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Dynamical Simulation

Introduction

Manchester Robotics

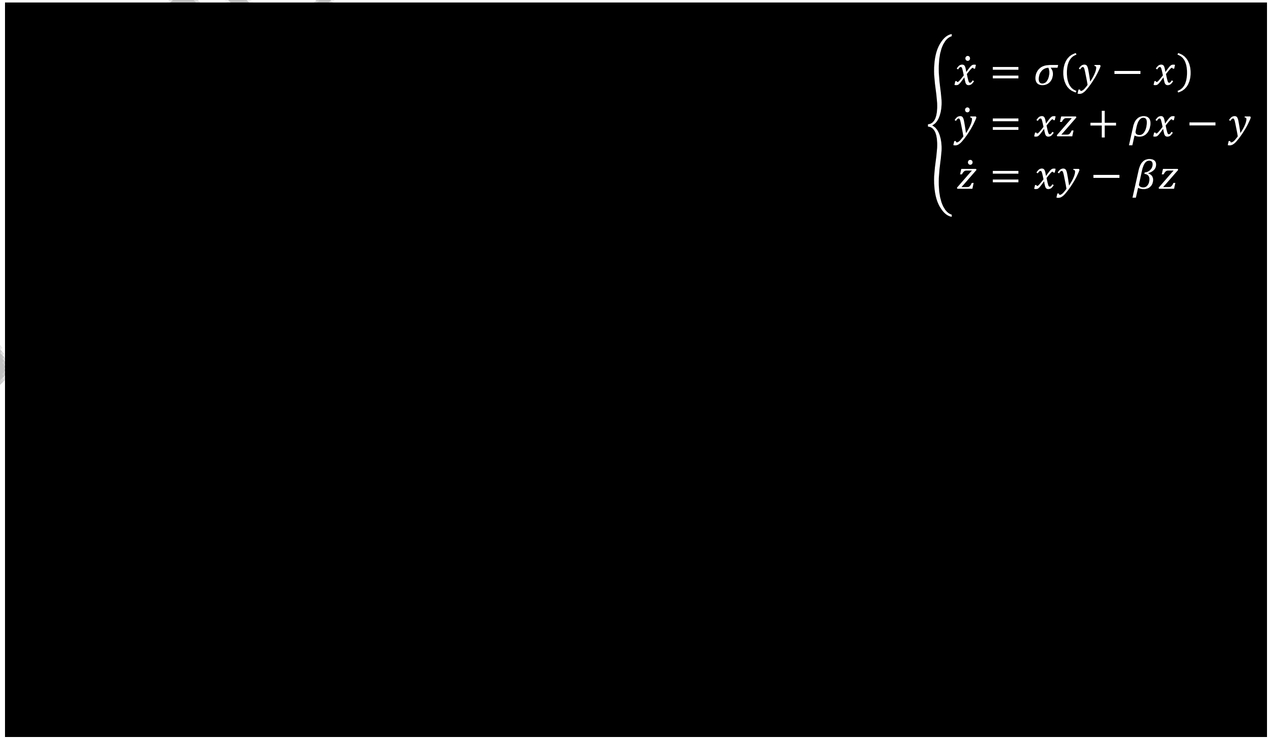
Dynamic Simulation

- **Dynamic simulation** (or dynamic system simulation) is using a computer program to model the time-varying behaviour of a dynamical system.
- Ordinary differential equations or partial differential equations typically describe the systems.
- The simulator solves these equations to determine the behaviour of state variables over a specified time.
- Creating a model of a dynamic system allows for predicting the values of the model-system state variables based on past state values.

Dynamic Simulation

- Simulation models are commonly obtained from discrete-time approximations of continuous-time mathematical models.
- Models can incorporate real-world constraints, like gear backlash, collisions, and rebound from a hard stop.
- As models are more complex, equations can become nonlinear, chaotic, with added disturbances and noise.

