ROBOTIC CONTROL SIMULATORS

for off-road environment

FINAL REPORT

SNOW SM Project

Team:

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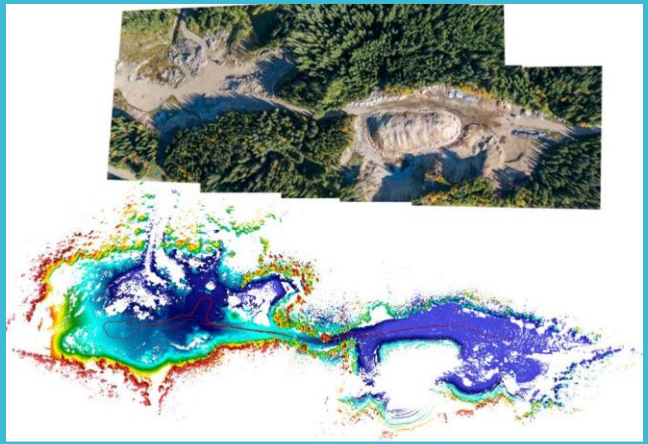
Co-supervisor: Luc Coupal

NORLab



PROJECT SNOW (Self-driving Navigation Optimized for Winter)

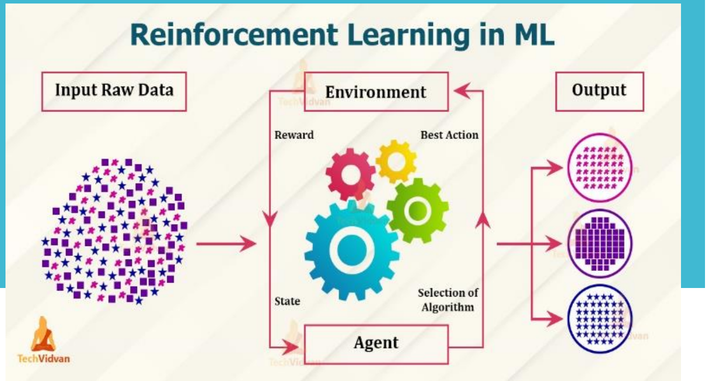
Current Self-Driving Research:

- Urban traffic
- Type of terrain: asphalt

Unexplored issues in autonomous driving:

- Winter driving
- Complex, unstructured and uncertain environment

Lien: https://norlab.ulaval.ca/research/snow/



PROJECT SNOW-SIM

Real Training :

- Lots of data
- Challenge: cost and limited time

Virtual Training :

- Generate lots of data
- Challenge: Simulation to Real

Simulator

NorLab

NORLAB

Best simulator for :

- Development
- Training
- Validation

- And more security
  - No damage(material/physical)

Mandate:
Find and deploy a simulator

INTERNSHIP: OBJECTIVE

STAGE 1: RESEARCH

- Research and analyze different simulation platforms.

STAGE 2: TESTING

- Experiment with successful candidate platforms

STAGE 3: DEPLOYMENT

- Deploy the selected simulator

STAGE 1: RESEARCH AND ANALYSIS

Annexe:
Presentation of results

Definition:
- Problem
- Requirements

Physic:
- Base of physic
- Physics for modelling

Simulators:
- Candidate
- Selected
- To follow


Extreme climate: Winds


Extreme climate: Blizzars


Complex Environment: mud


Complex Environment: sand

PROBLEM

Environment

- Off-Road (in the subarctic region)
- Complex/uncertain environment

Autonomous Driving

- Vehicle dynamics
- Environment dynamics

Extreme Climate

- Winds, Flurries, Blizzards, ...

Simulation in the snow

REQUIREMENTS

Reliability of physics engines

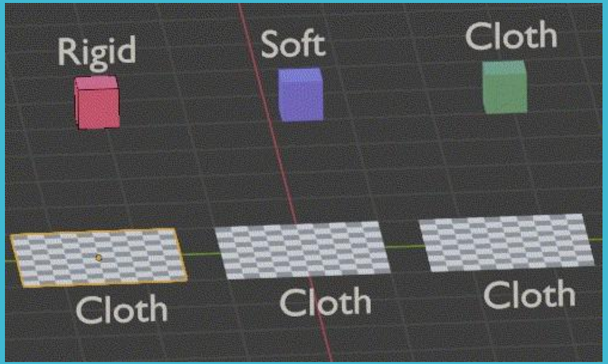
- Mobile robotics
- Real time, Realistic physics

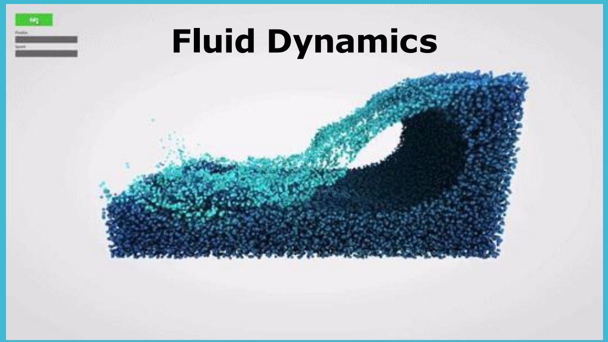
Hardware requirements

- Linux
- ROS, Sensors, Headless mode

Software

- Maintenance
- Support Community





ANALIZED PHYSICS

Basic physics
- Kinematic
- System dynamics,
- Particle & Fluid dynamics

Body physics
- Rigid, Multi & Soft body

Vehicle physics
- Drivetrain, sterring, tires, …

Modeling environment
- Objects
- Terrain, surface
- Climate

Ressource: *Fundamentals of Applied Dynamics by Roberto A.Tenenbaum, Edition Springer, 2004*

CANDIDATE SIMULATORS

Gazebo Ignition	~~GEM~~, ~~Highway~~,	CoppeliaSim
AGX Dynamics	~~WMRDE~~, ~~MujoCo~~	BeamNG
Nvidia Omniverse	(OpenAI Gym	Havok, AirSim
CARLA	Environment)	Chrono Project
~~SVL~~ (discontinued)		Applied Intuition

IMPORTANT FEATURES

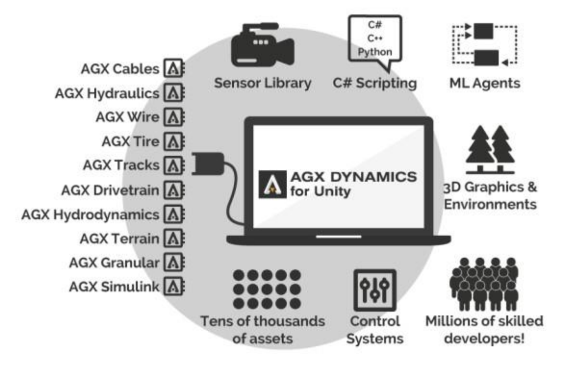
Physics engine

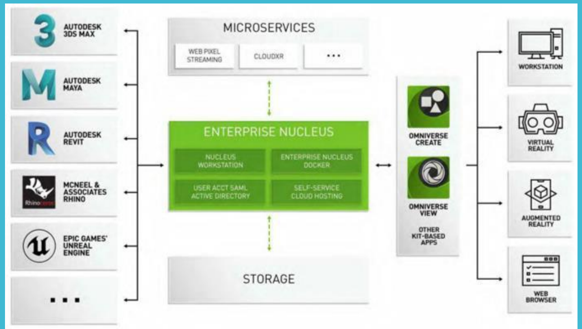
Modelization

Headless mode

ROS

Sensors





SELECTED CANDIDATES

Gazebo Ignition

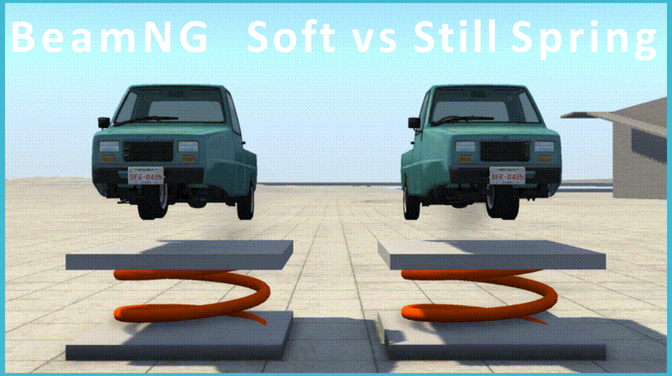
Complete, Modeling, Robotics, OpenAI Gym
Add/Custom engines like Chrono (All-terrain vehicles),
Environments like MuJoCo ...

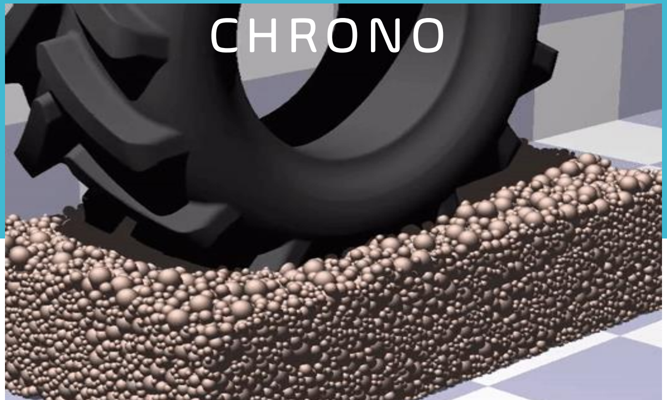
AGX Dynamics

Complete, Modeling, Fast & Robust,
ML-Agents, Plugin/3rd party Havok
(Physics), MuJoCo (Learning)...

Nvidia Omniverse (Optional)

Complete, Modeling, Fast & Robust,
Plugin/3rd party Unreal (Physics), Maya, Blender (Rendering), ...





