Autonomous and Mobile Robotics

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An Introduction to V-REP with an Application to Motion Planning

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outline

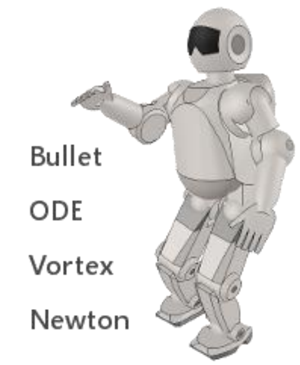
- introduction to V-REP
  - basic elements
  - dynamic modeling
  - C++ plugins
  - Matlab/Simulink interface
- application to motion planning
  - task-constrained motion planning with moving obstacles
  - problem formulation
  - approach
  - V-REP simulations

the V-REP simulator

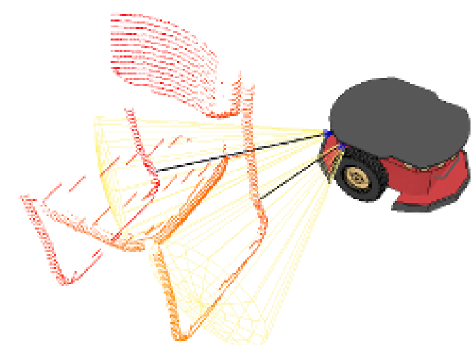
- V-REP = Virtual Robot Experimentation Platform
- a robotic simulator: a software environment aimed at generic robotic applications (not only motion planning)
- relatively new (2014), produced by Coppelia Robotics
- free and open source
- available on Windows, Linux and Mac
- example of applications
  - fast prototyping and verification
  - fast algorithm development
  - hardware control
  - etc

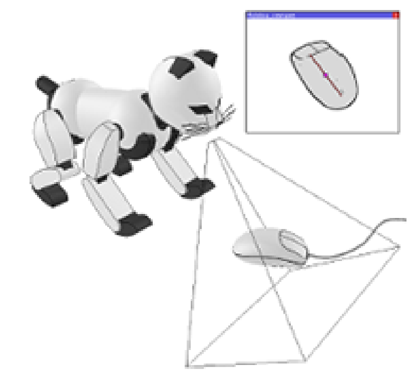
the V-REP simulator

- provides physical engines for dynamic simulations

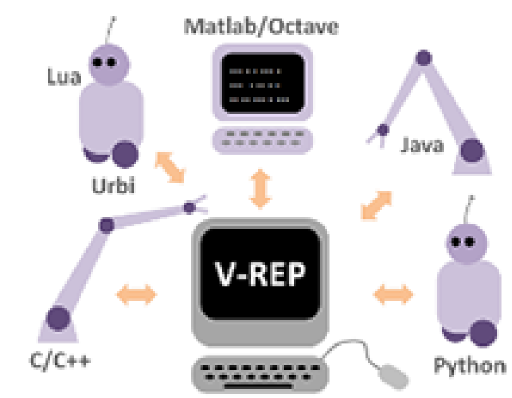


- allows the simulation of sensors





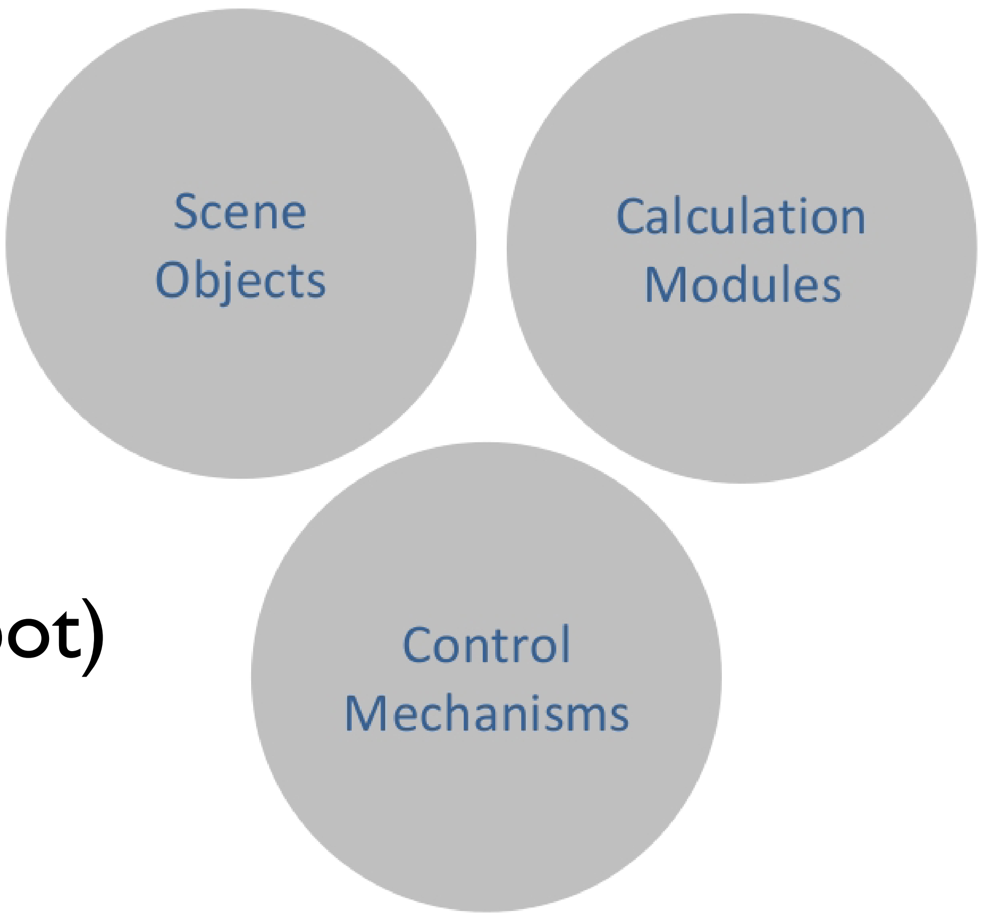
- its functionalities can be easily extended using many programming languages (C/C++, Python, Java, Lua, MATLAB, Octave, Urbi) and programming approaches (remote clients, plugins, ROS nodes,…)