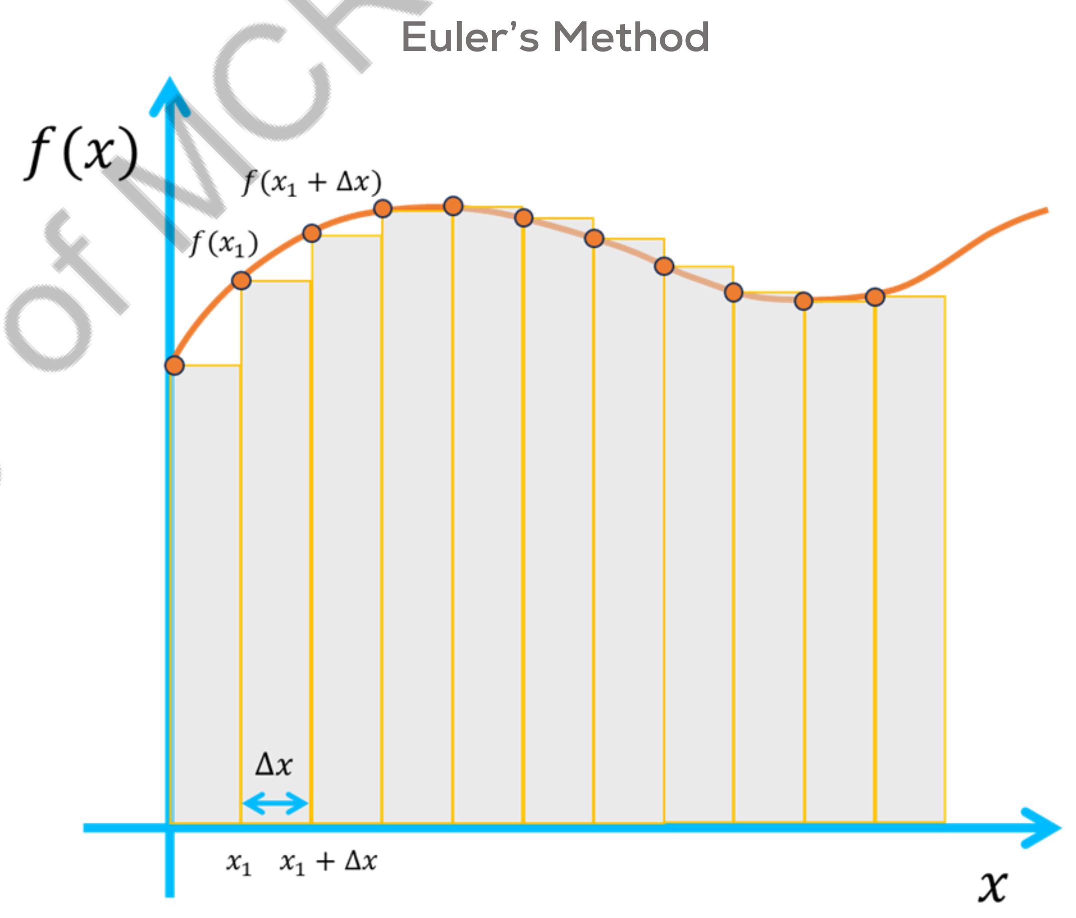
Lorenz Attractor



$$\begin{cases} \dot{x} = \sigma(y - x) \\ \dot{y} = xz + \rho x - y \\ \dot{z} = xy - \beta z \end{cases}$$