CANDIDATES TO FOLLOW

Simulators

CARLA Wait for fluid dynamics and offroad

BeamNG Wait for Linux support, environMent

CoppeliaSim Wait for more infos & community

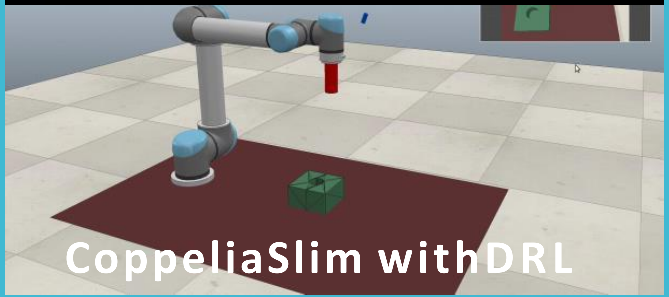
Physics engines

Havok Wait for robotics, doc & community

-> Add in AGXDynamics for **Unity**

Chrono Wait for more developments

-> Add in **Gazebo Ignition**, CARLA



Annexe:
Presentation of testing

STAGE 2: TESTING

Hardware

- Itegration ROS
- Platform
- Software

Files

- Creation
- Import / export
- Modeling

Modelling

- Dynamic
- Terrain
- Surface
- Climat

HARDWARE

Integration ROS

ROS 1 (Melodic 18-23, Noetic 20-25)

ROS 2 (Foxy 20-23, Galactic 21-22)

Platform

Linux (Ubuntu 18.04, 20.04)

Windows 10, MacOS

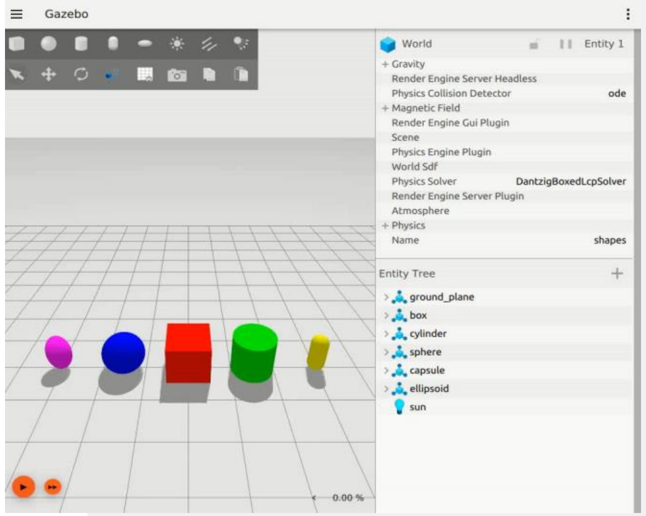
Software

Documentation, API, Community, Service

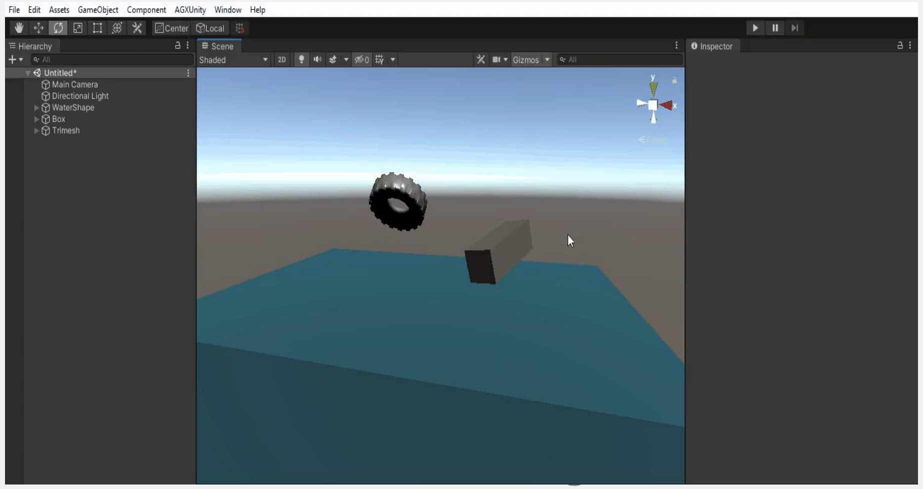
Visualization

HARDWARE: INTERFACES

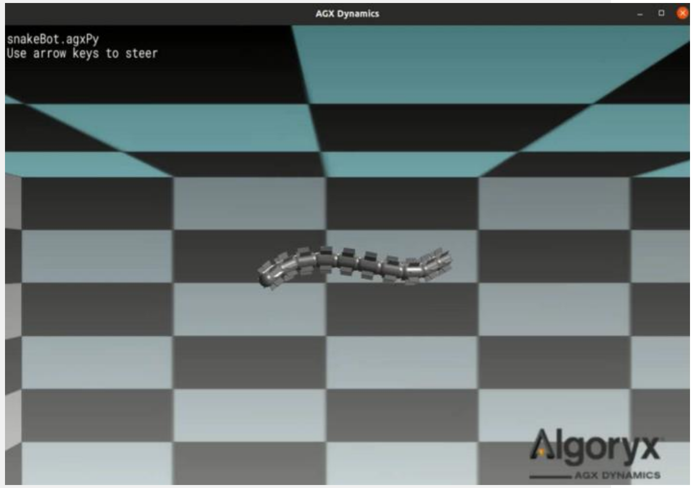
Visualization, Addition, Modification, Terrain deformation, Mixed surface



Gazebo Ignition



AGX Unity



AGX Dynamics

FILES

Creation

SDF with Worlds

Languages: C++, Python

Import / export of files

URDF with Meshes

Third-party software

Blender, MeshLab, …

Unity3D, VFX Graph

Annexe:

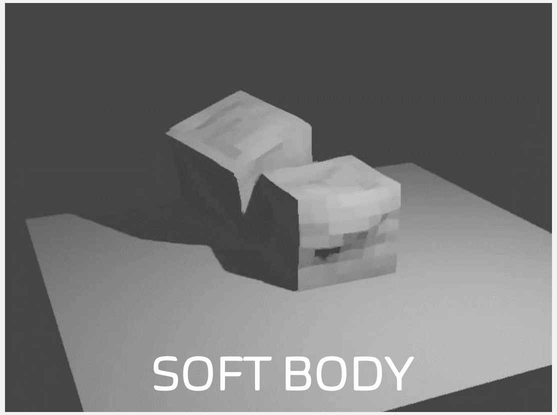
Files SDF

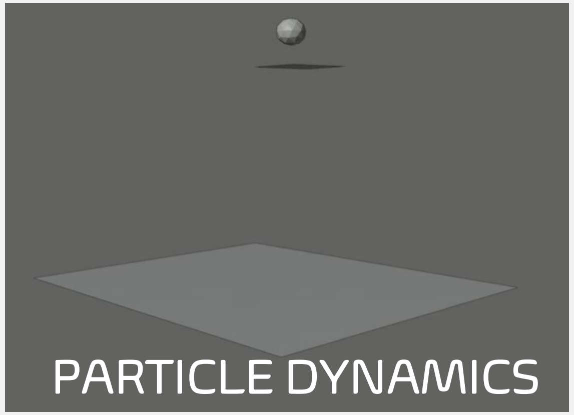
Blender

MeshLab

Unity3D

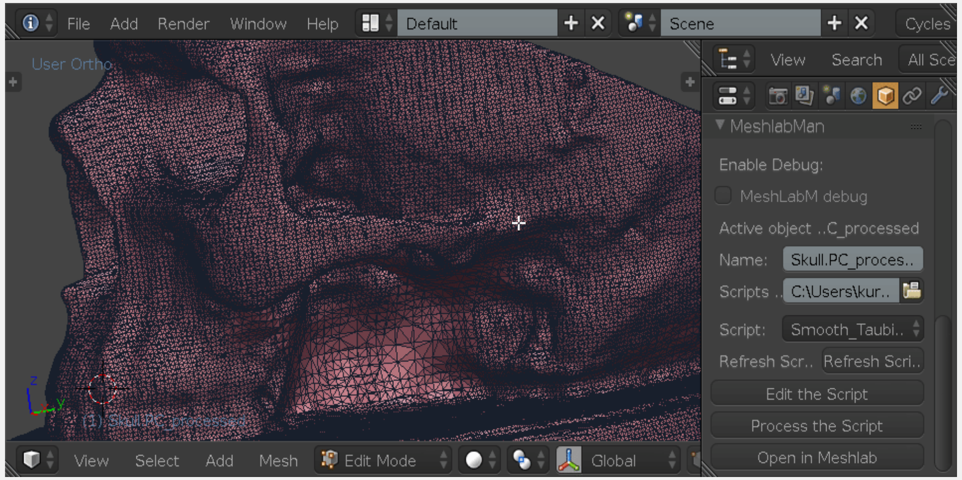
BLENDER - MESHLAB





BLENDER

MESHLAB



Annexe:

Rigid vs Soft Body

Method & Approch

MODELING

Dynamics

System, Fluid, Particle, Soft Body

Complex Terrain

Uneven ground, Terrain deformation,

Surface

Mixed surface, Deformable surface

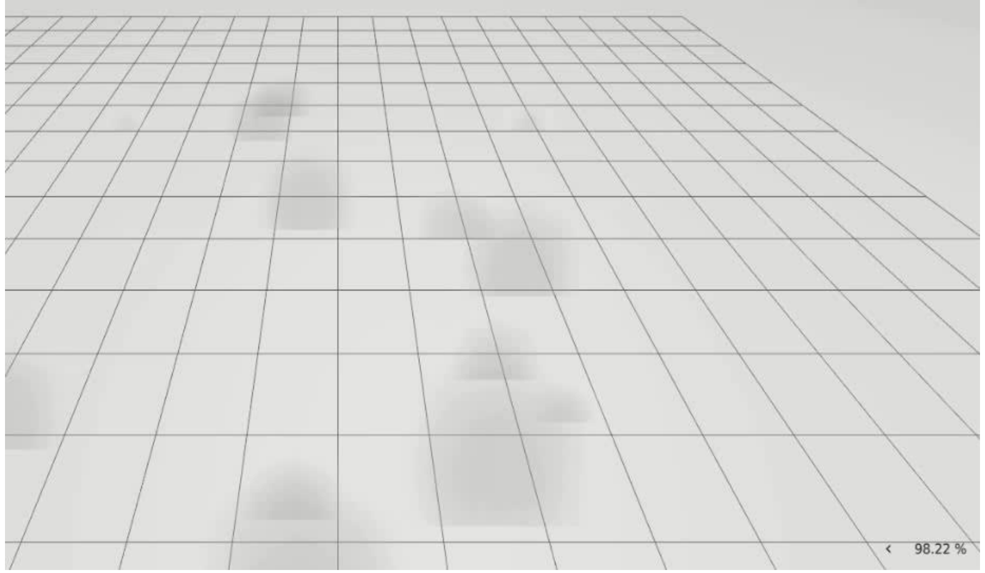
Climate

Blizzard, Flurries, Winds, Rain, Snow, …

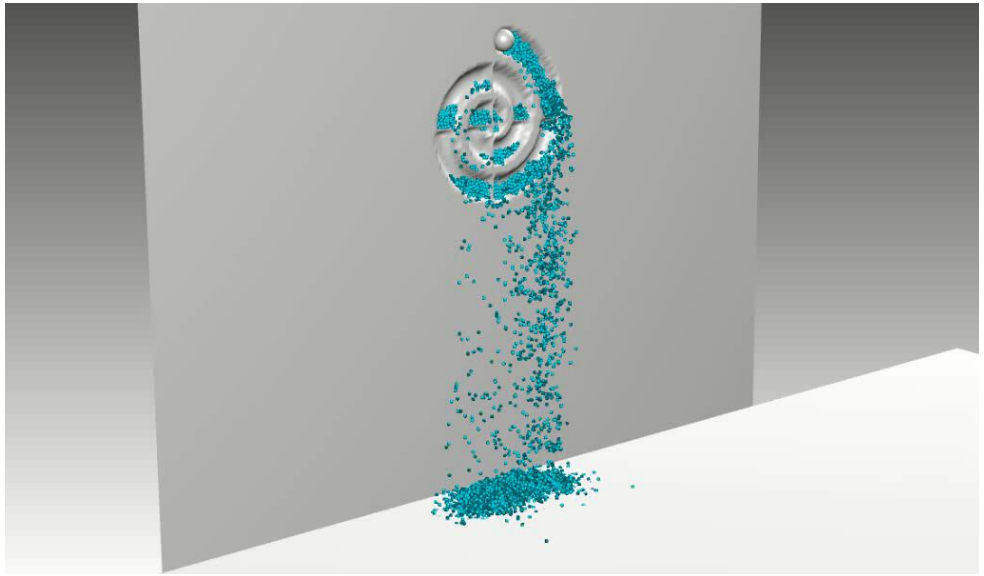
Modeling Event Simulation

Changing weather, Landslide, Micro-avalanche

DYNAMICS: PARTICLE DYNAMICS



Gazebo Ignition



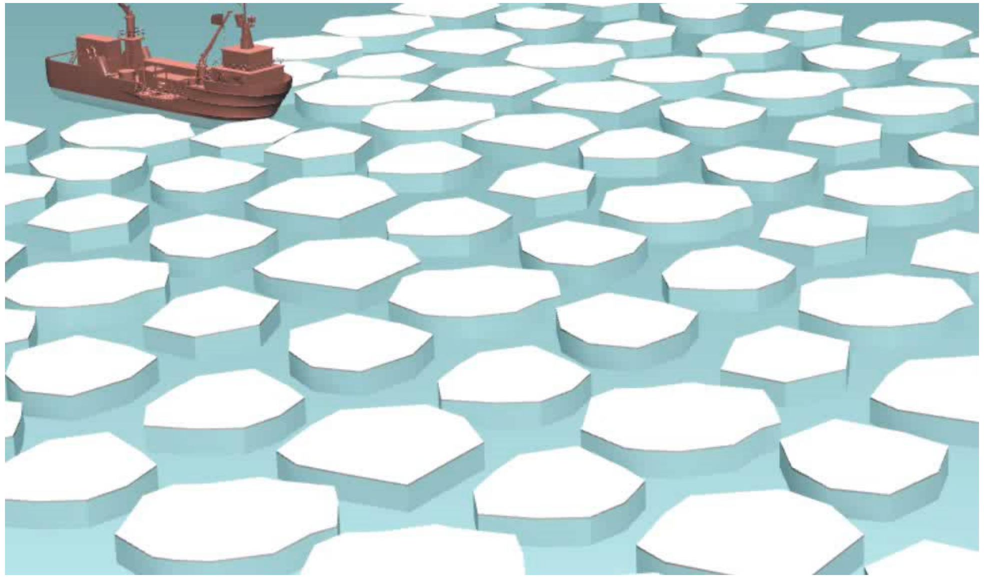
AGX Dynamics

SURFACE: Mixed surface

EXRTEME CLIMATE: Blizzard, Flurries, Winds, ...

DYNAMICS: FLUID DYNAMICS

Gazebo Ignition

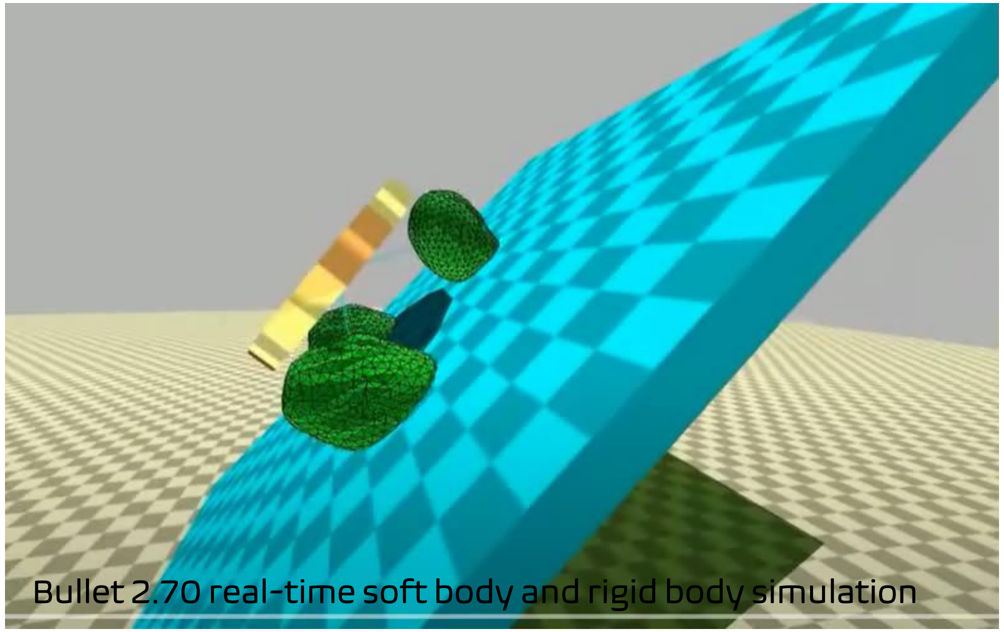


AGX Dynamics

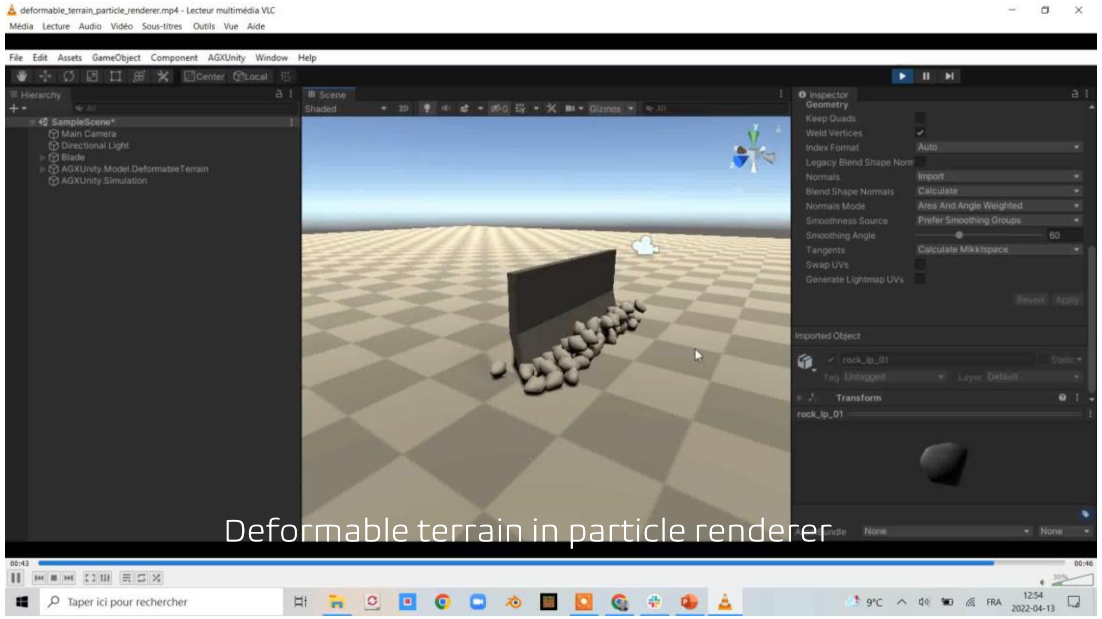
SURFACE: Mixed surface

EXRTEME CLIMATE: Blizzard, Flurries, Winds, ...