- provides a large and continuously growing library of robot models

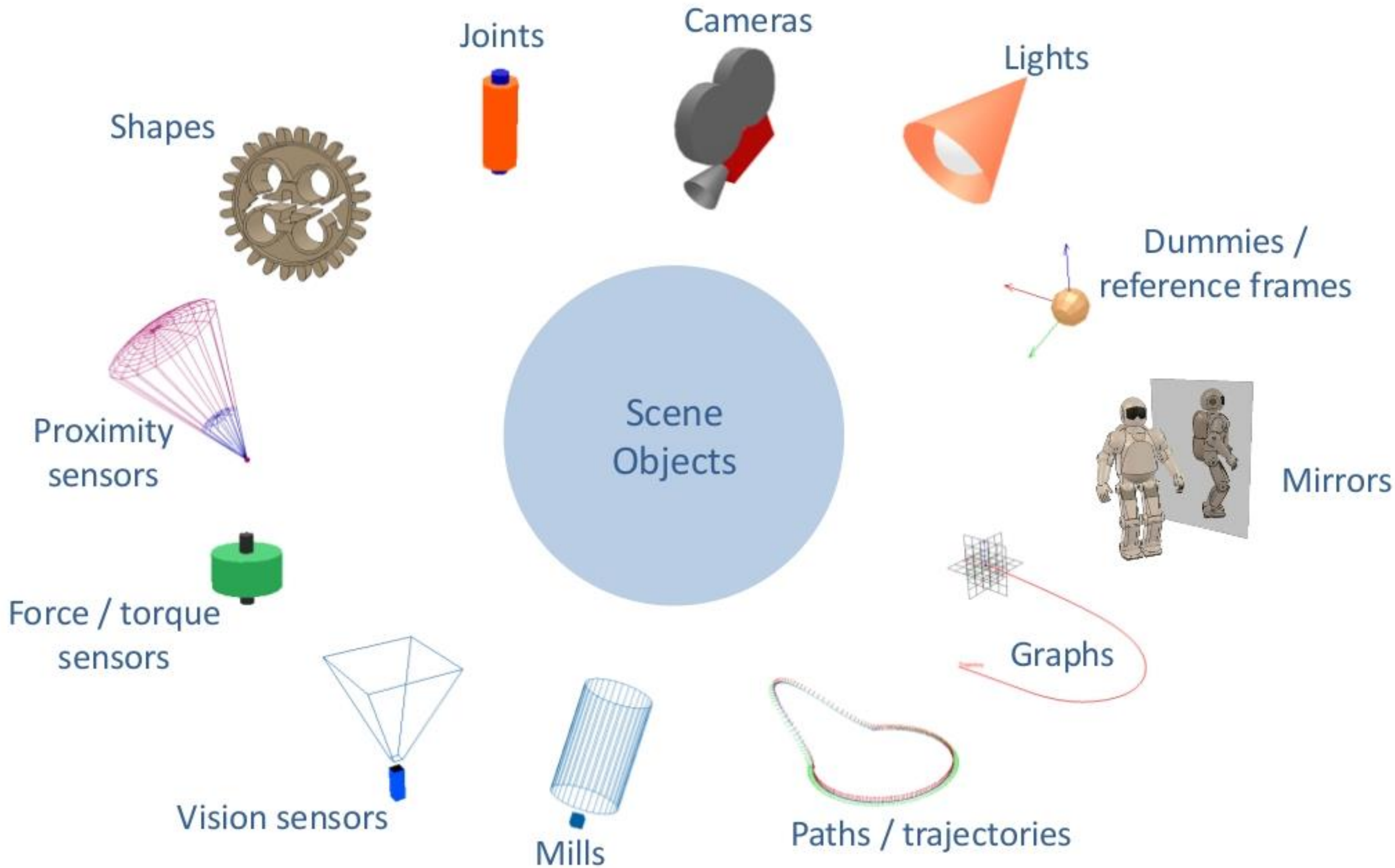
three central elements

- scene objects (how to build a robot)
  - basic building blocks
  - 12 different types
  - can be combined each other
- calculation modules (how to simulate a robot)
  - 5 basic modules
  - can be combined each other
- control mechanisms (how to control a robot)
  - 6 methods or interfaces
  - more than 7 programming languages
  - 6 methods can be used at the same time



scene objects

- how to build a robot

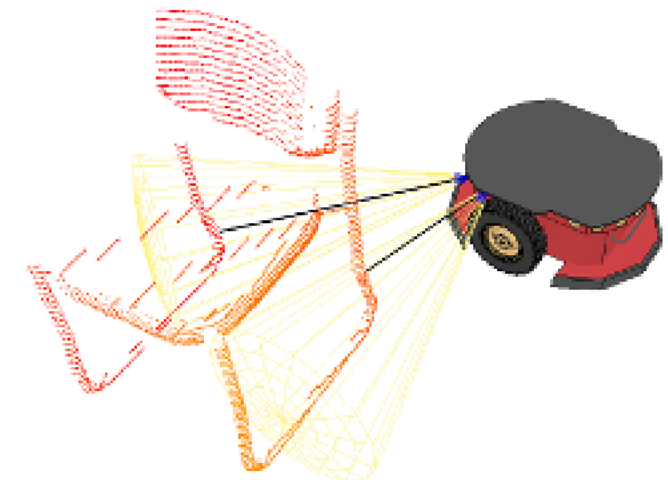


scene objects: basic components

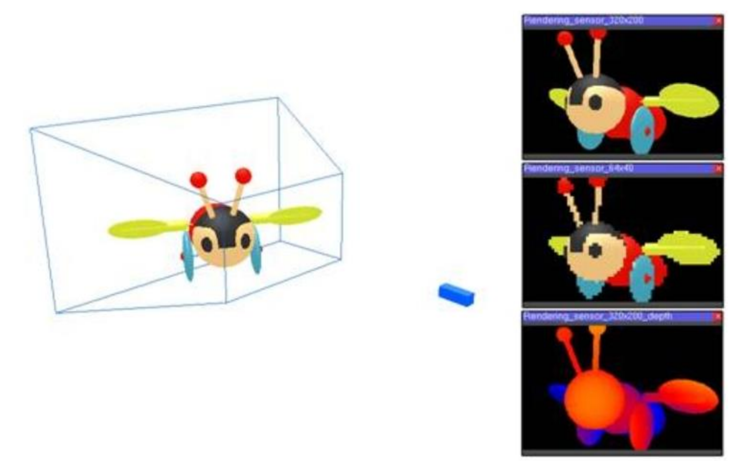
- shapes
  - rigid mesh objects that are composed of triangular faces
  - can be grouped/ungrouped
  - different types (random, convex, pure shapes)
- joints
  - revolute: rotational movement
  - prismatic: translational movement
  - screw: translational while rotational movement
  - spherical: three rotational movements
- a robot model can be created through a hierarchical structure including (at least) shapes and joints

scene objects: sensors

- proximity sensors
  - more than simple ray-type detection
  - configurable detection volume
  - fast minimum distance calculation within volume