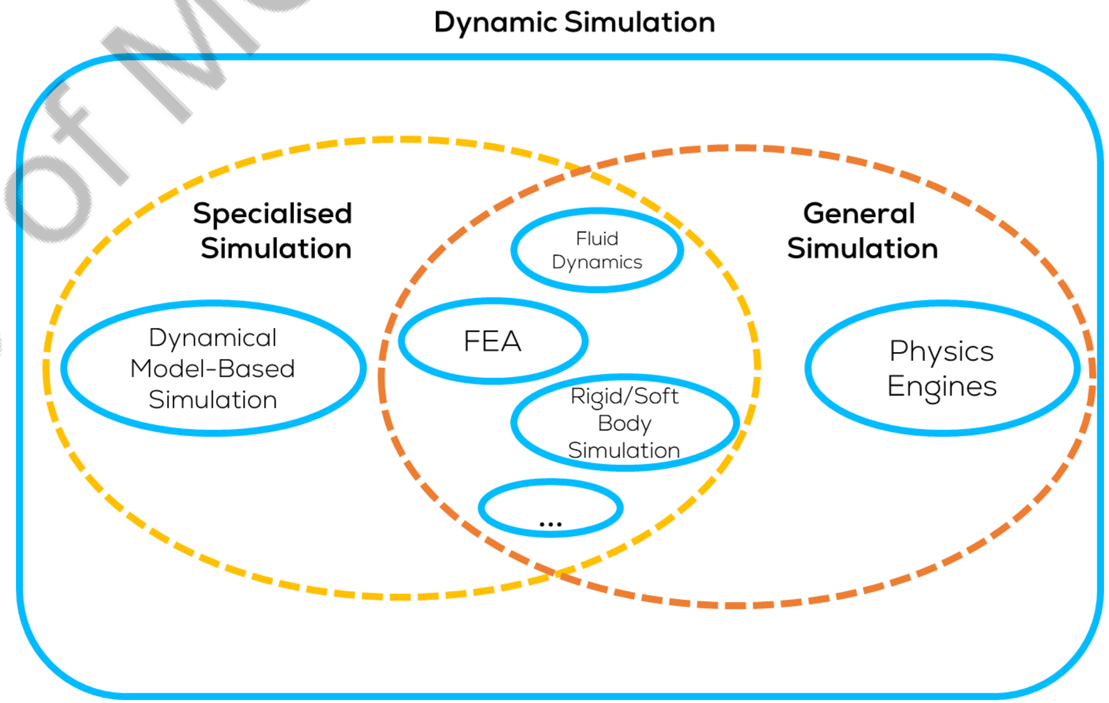
Dynamic Simulation

- Solving some nonlinear equations "by hand" can become difficult or almost impossible.
- Thanks to the advancement of computers, it is now possible to solve them using different computational algorithms.
- Dynamical models, in general, are solved through numerical integration methods to produce the transient behaviour of the state variables.
- Therefore, it can be said that a numerical simulation is done by stepping through a time interval and calculating the solution of the mathematical model solution through numerical integration.



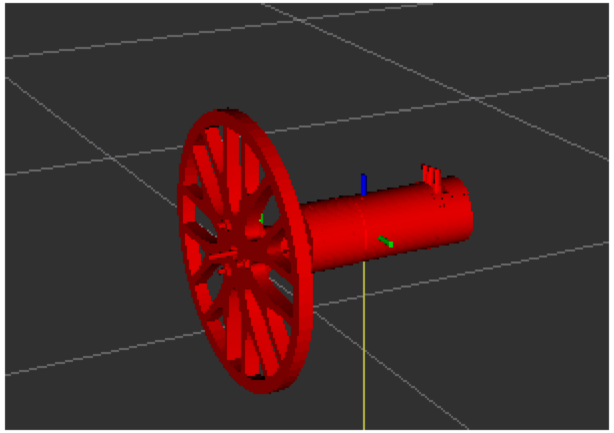
Categories of Dynamic Simulation

- Dynamic simulations can be subdivided into different categories. In robotics and mechanics, in general, two main categories are used:
  - **Specialised**: designed for one particular mechanism or dynamical system.
  - **General:** uses different (rigid, soft, fluid, etc.) body physics engines that simulate just about any configuration.



Specialised Simulations

- Specialised simulation are done as follows:
  1. Deriving the governing equations (mathematical model) of the dynamical system at a particular configuration.
  2. Define the States of the systems to be analysed (some systems can have thousands of state variables).
  3. The next step is using a computer to solve the governing equations, using different computational tools.
     - This process involves numerical analysis and numerical methods, such as Euler Integration or Runge Kutta Methods.
  4. For simulations that involve collisions, additional steps are required to define the collisions such as backing up in time to the moment before the collision to modify the velocities, based on the collisions input.
  5. Finally, specify details about how to display the results and the user input.
- Usually, this type of simulation is used for simple or very complex systems where physical engines fail due to dynamical behaviour or computational power.



Specialised Simulations

- As stated before, specialised simulation can be used for simple systems, dedicated simulations or very complex systems where the user requires more control over the dynamical behaviour.
- Specialised simulators, although widely used in robotics and other engineering fields, they have some disadvantages, shown in the following table.