DYNAMICS: SOFT BODY



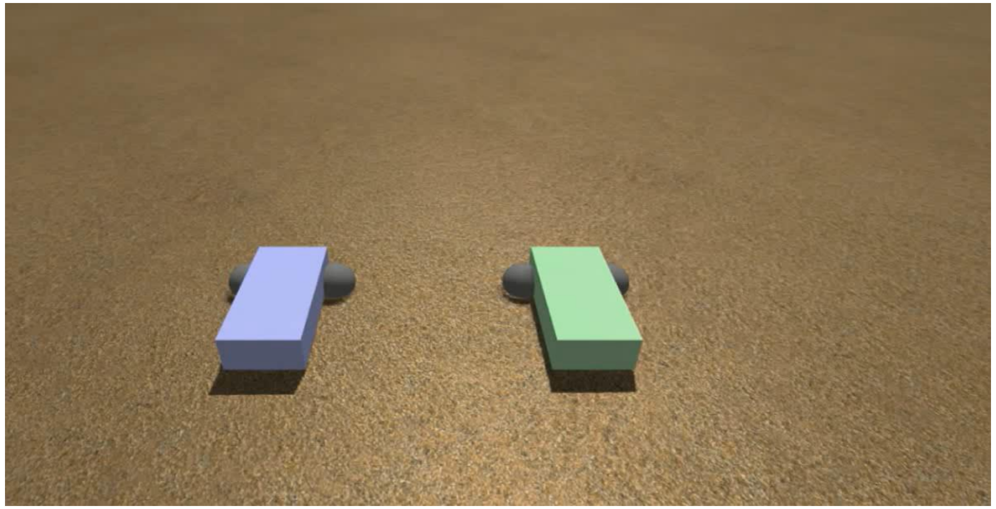
Gazebo Ignition



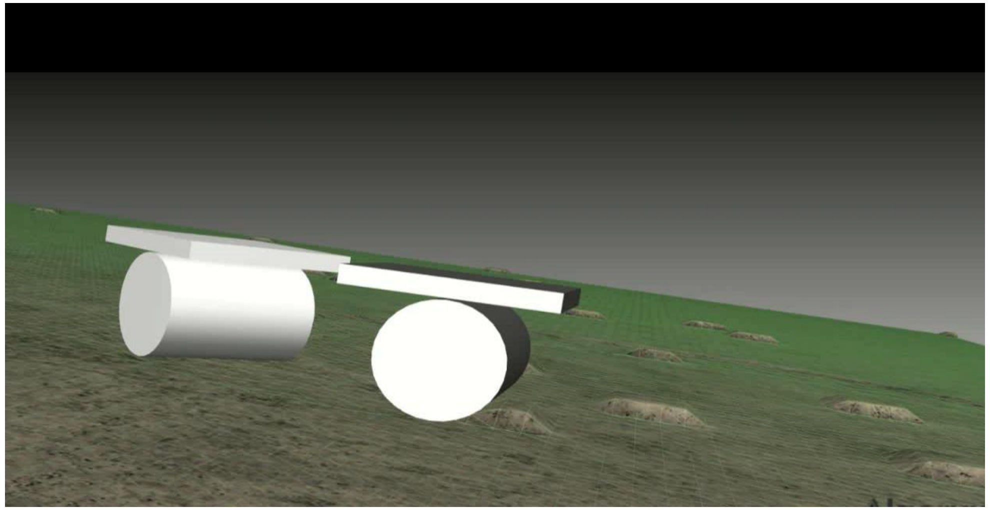
AGX Dynamics

The soft body model is Position-Based Dynamics
With Triangle Meshes

DYNAMICS: Vehicle



Gazebo Ignition

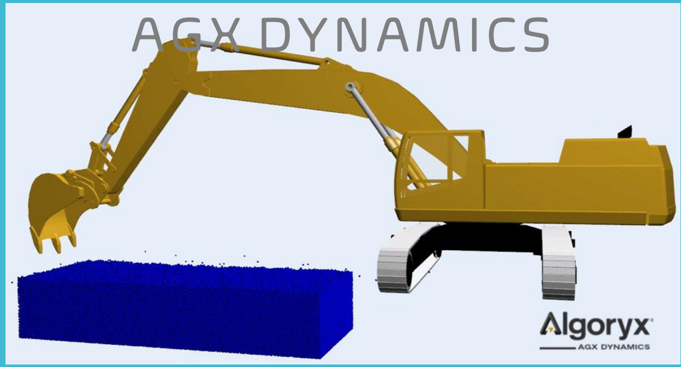


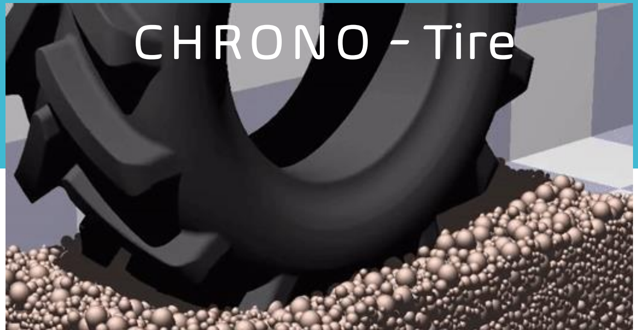
AGX Dynamics

COMPLEX TERRAIN: Uneven ground, deformation

ANALYSIS: GAZEBO IGNITION vs AGX DYNAMIC

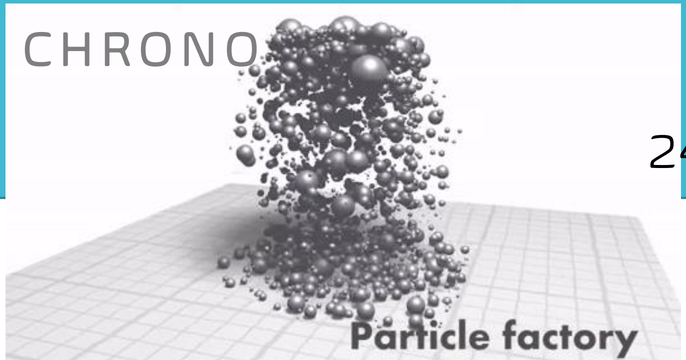
SIMULATORS	POINTS FORTS	POINTS FAIBLES
Gazebo Ignition	Interface Community, Forum ROS1 & ROS2 integration API Fuel with model & worlds Physics engine	Tools modelisation Models interaction
AGX Dynamic	Interface (Unity) Tools modelisation (Unity) Models interaction Good service Robust	Interface AGX Dynamics Platform Windows (AGX & AGXUnity) No soft Body, No interaction objets Unity-AGX No ROS1 integration No forum, No Free





HAVOK Physics

BeamNG DRIVE



STAGE 3: DEPLOYMENT

Tutorials

- Scripts for the installation
- Templates files for modelling
- Troubleshooting
- Resources, Wiki and README

Docker images

- Docker image: Gazebo Ignition
- Docker compose: Ignition + ROS 1 Noetic

ANNEXES

PRESENTATION OF SIMULATORS

Simulators	Physics Engines	Rendering Engines	Learning ML / DL / RL	Sensors	Supports	Applications	Options
Gazebo Ignition	DART, ODE, TPE, Bullet, Simbody + add & custom	Ogre, Optix	OpenAI Gym (Gym-Ignition)	Cameras, LIDAR, IMU, GPS	ROS, Docker, YARP		Headless mode
AGX Dynamics for Unity	Unreal Engine Unity 3D	Unity, Unreal, OSG + add & custom	OpenAI Gym (gym-agx) IsaacSim, DriveSim Kaolin app, ML Agents	Cameras, LIDAR, Depth, proximity	ROS, Docker MATLAB Simulink RobotStudio	Powerline, Drivetrain, Tire, Terrain, Granular, Hydro dynamics, …	Headless mode Offroad Plugin Havok for Unity
Nvidia Omniverse	Nvidia PhysX Plugin: Unreal	RTX Renderer Plugin: Blender, Houdini, CityEngine	Isaac Sim, Isaac Gym Kaolin app	Cameras, LIDAR	ROS, Docker	Plugin: Maya, 3DS max, Blender, CityEngine, Optix, …	Headless mode Ray tracing, Fast
CARLA	Unreal Engine Co-sim: SUMO, PT-Vissim	Vulkan OpenDrive	OpenAI Gym (gym-carla) Anys Real Time Radar (RTR)	Cameras, LIDAR, IMU, GPS, GNSS, Semantic LIDAR	ROS, Docker, AWZ MATLAB Simulink		Headless mode (No-rendering mode; Off-screen mode)
CoppeliaSim (V-REP)	Bullet, ODE, Vortex, Newton		OpenAI Gym (gym-vrep)	Cameras, LIDAR, IMU, GPS, Laser 2D, 3D	ROS MATLAB Simulink, Octave BlueZero		Headless mode
BeamNG	BeamNG.drive BeamNG.tech	Torque 3D Vulkan (soon)	OpenAI Gym (beamnggym)	Camera, LIDAR, IMU ultrasonic, electric	ROS, ~~Docker~~	SUMO, BeamNGpy Traffic Simulation, Roads, 12World ADAS algorithmes	No Headless mode
Project Chrono	Chrono Bullet (collision) + Cosimulation	Internal	OpenAI Gym (gym-chrono)	Camera, LIDARs, GPS, Radar,	~~ROS~~ Chrono-Gazebo MATLAB Simulink	Vehicle, Cosimulation,	headless rendering capabilities Multi-core CPUs, GPU and distribued
Havok Games Dynamics SDK	Havok Physiks FX Havok Cloth	Internal	Havok AI	NA	~~ROS~~	Havok Physics, AI, Cloth	Havok Unity/ Unreal, Multicore, GPU, 3Ds Max, Maya, …
Applied Intuition	Unreal Engine	Unreal	NA	Camera, LIDAR, IMU, GPS, Radar Simulate sensors	CARLA, ROS 1 ROS 2, Gazebo, Docker, Cloud: AWS, Azure, Google	Vehicle Dynamics: CarSim, TruckSim, BikeSim, SuspensionSim	Synthetic data Urban & highways, Off-road Rare or difficult events with limited sensor input
AirSim (**A**erial **I**nformatics and **R**obotics **Sim**ulation)	Unreal UE4 Unity	Unreal UE4 Unity	OpenAI Gym (airsim-gym, AirGym API)	Camera, LIDAR, IMU, GPS, Distance	ROS 1, ROS 2 Gazebo, Docker	Plugin for Unity,	Headless mode, GPUs API, Github, Unity APIs

PRESENTATION OF PYSICS AND MODELING

SIMULATORS	BASIC PHYSICS				BODY PHYSICS			VEHICLE PHYSICS			ENVIRONMENT PHYSICS		
	Kinematic	Particle Dynamics	System Dynamics	Fluid Dynamics	Rigid Body	Soft Body	Multi Body	Vehicle Dynamics	Vehicle Behavior	Collision Detection	Terrain Modeling	Surface Modeling	Climate Modeling
Gazebo Ignition	✓ + inverse	✓	✓	✓	✓	✓	✓	✓	✓	✓ Discrete Continuous	✓ Uneven, Deformable	✓	✓
AGX Dynamics for Unity	✓ + inverse	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓ Uneven, Deformable, Mixe	✓ Changing surface	✓ Changing weather Landslide, Avalanche
Nvidia Omniverse	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CARLA	✓	✓	✓	-	✓	-	✓	✓	✓	✓	✓	✓ Behaviors Dynamic world environment	✓ Precipitation, wind, fog, wet, cloud
CoppeliaSim (V-REP)	✓ + Inverse	✓	✓	-	✓	✓ (soon)	✓	✓	✓	✓ Discrete Continuous	NA Uneven	✓ Adhesive, friction	✓ Fog, water et air jet
BeamNG		✓	✓	✓	✓	✓	✓	✓	✓	NA	✓ Forest, Grassland, Jungle, River	NA Asphalt, dirt, gravel, mud, ice, rocky dirt, wave, foam, réflexion, bending effect	NA
Project Chrono	✓ + Inverse	✓	✓	✓	✓ DAE	✓	✓ & FEM	✓	✓	✓	✓ Deformable, Granular dynamic	✓ Fluid-solid interaction	NA
Havok Games Dynamics SDK	✓ + Inverse	✓	✓	✓	✓	✓	(✓)	✓	✓	✓ Continuous	✓ Havok AI	✓ Havok AI	✓ Fog, Smoke
Applied Intuition	✓	✓	✓	✓	✓	NA	✓	✓	✓	✓	✓ Bumpy, uneven	✓ Interaction terrain & vegetation, dirt	✓ Weather, Wind effect, lighting
AirSim	✓	(✓) Unreal	(✓) Unreal	(✓) Unreal	✓	NA	NA	✓	NA	✓		Road wetness, Snow, leaves, Dust, bumps / flickering	Rain, Snow, Failling leaves, Fog, Wind direction