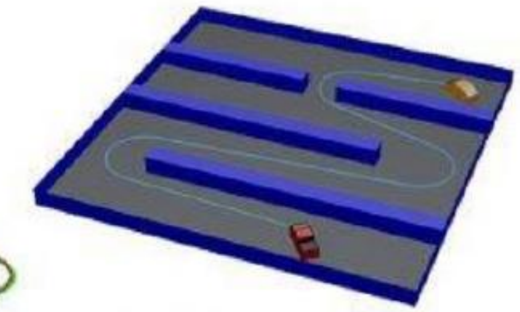
- vision sensors
  - render the objects that are in their field of view
  - embedded image processing
  - two different types: orthographic projection-type (e.g., close-range infrared or laser range finders) and perspective projection-type (e.g., camera-like sensors)



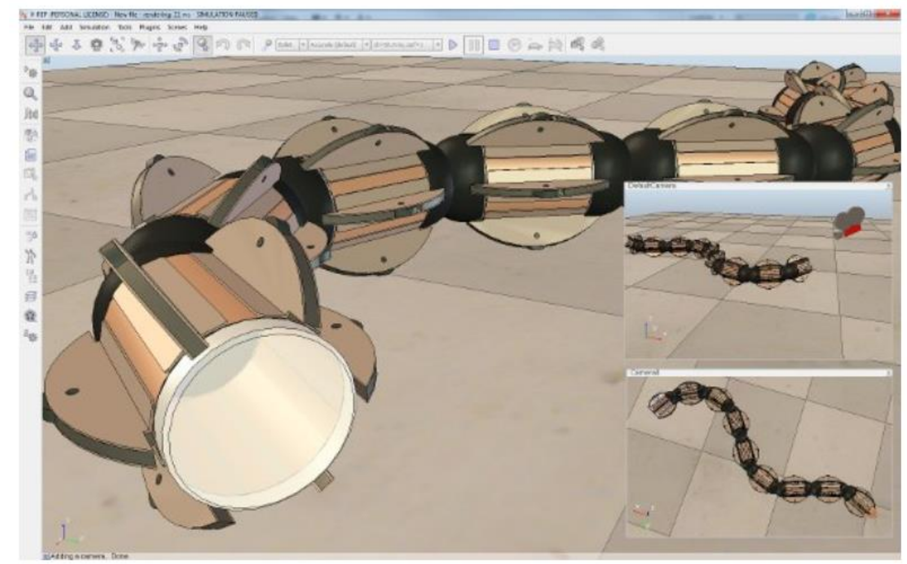
- torque/force sensors
  - measure applied force/torque (on 3 principal axes)

scene objects: other components

- paths/trajectories
  - allow 6D definitions
  - can be easily created
    (by importing a file or defining control points)



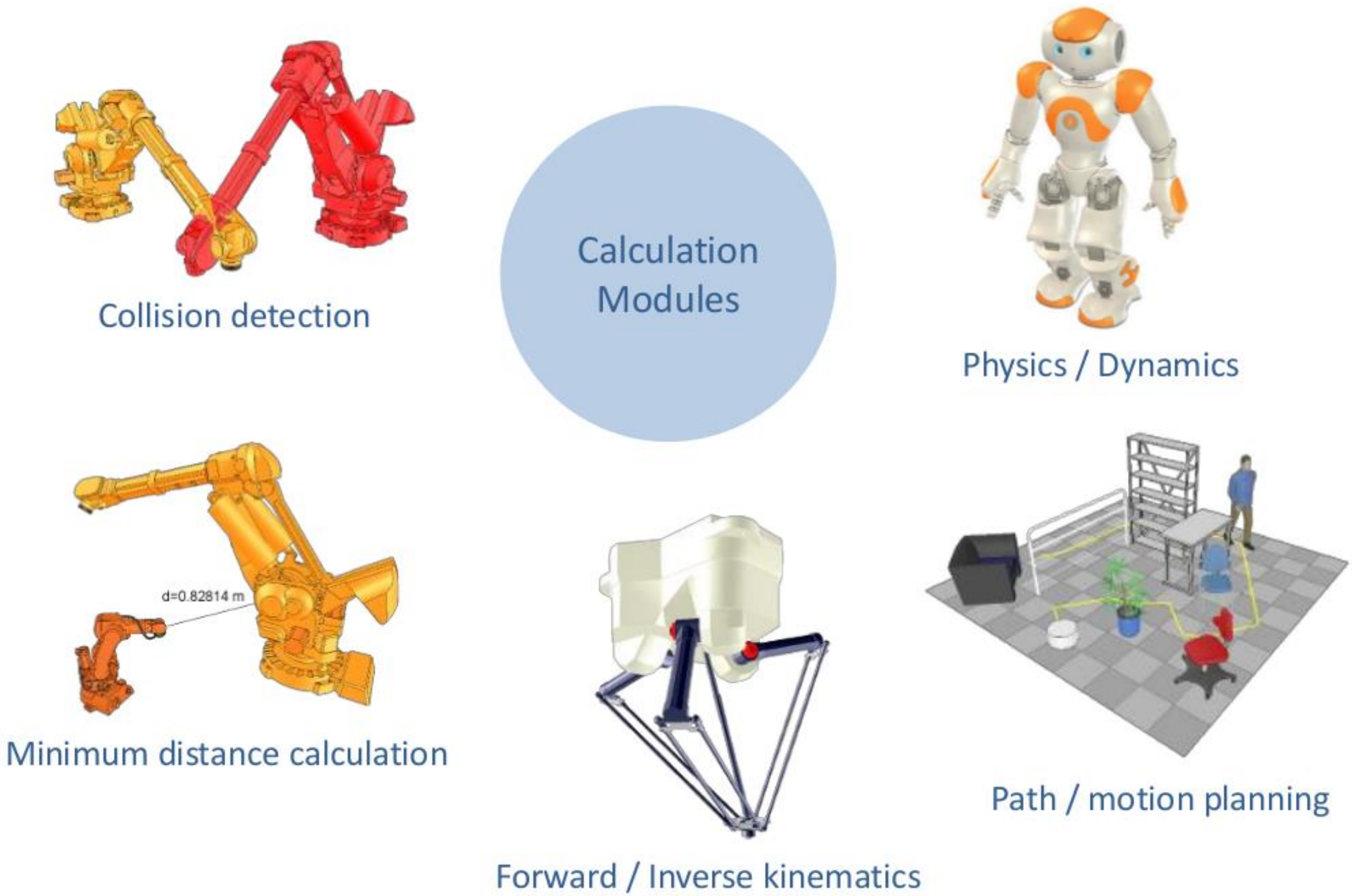
- cameras
  - perspective/orthographic projection
  - can track an object while moving