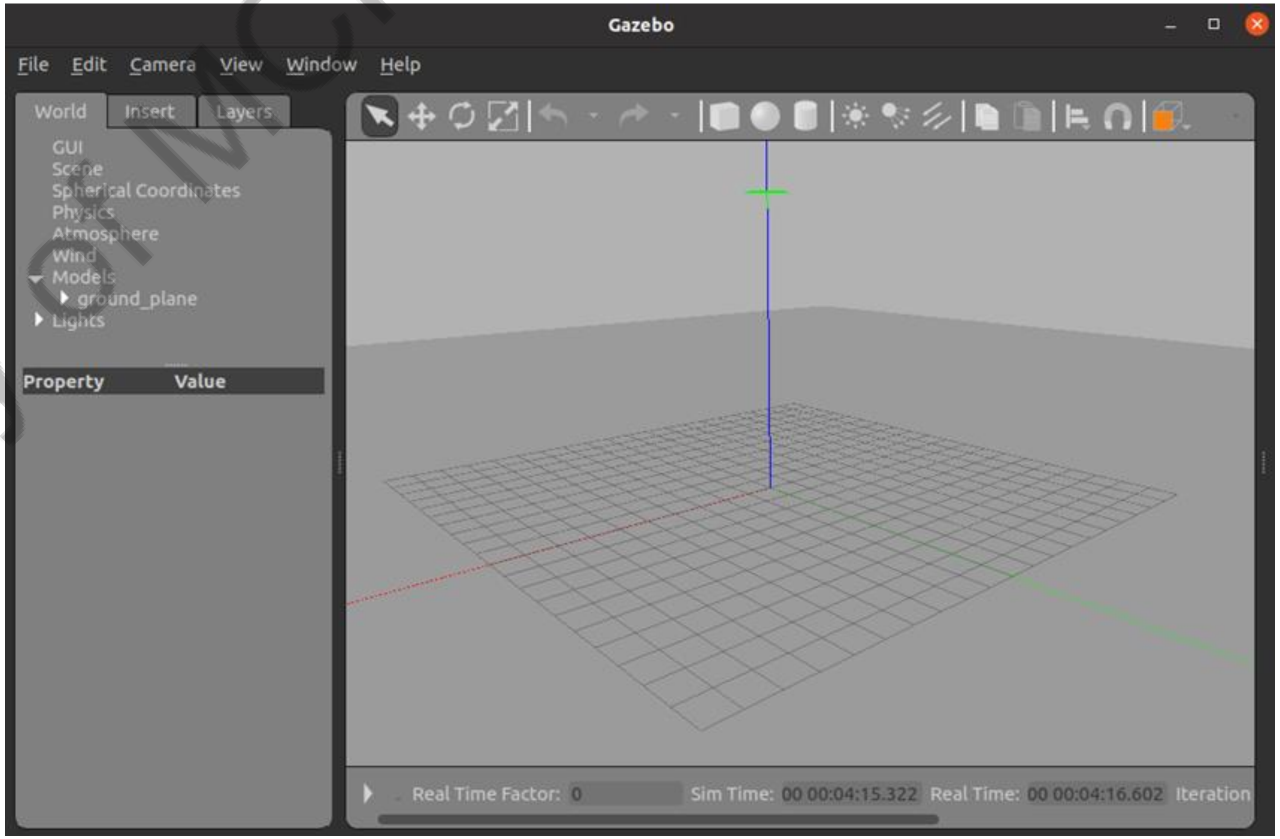
Pros	Cons
• **Flexibility:** They can be used to model a wide range of systems and phenomena, not limited to physics • Customization: You have greater control over the behaviour of the simulated objects and can define custom rules and interactions to suit your specific needs. • **Interdisciplinary:** Can be applied in fields beyond physics, including engineering, biology, economics, and social sciences. • **Realism:** Dynamic simulations can sometimes achieve higher realism for specific scenarios than generic physics engines.	• **Complexity:** Building and fine-tuning dynamic simulations can be complex and time-consuming. • **Performance:** Due to their custom nature, dynamic simulations may not always be as efficient as physics engines for real-time applications like video games and some robotic applications. • **Limited Physics Realism:** Dynamic simulations may lack some physical accuracy, especially when interacting with other components, unlike some physical engines.