(✓) : by deduction

PRESENTATION OF PHYSICS FOR VEHICLES

SIMULATORS	VEHICLE DYNAMICS							VEHICLE BEHAVIOR			EQUATIONS
	Drivetrain	Braking	Suspension	Steering	Tires	Mass Distribution	Aerodynamics	Vehicle Behaviors	DoF	Loops SIL/HIL	
Gazebo Ignition	✓	✓	NA	✓	✓	✓	✓	✓ body	NA	NA	ODE: iterative & exact solver
AGX Dynamics for Unity	✓	✓	✓	✓	✓	✓	✓	✓	NA	NA	Iterative solver Direct solver DEMs -> non-smooth
Nvidia Omniverse	NA	✓	✓	✓	✓	✓	✓	NA	NA	NA	Newtonian equations of motion
CARLA	✓ Transmission	✓	✓ Soft to Rigid	✓	✓	✓	NA	✓	9	SIL/HIL MIL/DIL	NA
CoppeliaSim (V-REP)	✓ Powertrain	✓	✓ Damping	NA	NA	✓	NA	✓ planning	6		Determinist solver
BeamNG	✓	✓	✓	✓	✓	✓ Mass' node	✓	✓	NA	MIL	Deterministic mode
Project Chrono	✓ Powertrain	✓	✓	✓	✓	NA	NA	NA	NA	NA	DAE -> connect PDE -> Deform DVI -> non-smooth contact DAEs -> smooth contact DAEs and PDEs -> fluid-solid ODE -> First-order dynamic
Havok Games Dynamics SDK	✓	NA	✓	✓	NA	NA	✓	NA	NA	NA	Newtonian equations of motion
Applied Intuition	✓ Powertrain (CarSim)	✓ (CarSim)	✓ (SuspensionSim)	✓	✓ (CarSim)	NA	✓ (CarSim)	✓	NA	NA	NA
AirSim	NA	NA	NA	✓	NA	NA	NA	NA	NA	SIL/HIL	NA

ANALYSIS REPORT

Gazebo Ignition
Strength: Robotics and Community
Advantages: Particle/Fluid dynamics, Soft body, Add-Custom physics engine
Disadvantages: Slow with Bullet, Few ready-made models

AGX Dynamics for Unity
Strength: Off-road vehicle control, Environment modeling
Advantages: Powerful engines (Unreal, Unity), MuJoCo plugins, Havok, ...
Disadvantages: Annual Academic License (1: €2945, group: €5890)

Nvidia Omniverse
Strength: Powerful (Multi-GPU), Plugins and Lots of Middleware
Advantages: Particle and fluid dynamics, plugins,...
Disadvantages: Lots of middleware, License

CARLA (Car Learning to Act)
Strength : Vehicle Traffic, Cosimulation and RL Learning
Advantages: Physics (Unreal), Rllib integrations, Chrono, CarSim
Disadvantages: No Soft body

CoppeliaSim (V-REP)
Strength: Full kinematic (IK et FK), Multi-robot application
Advantages: Complete, Multi-physics (Bullet, ODE, Vortex and Newton)
Disadvantages: Lack of information on terrain modeling

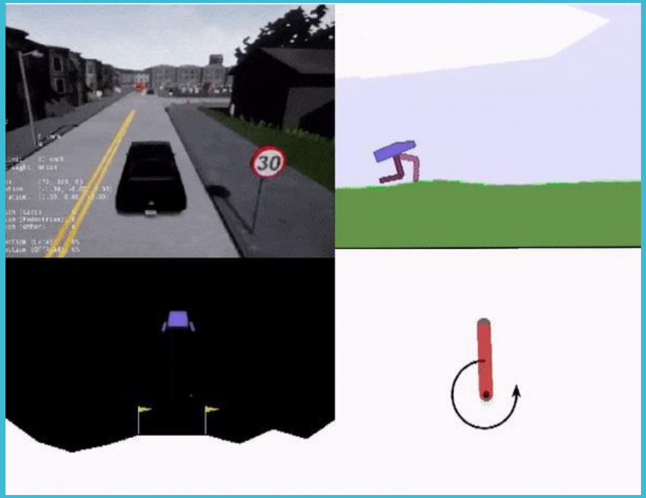
BeamNG (Beam Next Generation)
Strength: Drive vehicle complete
Advantages: Particle & Fluid dynamics, Soft body, Offroad, RL
Disadvantages: No Linux support, no Headless mode, more for gaming.

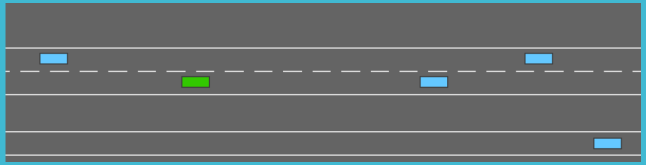
Havok Games Dynamics SDK
Strength : Robust simulation and AI for modeling environments
Advantages: Particle & Fluid dynamics, Soft body, AI
Disadvantages: No ROS support, more for video games.

Project Chrono
Strength : Multi-physics simulation, Multi-body analysis and FEM finite
Advantages: Multi-physics, Vehicle-Terrain interaction, Fluid-Solid interaction
Disadvantages: Recent, No much documentation, maintained by community

Applied Intuition
Strength : Physics vehicle, urban and Highways environment
Advantages: Vehicle-Terrain interaction, Offroad, Software tools for vehicles
Disadvantages: No API or documentation, Difficult to contact, ROS, Particle, fluid?

AirSim de Microsoft
Strength : Flight simulator
Advantages:
Disadvantages: Better on Windows





LEARNING ENVIRONMENTS

OpenAI Gym: is a toolkit for developing and comparing reinforcement learning algorithms.

Environments based on OpenAI Gym:

Gym-Ignition is designed for repeatable results and allows **parallel** or **headless** mode simulation while providing common **rigid body dynamics** utilities.

Wheeled Mobile Robot Dynamics Engine (WMRDE) is for simulation and **modeling** of **wheeled mobile robots** (WMR) and **tracked vehicles**.

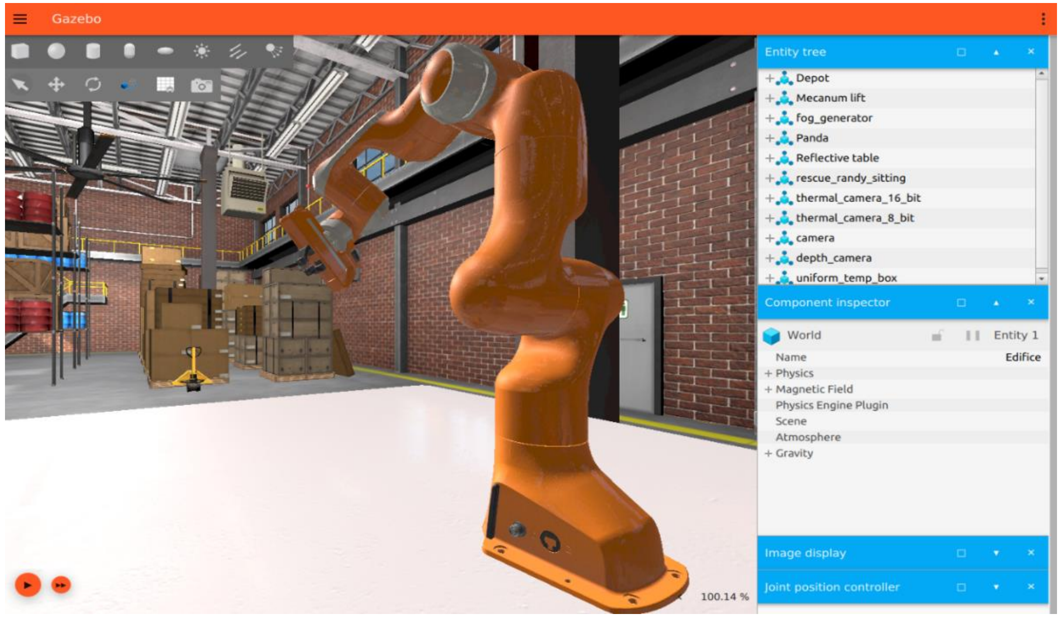
Highway-Env : A **collection of environments** for autonomous driving and **tactical decision-making tasks**.

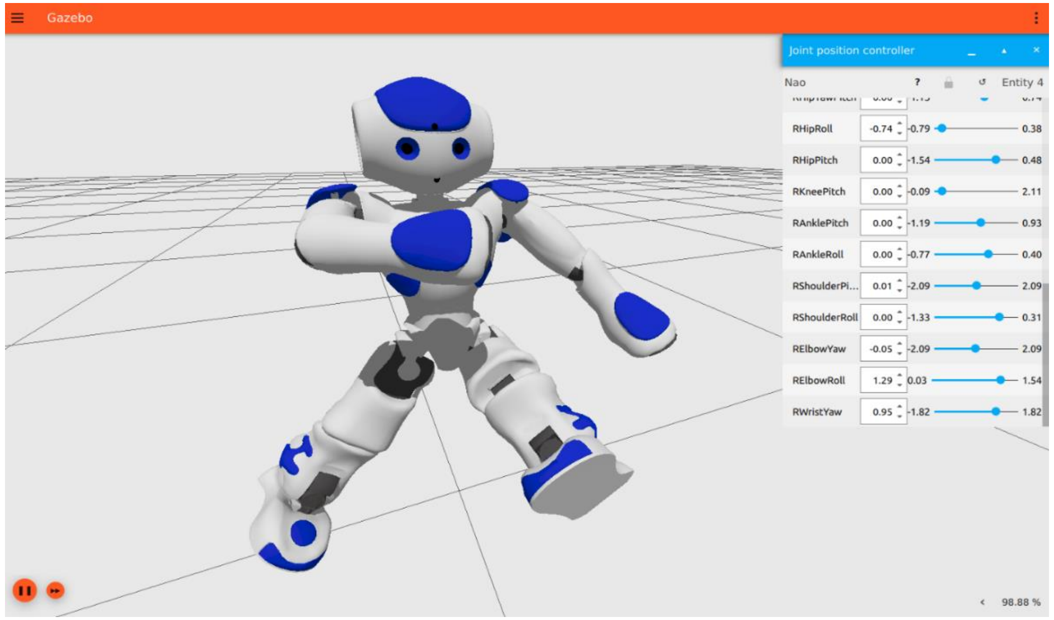
Gym Electric Motor (GEM) is an OpenAI Gym environment for simulating **electric motor control** and RL experiments.