- lights: omnidirectional, spotlight, directional
- mirrors: reflect images/light, auxiliary clipping frame
- graphs: draw 3D curves, easily exportable
- mills: cutting operations
- dummies: auxiliary reference frame

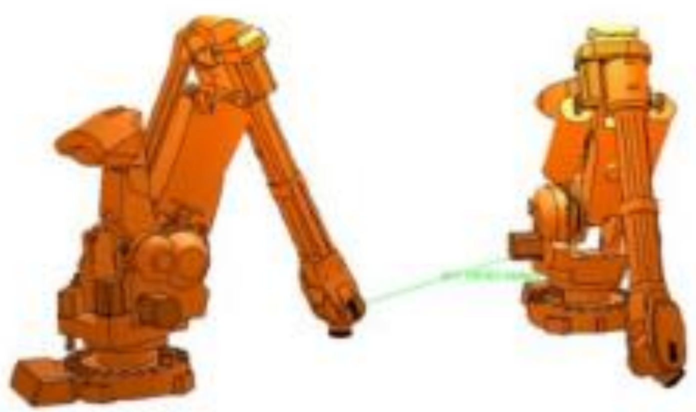
calculation modules

- how to simulate a robot



calculation modules

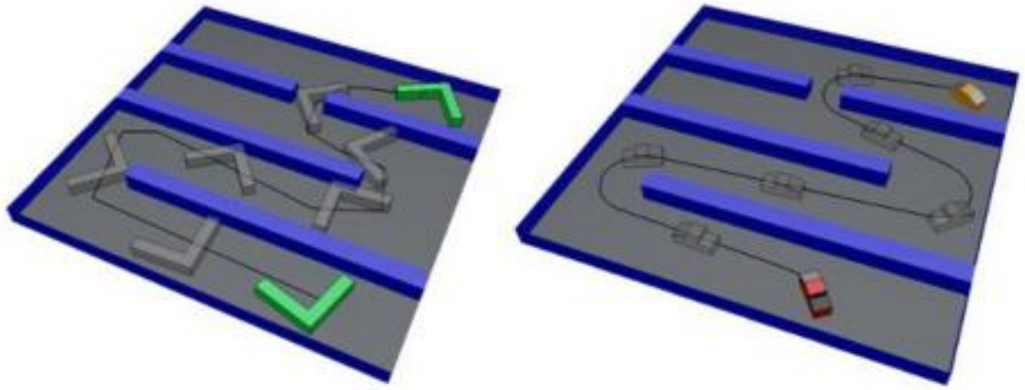
- forward/inverse kinematics
  - can be used for any kinematic chain (closed, redundant, …)
  - build inverse kinematic (IK) group
  - different techniques for inverse kinematics (pseudoinverse, damped least square)
  - accounts for joint limits and obstacle avoidance
- minimum distance computation
  - can be used between any pair of meshes
  - very fast and optimized



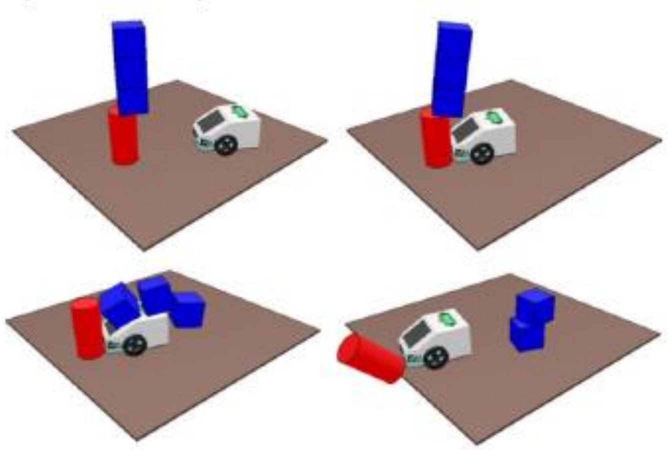
- collision detection
  - can be used between any pair of meshes
  - scene objects can be defined as collidable or not

calculation modules

- path/motion planning
  - can be performed for any kinematic chain
  - holonomic/non holonomic path planning
  - requires the specification of: start/goal configuration, obstacles, robot model
  - uses the OMPL library