Specialised Simulations

- An example in the "specialised" category can be a simple pendulum system.
  - That simulation can only simulate that particular mechanism.
  - The length of the pendulum, the mass of the objects, or spring stiffness can be modified.
  - The problems of this simulation how the parts are connected (change unions), apply new forces, or collide with another object. For such cases, new governing equations must be derived or using another type of simulator.

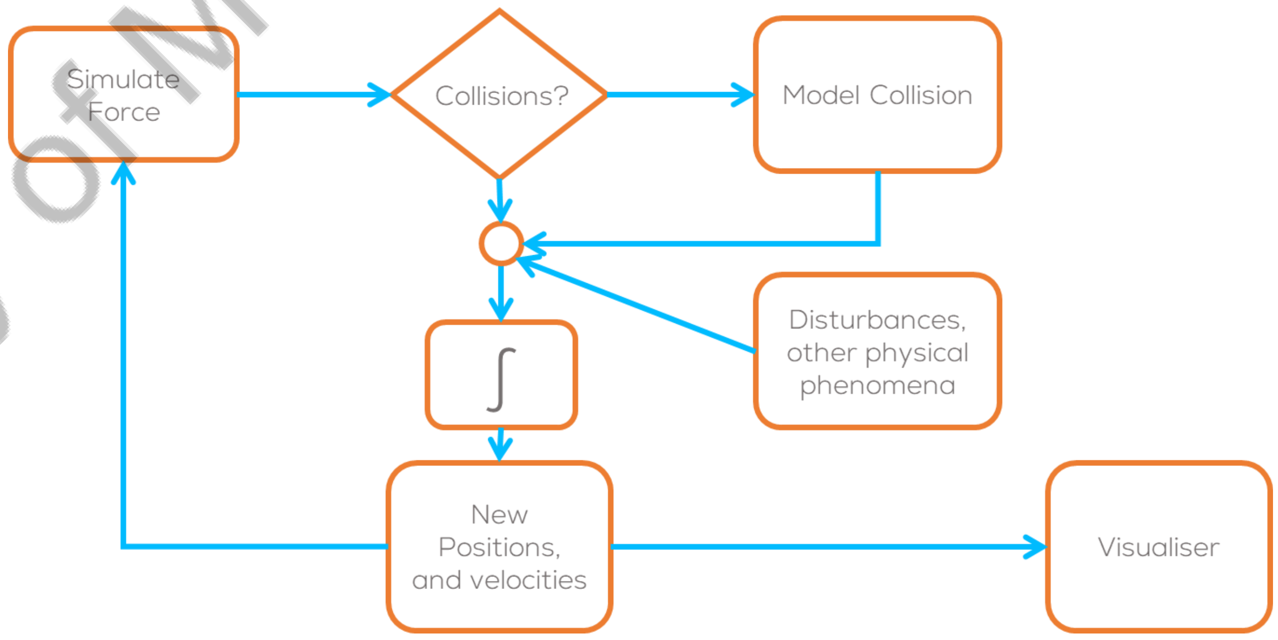
General Simulations

- In contrast, general simulators such as physics engines can model a wide variety of mechanisms.
- The physics engine calculates an object's acceleration, velocity, and displacement based on the forces and torques acting upon it.
- A physics engine is responsible of forming the equations of motion according to the systems' characteristics, solving the equations of motion, and detecting collisions and interactions with other components.
- Some software using physics engines are CoppeliaSim, Gazebo, Unity, etc.



General Simulations

- Physics engines work as a continuous loop.
  - Initialises by checking the joints and establishing the dynamical equations to solve.
  - Identifies all the forces and moments acting on the objects.
  - Solve the equations, by integrating the accelerations to obtain the velocities and positions of the objects.
  - At each new time step, if it detects any collisions, then recalculates the velocity and position of an object.
  - Finally, send the location data to the visualiser.
- This continuous loop is repeated until the simulation is complete.