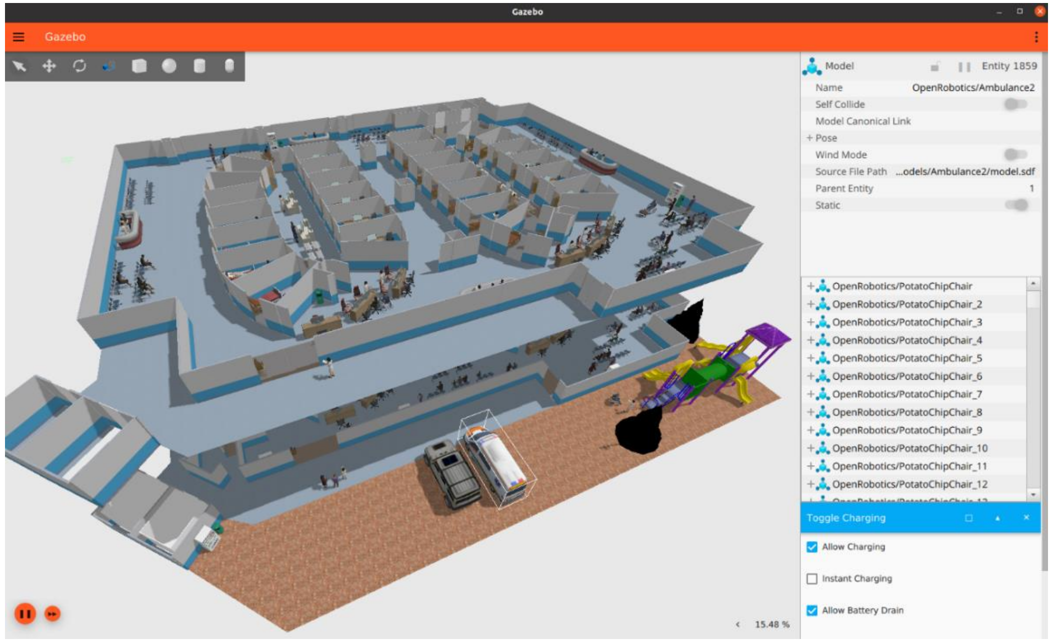
MuJoCo (Multi-Joint dynamics with Contact) is intended for **continuous control tasks**, performed in a **multi-body dynamics simulator with contact**.

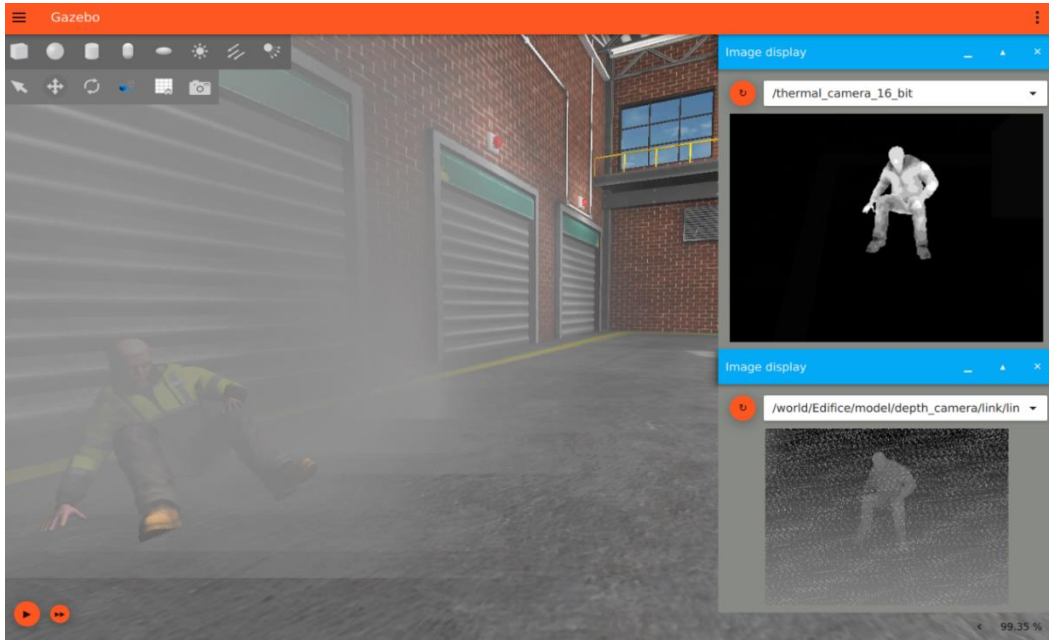
Gym-Chrono is a **set of continuous state and action space** DRL environments based on the **Chrono physics engine**.

INTERFACE: GAZEBO IGNITION (IMAGES)

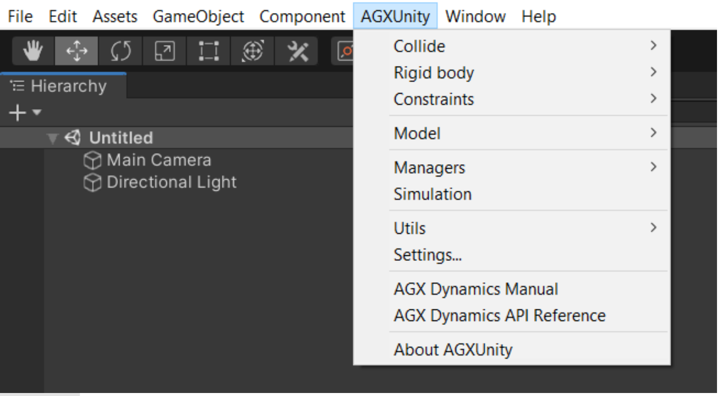


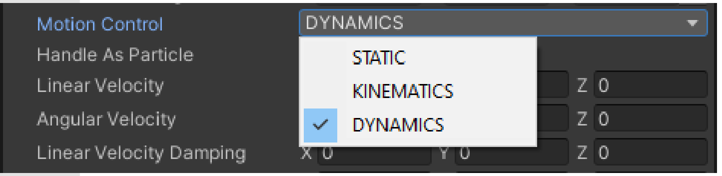


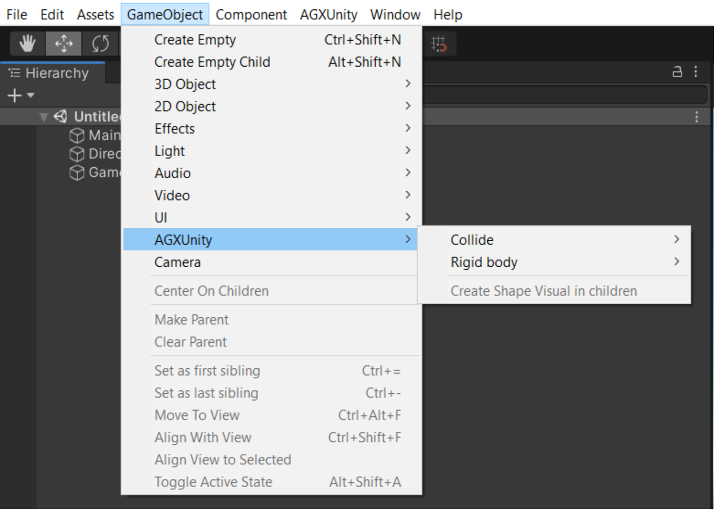


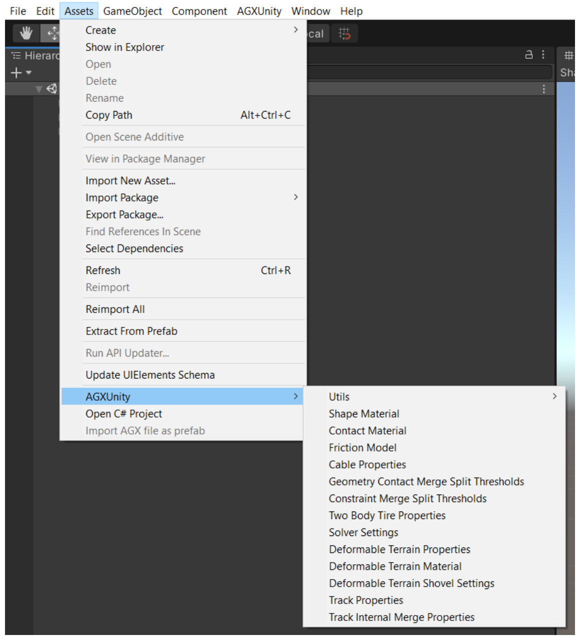


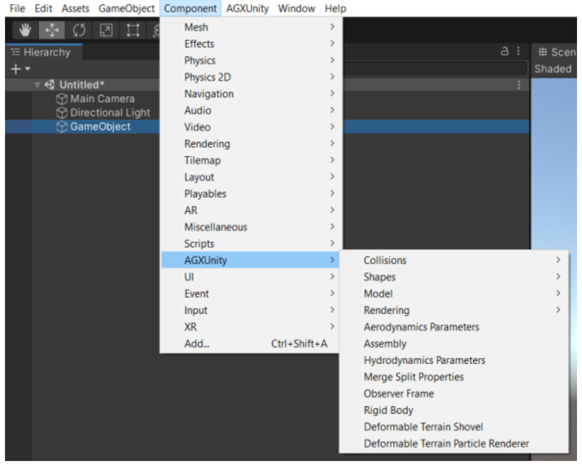
INTERFACE AGX DYNAMICS FOR UNITY (IMAGES)