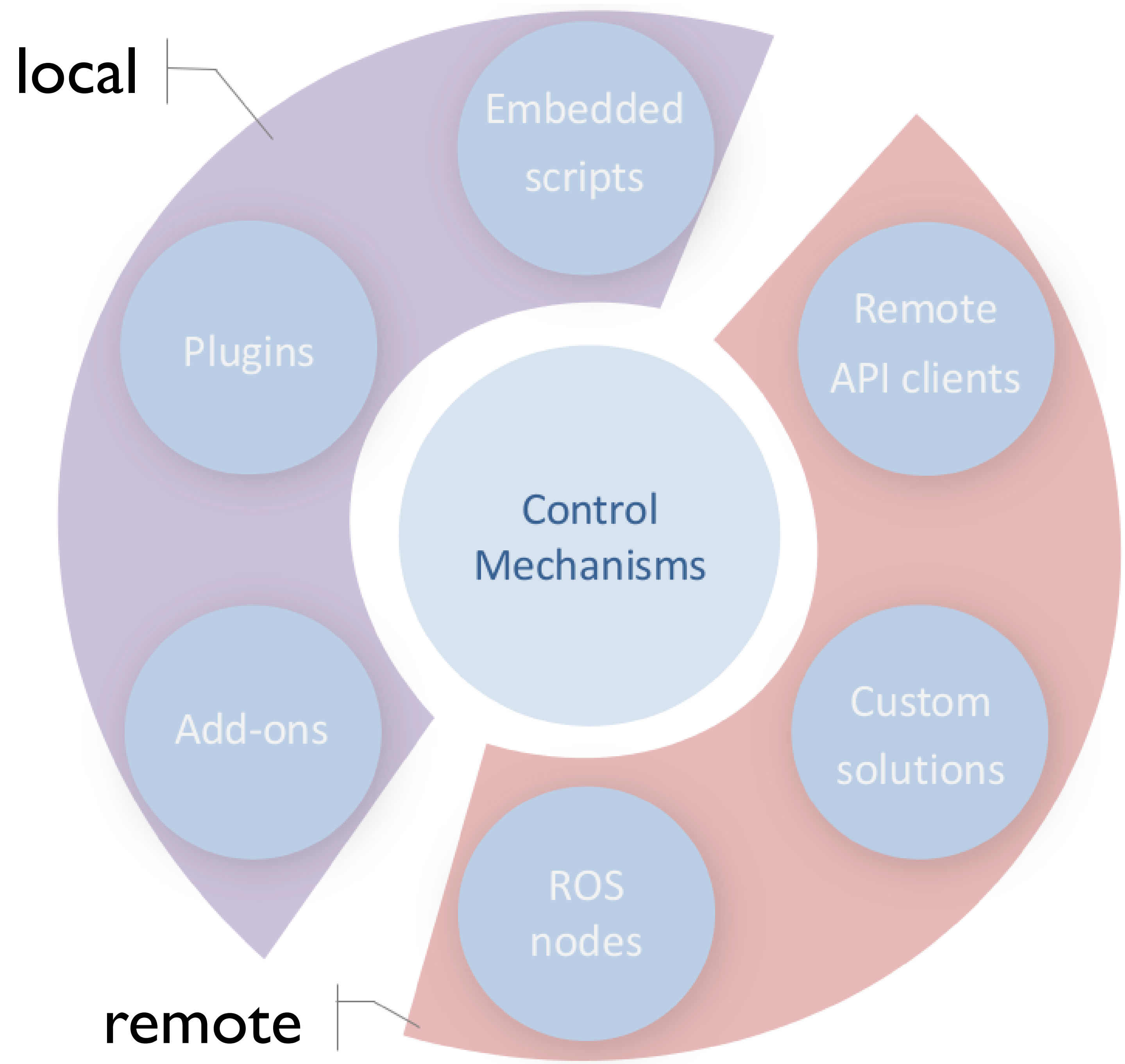


- physics/dynamics
  - enable dynamic simulations (gravity, friction, …)
  - four different physical engines: Bullet, ODE, Vortex, Newton (ordered by computational demand)
  - dynamic particles to simulate air or water jets