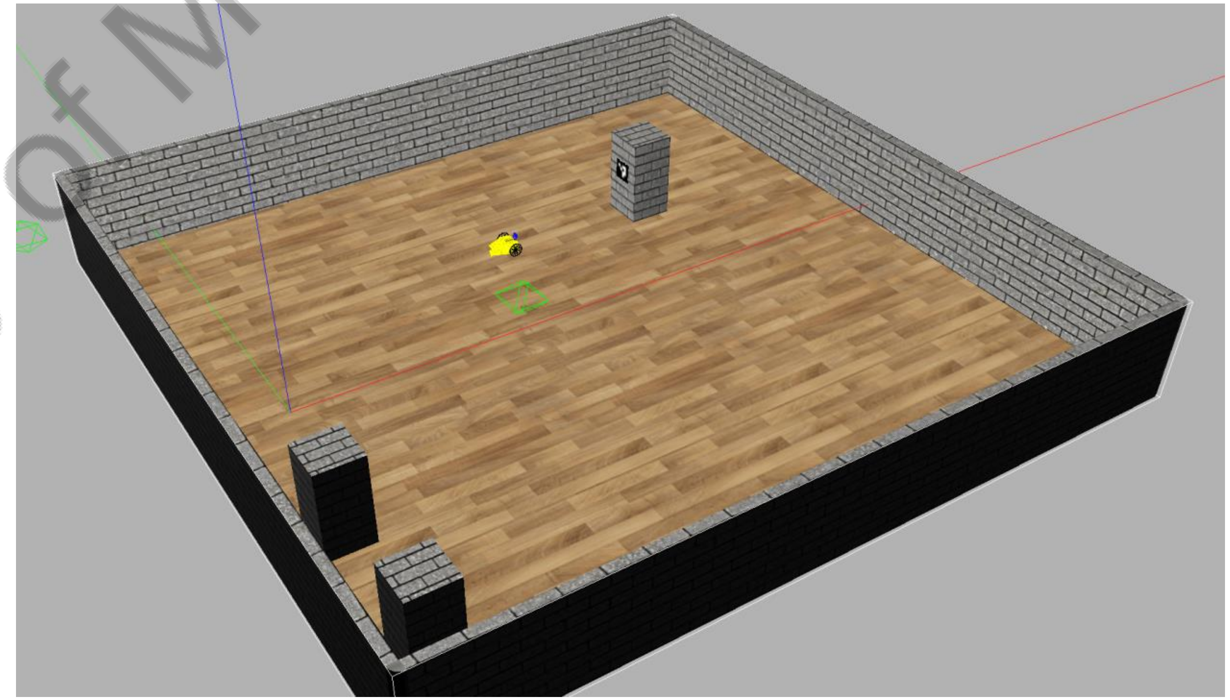
General Simulations

- As stated before, general simulation can be used for a wider range of systems where the user prioritises the behaviour of the system and its interaction with the environment and other systems.
- Physics engine simulators, although widely used in robotics and computer science, have some disadvantages, as shown in the following table.

Advantages	Disadvantages
• **Realistic Physics:** Physics engines provide realistic physics simulations out of the box, making them well-suited for applications where physics interactions are critical. • **Efficiency:** They are optimized for performance and can handle real-time simulations, making them ideal for video games and interactive simulations. • **Collision Detection:** Physics engines excel at collision detection and response, which is essential for creating realistic interactions between objects. • **Pre-built Components:** They come with pre-built components for common physical phenomena, saving development time	• **Limited Flexibility:** Physics engines are specialized and may not be as flexible as dynamic simulations. Modifying their behavior or adding custom rules can be challenging. • **Complex Integration:** Integrating a physics engine into a project can be complex, especially for beginners. • **Resource Intensive:** Realistic physics simulations can be resource-intensive and may require optimization for performance.

General Simulations

- One example is a robot simulated in Gazebo, using the physics engine to interact with the environment.
    - The simulator takes into consideration the light, forces applied to each joint of the robot, collisions, friction, inertias, etc.
    - Also simulate the interaction with cameras, LiDARS, and other sensors.



One vs. the other?

- In practice, the choice between dynamic simulation and a physics engine depends on the specific requirements of the application.
- For video games and interactive simulations that rely heavily on realistic physics, a physics engine is often the preferred choice.
- Dynamic Model simulations are more suitable when flexibility and customization are paramount or when modelling complex systems that go beyond traditional physics.
- In some cases, a combination of both approaches may be used to achieve the desired level of realism and customisation.

Thank you

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