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OpenSoT: a Software Tool for Advanced Whole-Body Control

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OpenSoT: a Software Tool for Advanced Whole-Body Control

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CENTERED MECHATRONICS



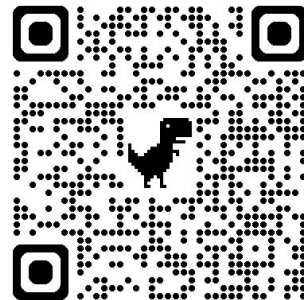
OpenSoT

Whole-Body Control

- Defines a set of low-dimensional rules, e.g. equilibrium, self collision avoidance, ...
- Guarantees the correct execution of single task and/or simultaneous multiple tasks, e.g., reaching different objects simultaneously with different end-effectors
- Exploits the full capabilities of the entire body of redundant, floating-based robots in compliant multi-contact interaction with the environment



IEEE-RAS Technical Committee for Whole-Body Control



ieewbc.org

Open Stack of Tasks (OpenSoT)

OpenSoT is a C++ library designed to streamline the process of writing and solving QP and LP tailored to whole-body control and robotic applications:

- focus on instantaneous (reactive) whole-body control problems
- modular, scalable, and easy-to-use
- designed for research, educational, and industrial applications



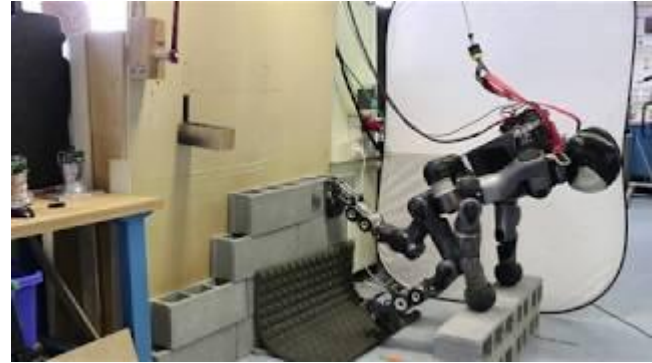
<https://github.com/ADVRHumanoids/OpenSoT>

I





Hierarchical Cartesian Impedance Control



Whole-Body Inverse Kinematics + Statics



Whole-Body Inverse Kinematics

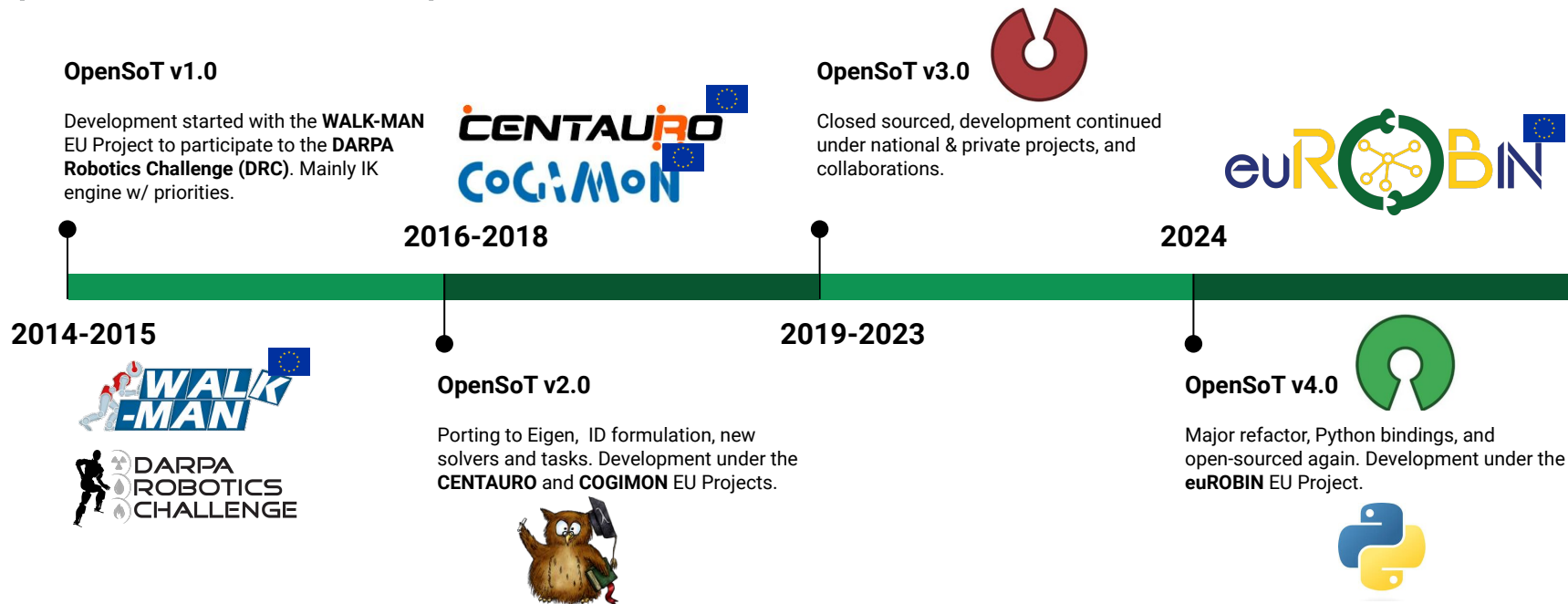


Whole-Body Inverse Kinematics

Features

- **Robot-Agnostic:** support to generic fixed-/floating-base systems
- **Efficient:** based on [Eigen](#) for fast and real-time computation
- **Ready & Easy to Use:** out-of-the-box library of *Tasks* and *Constraints* to create complex control problems, efficiently solvable using dedicated *Solvers*
- **Easy to Extend:** C++ API to implement new *Tasks*, *Constraints*, and *Solvers*