control mechanisms

- how to control a robot

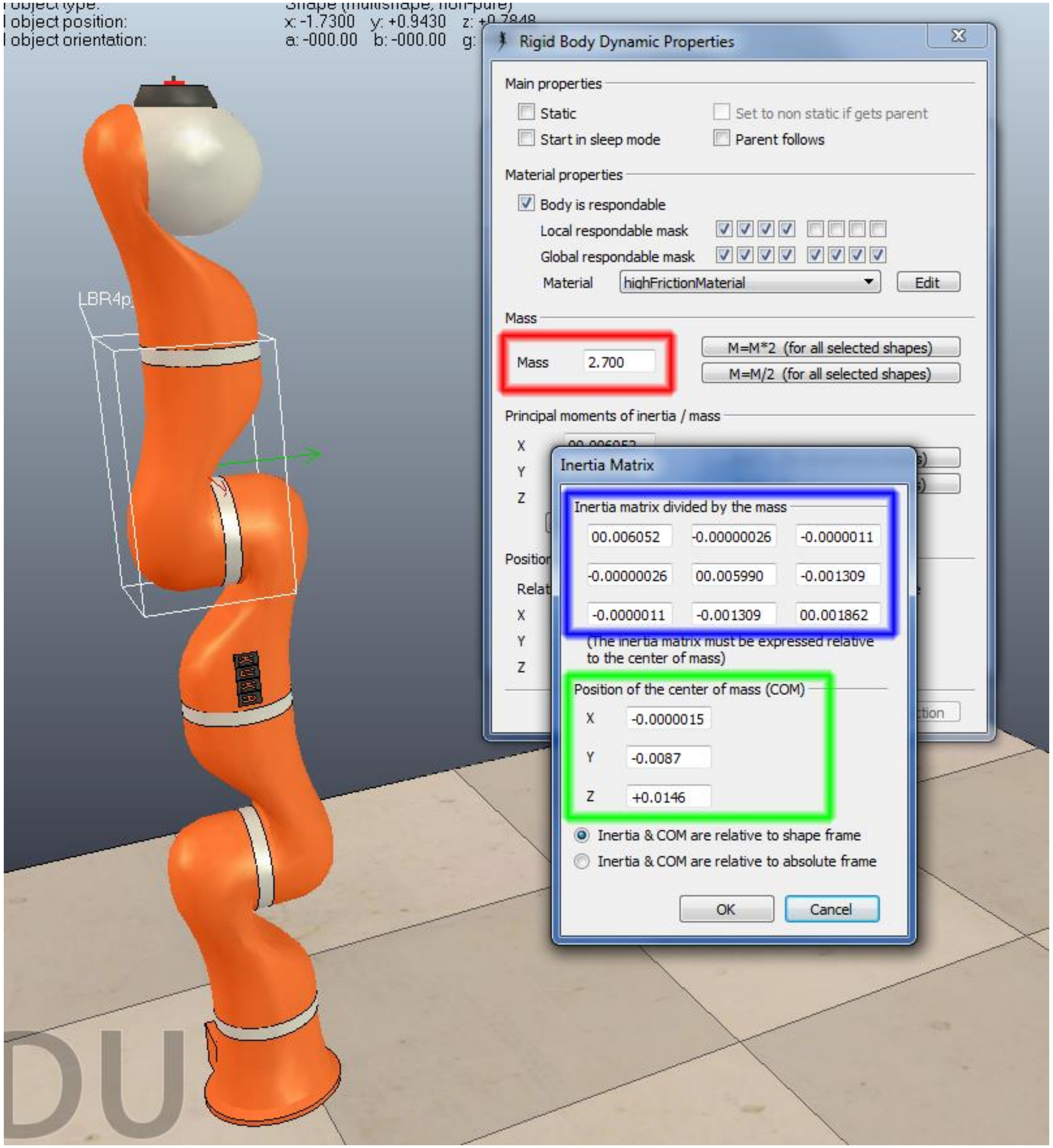


control mechanisms

- local approach: control entity is internal
  - embedded script: associated to a single robot
  - add-on: can only execute minimalistic code
  - plugin: most general tool, fast computation, written in C++
- remote approach: control entity is external
  - ROS node: bridge between V-REP and ROS
  - custom solution: client/server paradigm using the BlueZero framework
  - remote API client: communication between VREP and an external application (e.g., Matlab/Simulink)

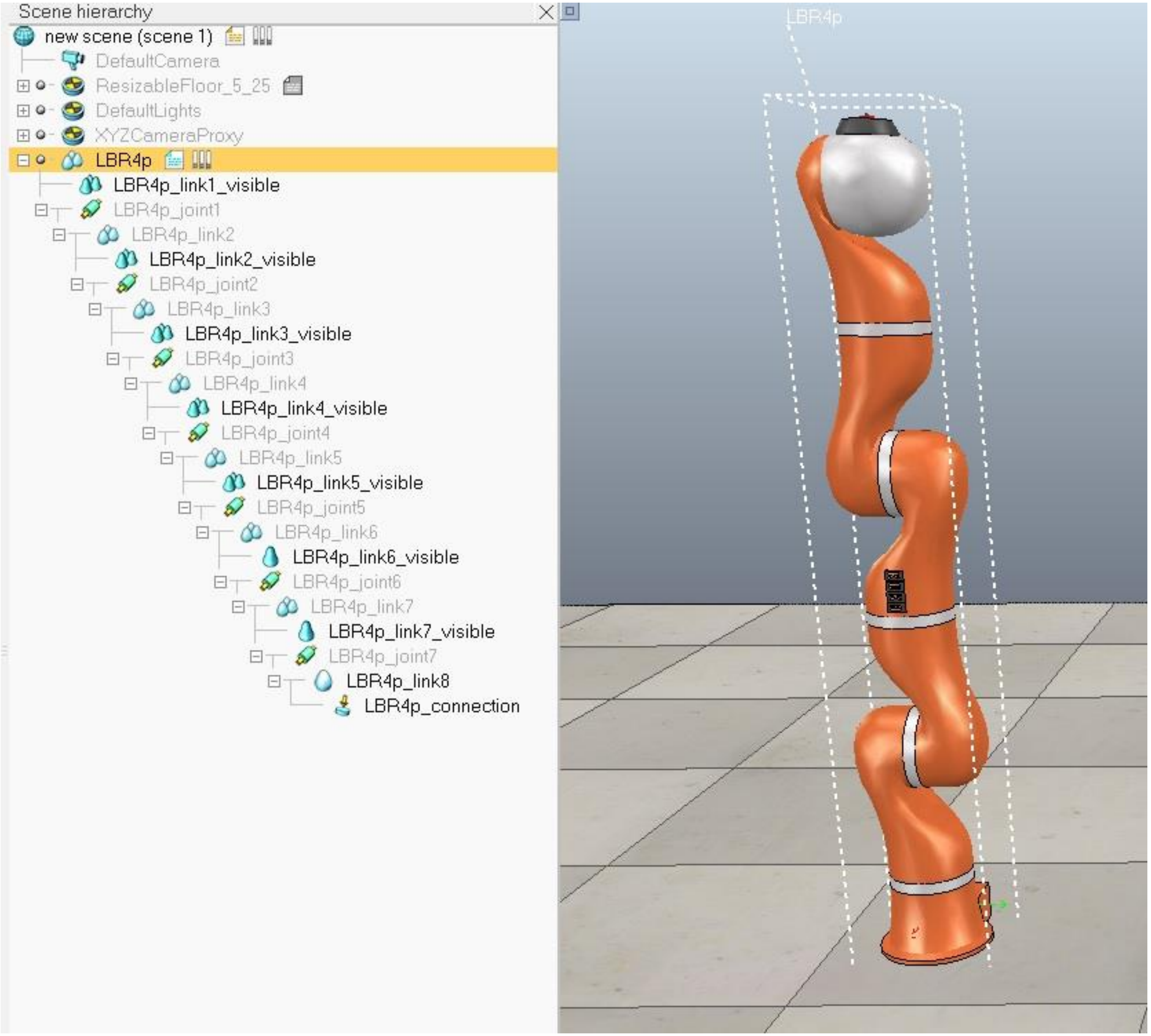
dynamic modeling of a robot

- building a dynamic model in V-REP is very easy: no equations are needed
- it requires a few simple steps:
  - 1) import a CAD model of the robot
  - 2) associate to each body of the robot its dynamic parameters: mass, center of mass, inertia matrix



dynamic modeling of a robot

- 3) build a model tree: a tree that represents all hierarchical information of the kinematic chains (links and joints)



C++ plugins

- uses the V-REP regular APIs (more than 450 functions available)
- produces a shared library (e.g., .so for Linux and .dll for Windows)
- automatically loaded by V-REP at program start-up
- can be integrated with other C++ libraries (e.g., Eigen, Octomap, etc)
- two main applications
  - extend V-REP's functionality through user-written functions (e.g., motion planning algorithms, controllers, …)
  - used as a wrapper for running code written in other languages
- a single plugin can manage more than one robot
- fast execution (particularly suited for motion planning)

C++ plugins

- at each event in the V-REP interface, a corresponding message is sent to the plugin
- each message triggers the execution of a particular portion of the code in the plugin

before starting the simulation ("offline" functions)