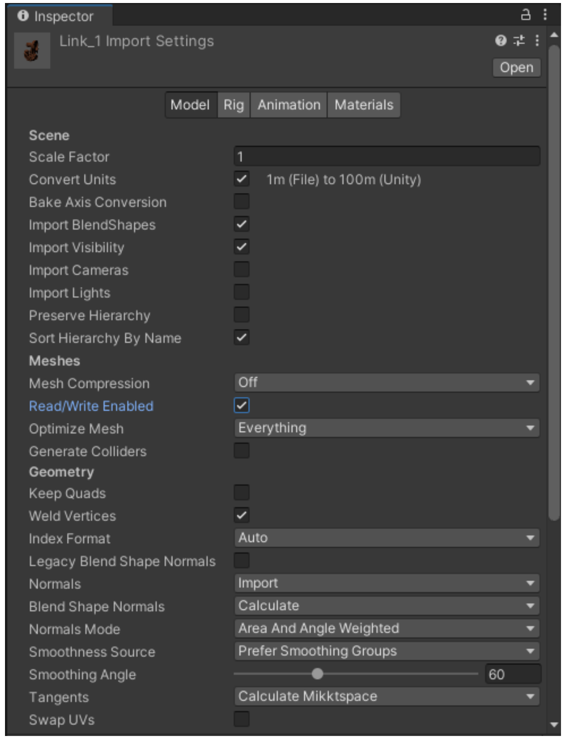


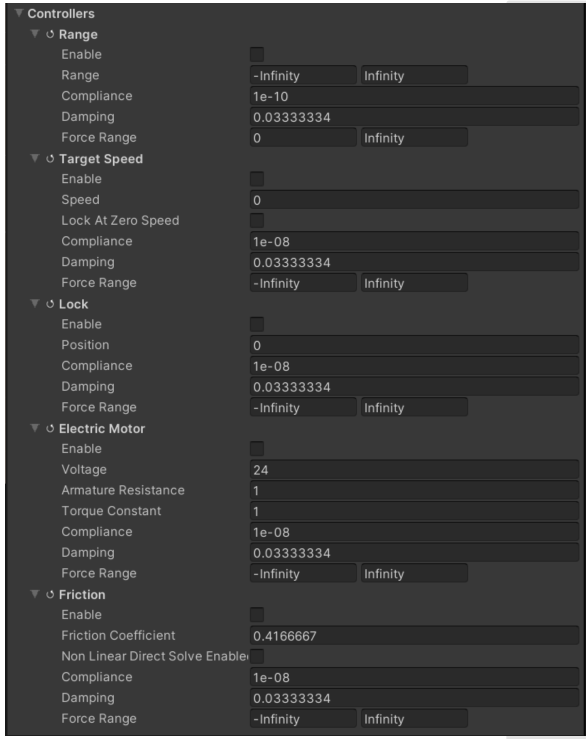




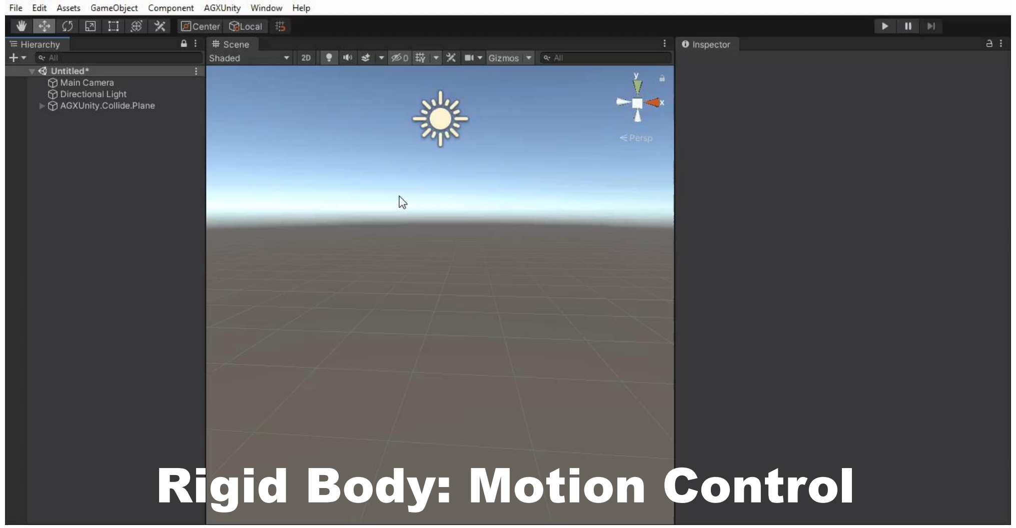


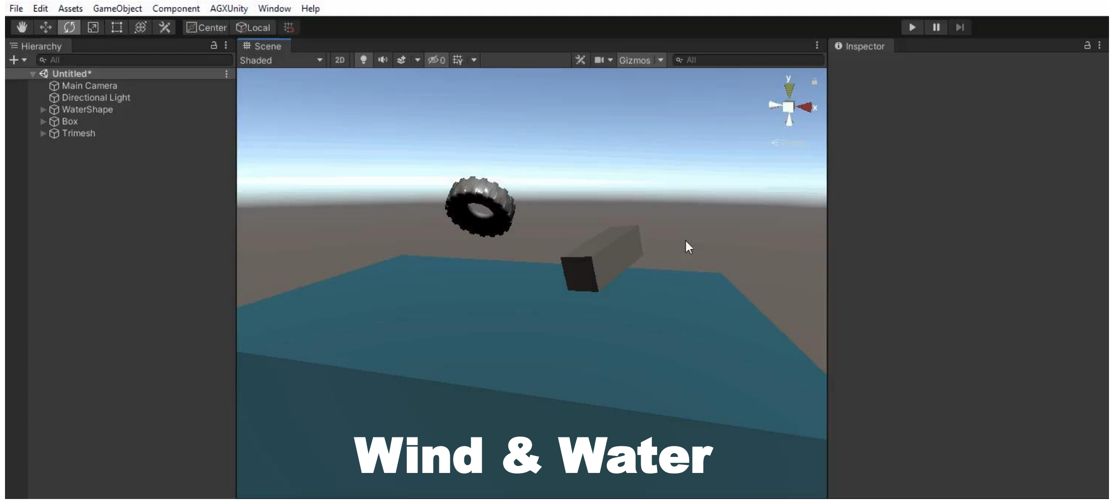


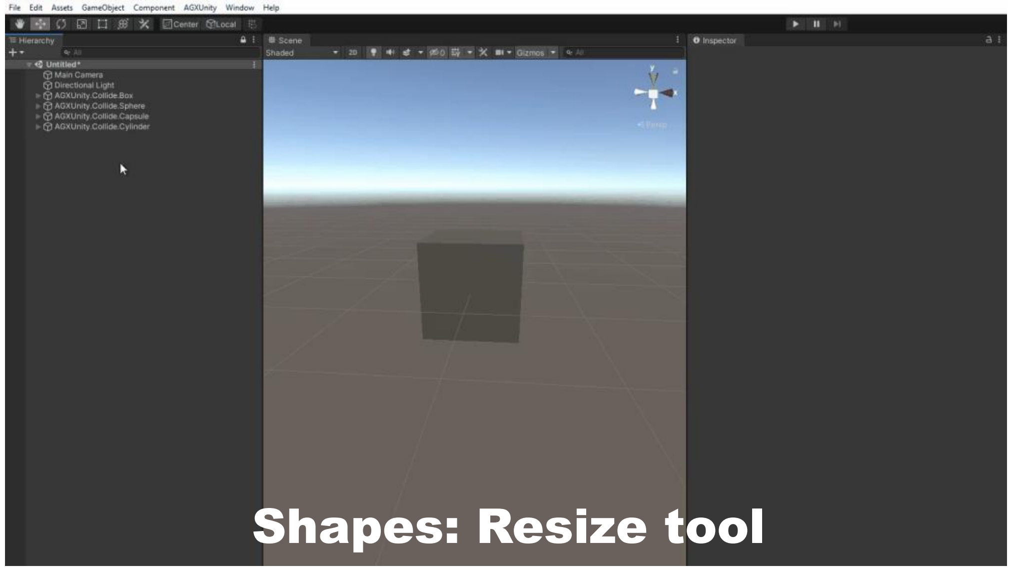


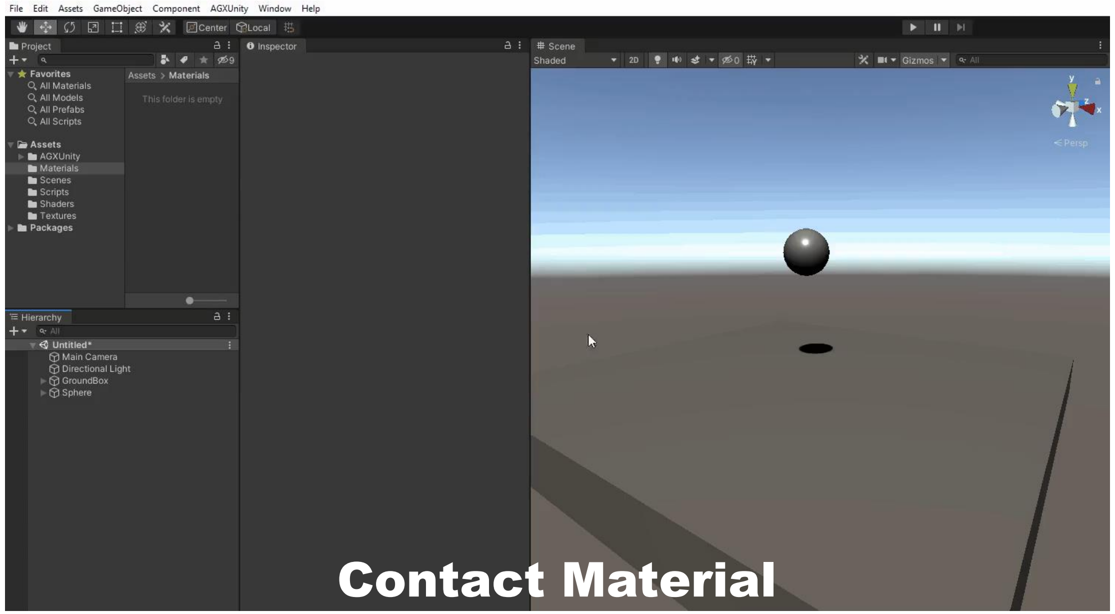


INTERFACE AGX DYNAMICS FOR UNITY (VIDEOS)









DYNAMICS: RIGID BODY

Rigid Body: the object is fixed.

