. This current modification is facilitated by two connectors positioned at the center of the armature, known as brushes. It's worth noting that in lower-cost electrical motors, the external magnets remain stationary. However, these budget-friendly versions encounter several issues related to their brushes:

- Brushes gradually wear out over time.
- Brushes generate noise during operation.
- They impose a maximum speed limit.
- Cooling them proves to be challenging.
- They restrict the number of poles that can be utilized.

To circumvent this issue, one can opt for brushless motors, where external magnets are substituted with copper coils and a magnet is positioned at the center. This configuration yields a motor wherein brushes are replaced by electronics, permanent magnets reside on the rotor, and electromagnets are situated on the stator. While these motors offer superior performance, they also come at a higher cost compared to their brushed counterparts.

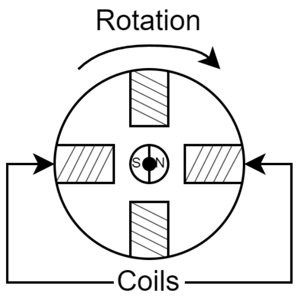


Figure 2.8: Brushless motor structure

2.3.2 Stepper motor

The stepper motor, a type of synchronous electric motor lacking brushes, transforms digital pulses into mechanical shaft rotations.

A stepper motor offers several advantages: it provides a direct correlation between input pulse and rotation angle, maintains full torque even at standstill when windings are energized, enables precise positioning and repeatability, responds promptly to starting, stopping, and reversing commands, boasts high reliability due to the absence of contact brushes, facilitates open-loop control which simplifies and reduces costs, supports very low-speed synchronous rotation with directly coupled loads, and offers a wide range of rotational speeds. However, there are also disadvantages: it necessitates a specialized control circuit, consumes more current compared to DC motors, experiences a reduction in torque at higher speeds, risks resonances if not adequately managed, and finds it challenging to operate at extremely high speeds.

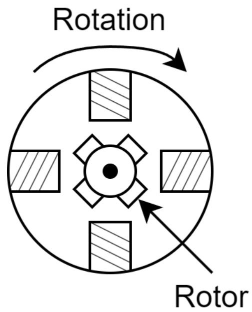


Figure 2.9: Stepper motor structure

The step angle, denoted by φ, can be determined using the following formula:

$$\varphi = \left(\frac{N_s - N_r}{N_s \cdot N_r}\right) \times 360^\circ$$

In this equation, N_s represents the number of teeth on the stator, and N_r represents the number of teeth on the rotor.

2.3.3 Servo motor

A servo is a type of specialized motor designed to precisely move its shaft to a specific position. These motors find common use in hobby radio control applications. They possess the capability to measure their own position and adjust for external loads in accordance with a control signal.

Servo motors are typically constructed from direct current motors with additional components including gear reduction, a position sensor, and control electronics. The travel range of the shaft is usually limited to 180 degrees, which is adequate for the majority of applications.

CHAPTER 3

Robot odometry

3.1 Introduction

For autonomous robots and unmanned vehicles to execute their tasks effectively, they require: accurate self-location information, and detailed maps of the environment. However, these requirements aren't always feasible or dependable due to the following reasons:

- Global Navigation Satellite Systems (GNSS) may not always be reliable or available.
- Not all areas have been accurately mapped.
- Environmental conditions can change dynamically.
- Maps need regular updates to remain current and reliable.

The robot's position can be regarded as a random variable due to the uncertainty inherent in our estimation of its true position. The full SLAM (Simultaneous Localization and Mapping) problem involves determining the distribution of both the robot's poses and the positions of landmarks, considering the robot's actions and sensor measurements:

$$\mathrm{P}\left(\Gamma_{1:t}, l_1, \ldots, l_N | Z_{1:t}, U_{1:t}\right)$$

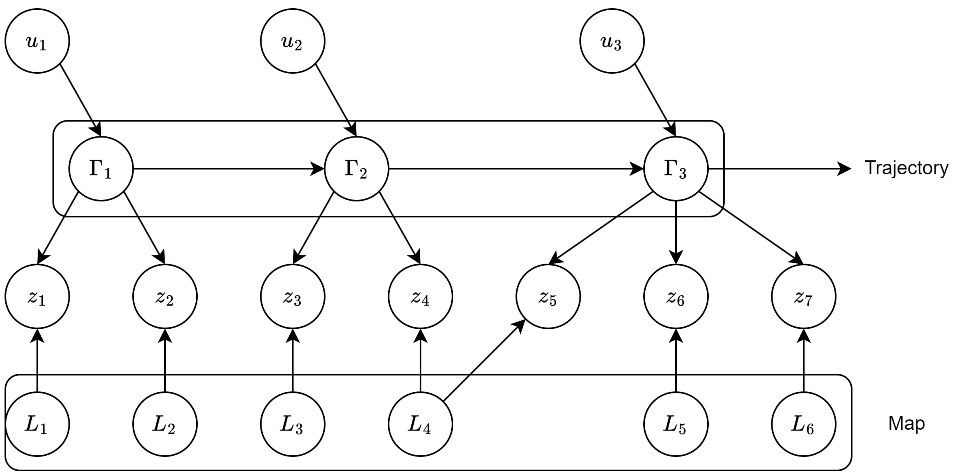


Figure 3.1: Simultaneous localization And Mapping

If a complete trajectory isn't necessary, a simplified version known as online SLAM can be used. This method provides the entire map and calculates the probability of only the most recent pose based on all measurements and actions:

$$\mathrm{P}\left(\Gamma_t, l_1, \ldots, l_N | Z_{1:t}, U_{1:t}\right) = \int\int\int_1^{t-1} \mathrm{P}\left(\Gamma_{1:t}, l_1, \ldots, l_N | Z_{1:t}, U_{1:t}\right)$$

It's important to note that the term pose encompasses not only the position but also the orientation of the robot relative to the environment.