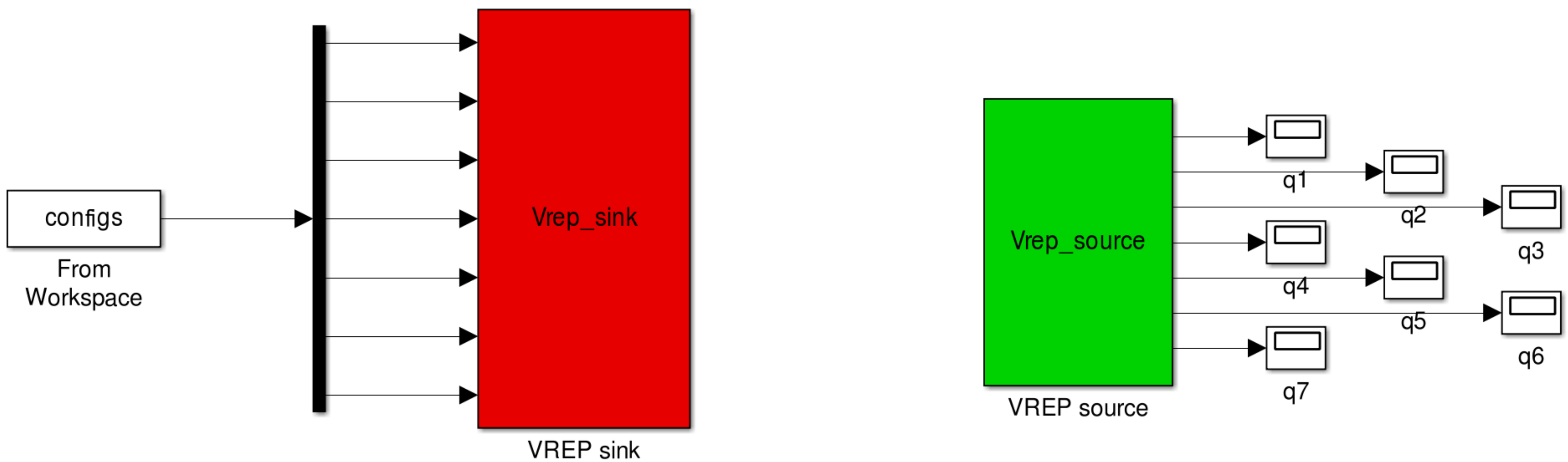
simulation is stopped

```
if (message == sim_message_eventcallback_simulationabouttostart) { // Simulation is about to start
    Planning();
}
if (message == sim_message_eventcallback_simulationended) { // Simulation just ended
    std::cout << "Simulation Concluded" << std::endl;
}
if (message == sim_message_eventcallback_modulehandle) { // Simulation is running
    Execution();
}
```

during the simulation ("online" functions)

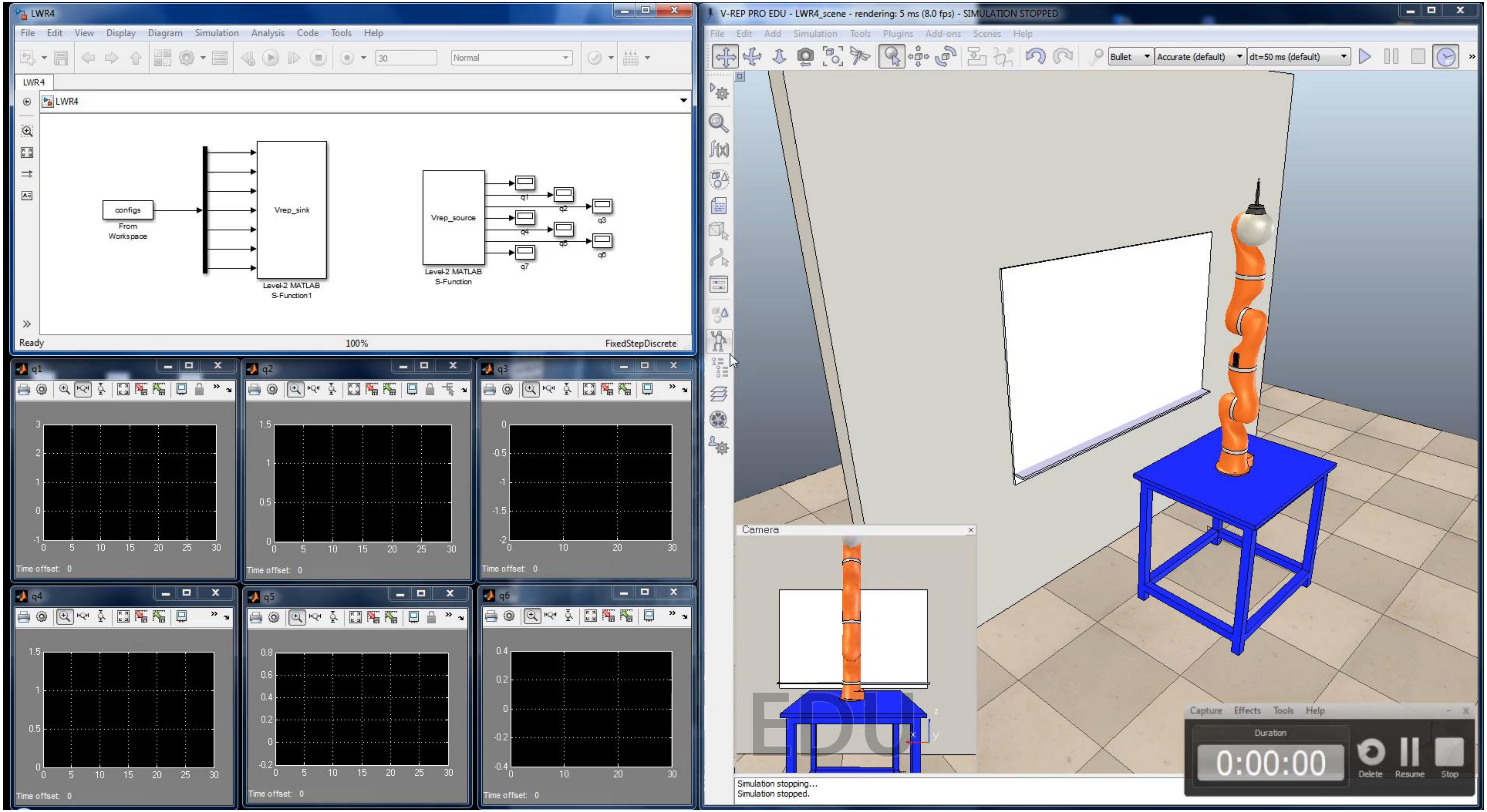
Matlab/Simulink interface

- uses the V-REP remote APIs (more than 100 functions available)
- an interface for sending/receiving commands to/from V-REP
- two main blocksets: V-REP sink and V-REP source respectively sends/reads values from V-REP joints