Soft Body: the relative distance of two points on the object is not fixed and e corp garde sa forme contrairement à un Fluide

Méthodes:

- **Approximative**: Effet visuel mais non exacte
- **Précise**: Finite element simulation (FEM)

SOFT BODY DYNAMICS

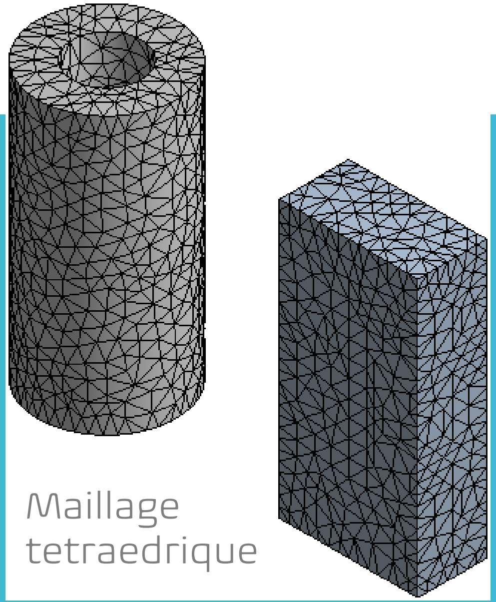
Approaches:

- Spring/mass models,
- Finite element simulation (FEM),
- Energy minimization methods,
- Shape matching
- Rigid-body based deformation (Havok Destruction)

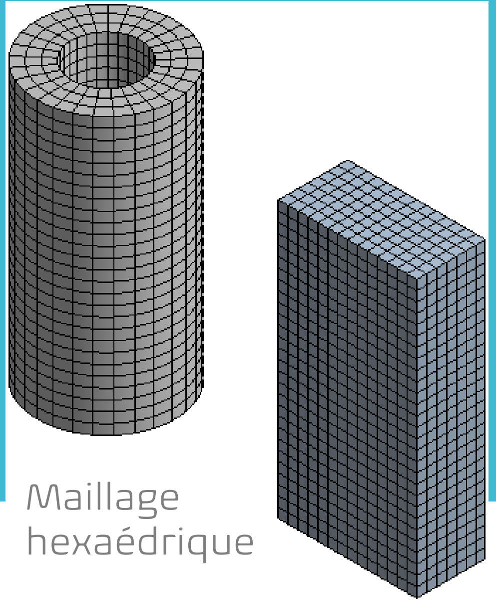
Solveurs basés

- **Force-Based Dynamics or Pressure-Based Dynamics**: is a system of ODEs (couteux)
  - The mass-spring model is a polygonal mesh representation 2D or 3D) and is solved via standard ODE solvers
- **Position-Based Dynamics (PBD)**: PhysX, Havok Cloth, Maya nCloth
  - The mass-spring model is converted into a system of constraints and is solved sequentially and iteratively.

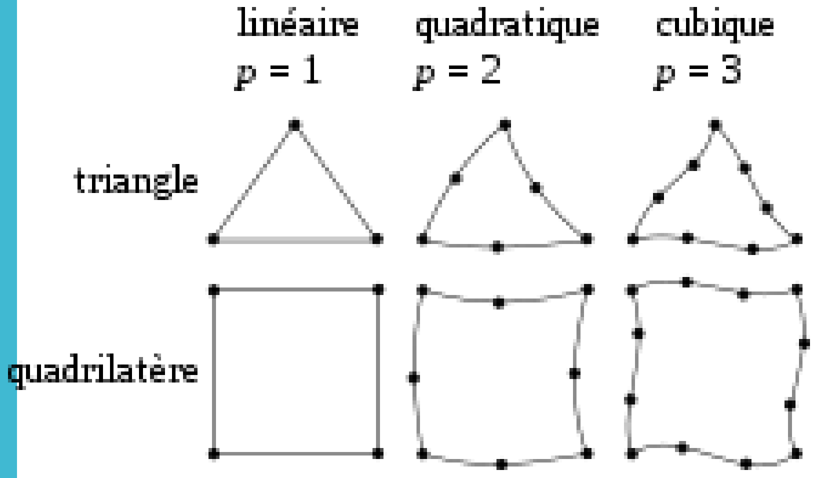
TYPES OF MESHES



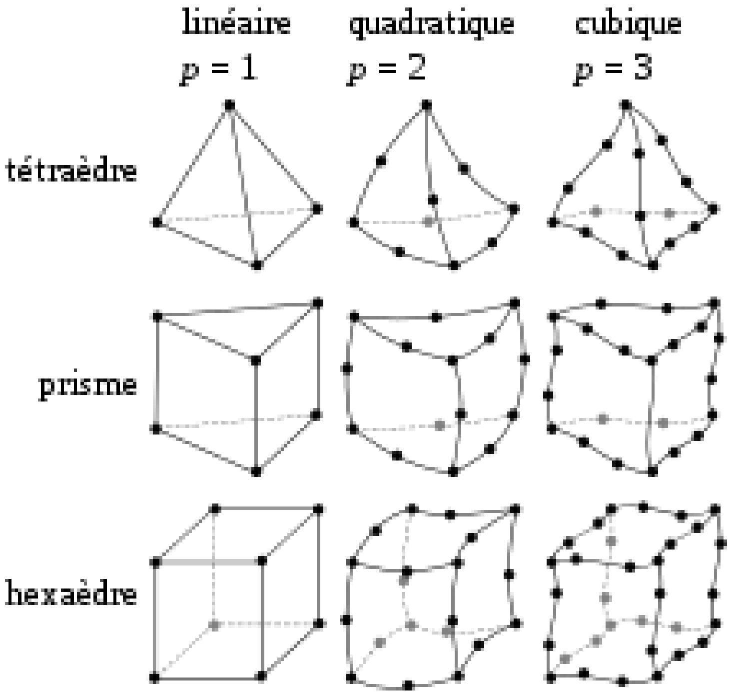
Maillage tetraedrique



Maillage hexaédrique



2D



3D

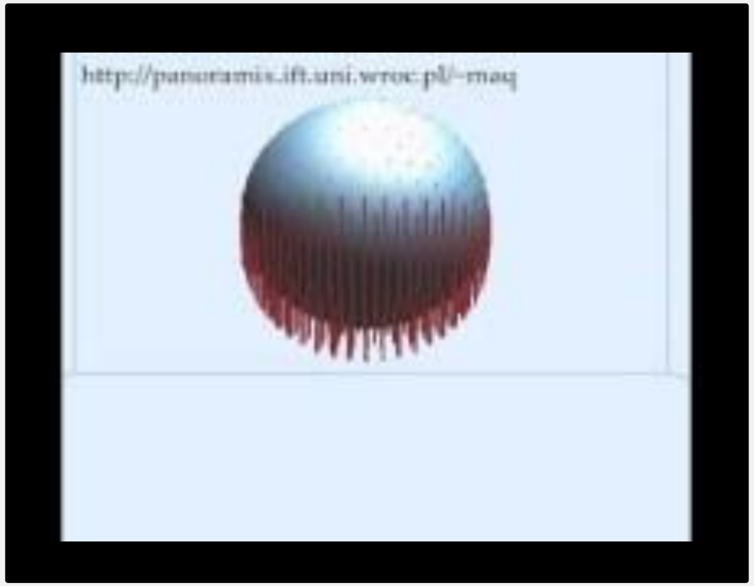
Triangle + Quadrilatere == Hybride

Souvent lineaire == Polyotopes

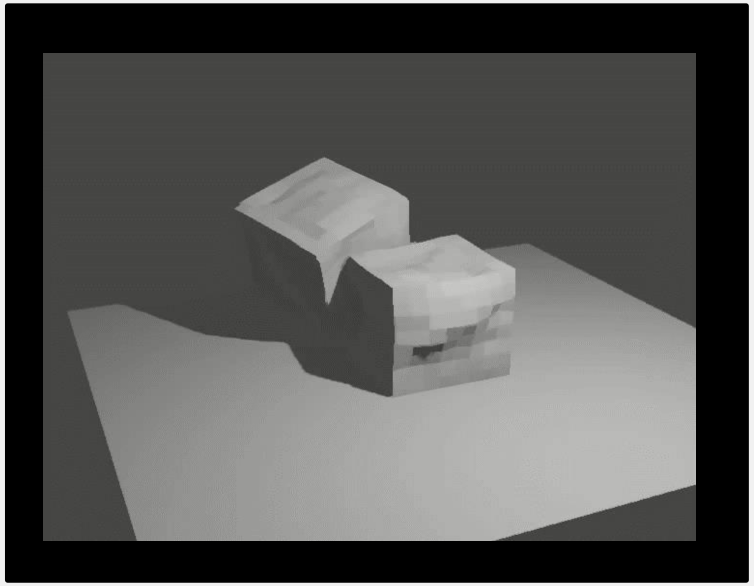
Polynomiaux de degré 2 ou +
== Maillage d’ordre géométrique élevé

SOFT BODY DYNAMICS

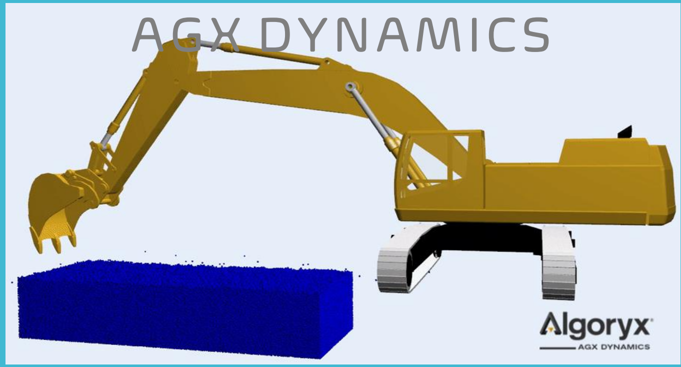
Properties of deformables objects

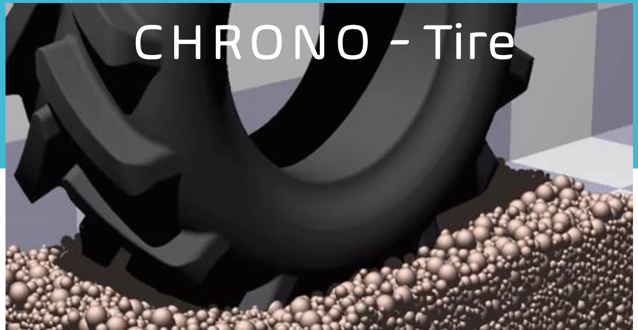


SOFT BODY
(Meshes)



SOFT BODY
(Meshes)





HAVOK Physics

BeamNG DRIVE