The motion model incorporates all actions $u_1, \ldots, u_N$ and their resulting poses $\Gamma_1, \ldots, \Gamma_N$ describing how the robot's pose changes through the actuators.

On the other hand, the sensor model involves all poses $\Gamma_1, \ldots, \Gamma_N$, all position probabilities $z_1, \ldots, z_N$, and the map with landmarks $L_1, \ldots, L_N$. It defines the probability distribution of a specific measurement given the robot's pose and the positions of the landmarks.

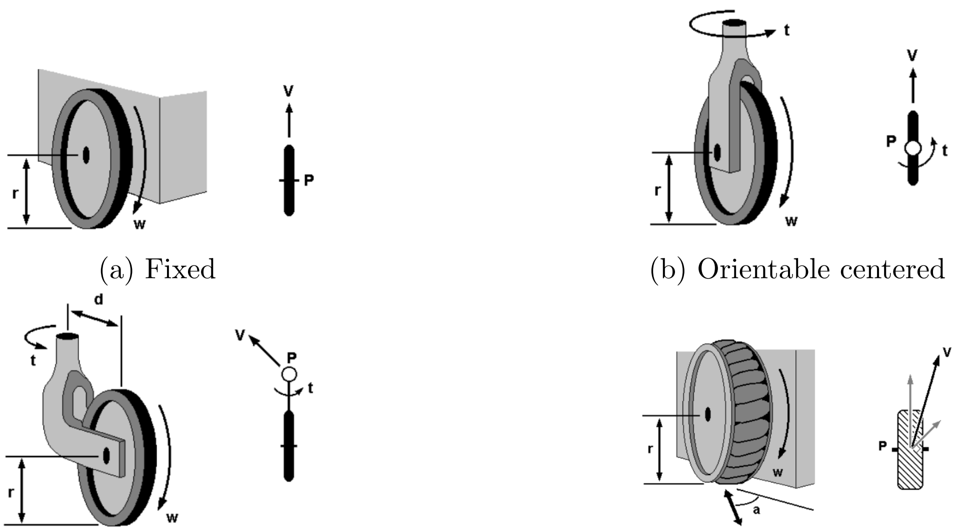
3.2 Robot kinematic

The robot kinematic is based on the motion model.

Definition (*Wheeled mobile robots*)**.** A robot capable of locomotion on a surface solely through the actuation of wheel assemblies mounted on the robot and in contact with the surface. A wheel assembly is a device which provides or allows motion between its mount and surface on which it is intended to have a single point of rolling contact.

Various kinematic configurations are feasible:

- *Differential drive* (two wheels): basic design, prone to disturbances from uneven terrain, and lacks lateral translation capability.
- *Tracks*: ideal for outdoor surfaces, movement precision compromised, especially during rotations, intricate structure and behavior, and lateral translation not achievable.
- *Omnidirectional* (synchro drive): utilizes all three degrees of freedom, sophisticated design and functionality, and intricate structural composition.



(a) Fixed

(b) Orientable centered

(c) Caster omnidirectional

(d) Swedish or meccanum

Figure 3.2: Wheel classification

Definition (*Locomotion*)**.** Locomotion involves initiating movement in an autonomous robot:

Motion is achieved by applying forces to the vehicle.

Definition (*Dynamics*)**.** Dynamics encompasses the analysis of motion through the modeling of forces, as well as the associated energies and velocities involved in these movements.

Definition (*Kinematics*)**.** Kinematics is the examination of motion devoid of considerations regarding influencing forces.

It focuses on the geometric relationships dictating the system's behavior and the correlation between control parameters and the system's behavior in state space.

Definition (*Direct kinematics*)**.** Direct kinematics involves determining the pose (x, y, θ) that a robot achieves given specific control parameters and a time of movement t.

Definition (*Inverse kinematics*)**.** Inverse kinematics pertains to finding the control parameters necessary to reach a specified final pose (x, y, θ) within a given time t.

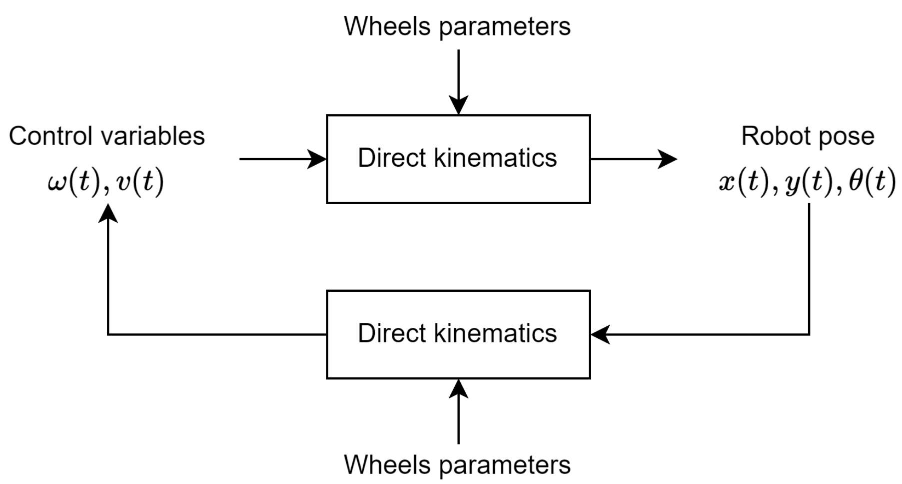


Figure 3.3: Direct and inverse kinematics