- V-REP and Matlab/Simulink times automatically synchronized
- Matlab/Simulink commands start/stop V-REP simulations

Matlab/Simulink interface



summary

- V-REP main advantages
  - very good online documentation
  - four different physics engines
  - most complete open source software for dynamic simulations
  - very good set of APIs and control mechanisms
  - very fast software development when one gets the V-REP structure
- V-REP main drawbacks
  - vision sensors have high computational payload
  - since it is a huge software, it is not so friendly at the beginning
  - multi-robot simulations have high computational payload
  - collision checking library is slow

task-constrained motion planning with moving obstacles

- consider
  - a robot whose configuration $\boldsymbol{q}$ takes values in an n-dimensional configuration space
  - an assigned task path $\boldsymbol{y}_d(s)$, $s \in [s_{ini}, s_{fin}]$, that takes values in an m-dimensional task space
  - an environment populated by fixed and moving obstacles
- assume
  - the robot is redundant wrt the task ($n > m$)
  - obstacle trajectories are known
- the TCMP-MO problem consists in finding a feasible, collision-free configuration space trajectory that allows the robot to exactly execute the assigned task

problem formulation

- kinematic case
  - robot described by the kinematic-level model $\dot{\boldsymbol{q}} = \boldsymbol{v}$
  - generalized velocities can be expressed as $\dot{\boldsymbol{q}} = \dot{s}\boldsymbol{q}'$
- dynamic case
  - robot described in the Euler-Lagrange form $\boldsymbol{B}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{n}(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \boldsymbol{\tau}$
  - generalized accelerations can be expressed as $\ddot{\boldsymbol{q}} = \dot{s}^2\boldsymbol{q}'' + \ddot{s}\boldsymbol{q}'$
- a solution to the TCMP-MO problem consists of a configuration-space trajectory $\boldsymbol{q}(t)$, composed by a path $\boldsymbol{q}(s)$ and a time history $\boldsymbol{s}(t)$, such that:
  - joint velocity limits (kinematic case) or joint velocity/torque limits (dynamic case) are respected
  - the assigned task path is continuously satisfied
  - collisions are always avoided

approach

- an offline randomized algorithm
- builds a tree, similarly to the RRT, to search for a solution in the planning space
  - a vertex contains a state of the robot and an associated time instant
  - an edge between two adjacent vertexes represents a feasible collision-free subtrajectory in the configuration space
- makes use of N samples of the assigned path $\{\boldsymbol{y}_1, \ldots, \boldsymbol{y}_k, \ldots \boldsymbol{y}_N\}$
- each sample is located in correspondence of a value of the parameter s in the predefined sequence $\{s_1 = s_{ini}, \ldots, s_k, \ldots s_N = s_{fin}\}$
- the algorithm has been implemented as a C++ plugin for V-REP

planning for the kinematic case

- root the tree at $(\boldsymbol{q}_{ini}, 0)$
- iteratively
  - randomly select a sample $\boldsymbol{y}_{rand}$
  - compute an IK solution $\boldsymbol{q}_{rand} = \boldsymbol{f}^{-1}(\boldsymbol{y}_{rand})$
  - randomly assign to $\boldsymbol{q}_{rand}$ a time instant t_{rand}
  - search the closest vertex $(\boldsymbol{q}_{near}, t_{near})$ to $(\boldsymbol{q}_{rand}, t_{rand})$, and extract s_k associated to $\boldsymbol{q}_{near}$
  - randomly choose two values of $\dot{s}$ (forward/backward motions)
  - randomly choose $\widetilde{\boldsymbol{w}}$
  - numerically integrate (forward/backward motions)

$$\boldsymbol{q}' = \boldsymbol{J}^{\#}\left(\pm\boldsymbol{y}_d' + k_p \boldsymbol{e}_y\right) + (\boldsymbol{I} - \boldsymbol{J}^{\#}\boldsymbol{J})\widetilde{\boldsymbol{w}}$$

  - if no violation occurs, add new vertices and edges to the tree

planning for the dynamic case

- root the tree at $(\boldsymbol{q}_{ini}, \dot{\boldsymbol{q}}_{ini}, 0)$
- iteratively
  - randomly select a sample $\boldsymbol{y}_{rand}$
  - compute an IK solution $\boldsymbol{q}_{rand} = \boldsymbol{f}^{-1}(\boldsymbol{y}_{rand})$
  - randomly assign to $\boldsymbol{q}_{rand}$ a time instant t_{rand} and a generalized velocity $\dot{\boldsymbol{q}}_{rand}$
  - search the closest vertex $(\boldsymbol{q}_{near}, \dot{\boldsymbol{q}}_{near}, t_{near})$ to $(\boldsymbol{q}_{rand}, \dot{\boldsymbol{q}}_{rand}, t_{rand})$, and extract s_k associated to $\boldsymbol{q}_{near}$
  - randomly choose two values of $\ddot{s}$ (accelerating/decelerating motions)
  - randomly choose $\tilde{\boldsymbol{z}}$
  - numerically integrate (accelerating/decelerating motions)
$$\boldsymbol{q}'' = \boldsymbol{J}^{\#}\left(\boldsymbol{y}_d'' - \boldsymbol{J}'\boldsymbol{q}' + k_p\boldsymbol{e}_y + k_d\boldsymbol{e}_y'\right) + (\boldsymbol{I} - \boldsymbol{J}^{\#}\boldsymbol{J})\tilde{\boldsymbol{z}}$$
  - if no violation occurs, add new vertices and edges to the tree

V-REP simulations

references

- V-REP User Manual, link: http://www.coppeliarobotics.com/helpFiles/index.html
- V-REP Remote APIs, link: http://www.coppeliarobotics.com/helpFiles/en/remoteApiFunctionListAlphabetical.htm
- V-REP Regular APIs, link: http://www.coppeliarobotics.com/helpFiles/en/apiFunctionListAlphabetical.htm
- M. Cefalo, G. Oriolo, "*A general framework for task-constrained motion planning with moving obstacles*"– Robotica, vol. 37, pp. 575-598, 2019