OpenSoT Development



Actual community:    

Introduction

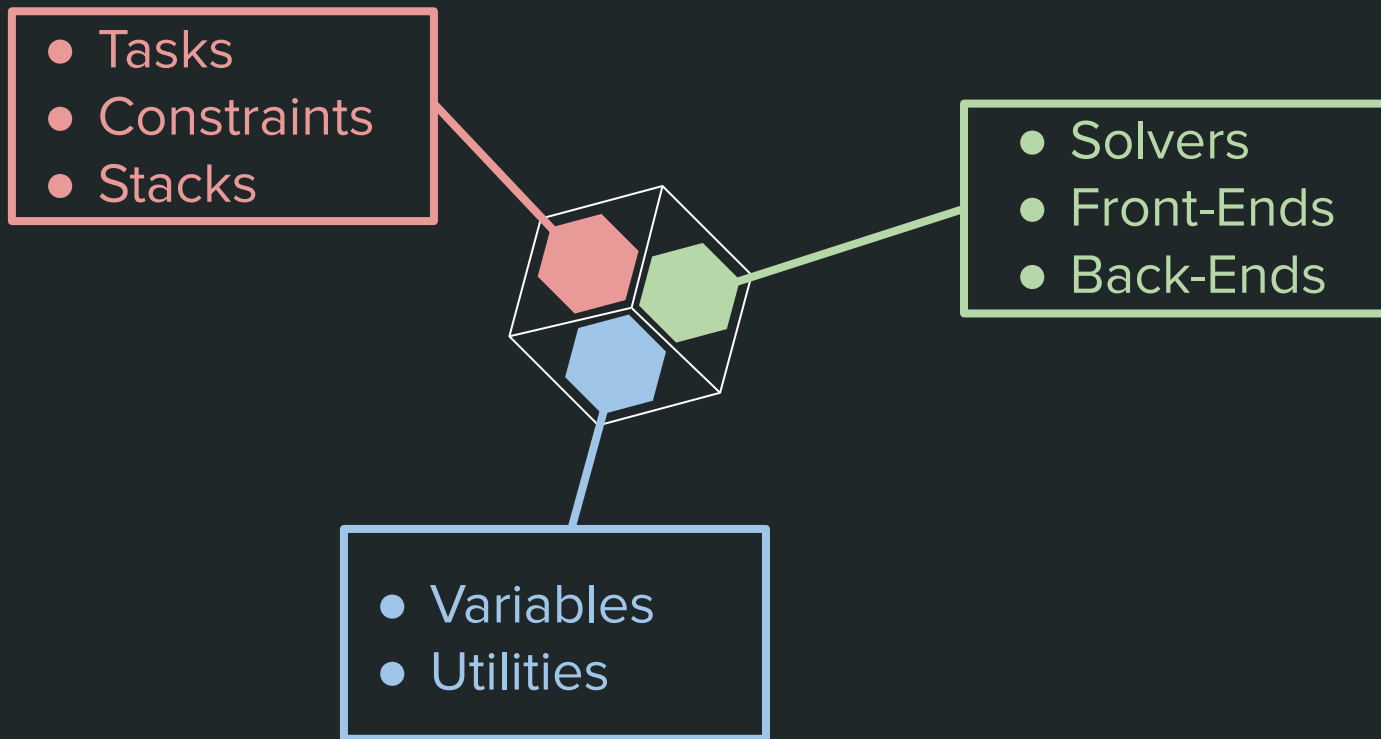
OpenSoT provides an API to setup and solve generic Least-Squares like optimization problems in the form:

$$\begin{aligned} \min_{\mathbf{x}} \quad & \|\mathbf{Ax} - \mathbf{b}\|_{\mathbf{W}}^2 + \mathbf{c}^T \mathbf{x} + \epsilon \|\mathbf{x}\|^2 \\ \text{s. t.} \quad & \mathbf{d}_m \leq \mathbf{Cx} \leq \mathbf{d}_M \end{aligned}$$

Tasks to be solved

Constraints to fulfill

OpenSoT Concepts



Tasks

A **Task** is an atomic element denoted by:

$$\mathcal{T}_1 = \{ \mathbf{A}_1 \in \mathbb{R}^{m \times n}, \mathbf{W}_1 \in \mathbb{R}^{m \times m}, \mathbf{b}_1 \in \mathbb{R}^m, \mathbf{c}_1 \in \mathbb{R}^n \}$$

↑
Task
Matrix

↑
Task
Weight

↑
Task
Vector

↑
Linear
Term

which defines the scalar cost function:

$$\mathcal{F}_1 = \|\mathbf{A}_1 \mathbf{x} - \mathbf{b}_1\|_{\mathbf{W}_1}^2 + \mathbf{c}_1^T \mathbf{x}$$

Sum of Tasks

Multiple tasks can be **summed** together to form complex cost functions, for instance:

$$\mathcal{T}_3 = \mathcal{T}_1 + \mathcal{T}_2 = \left\{ \begin{bmatrix} \mathbf{A}_1 \\ \mathbf{A}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{W}_1 & \mathbf{0} \\ \mathbf{0} & \mathbf{W}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \end{bmatrix}, \mathbf{c}_1 + \mathbf{c}_2 \right\}$$

which defines the scalar cost function:

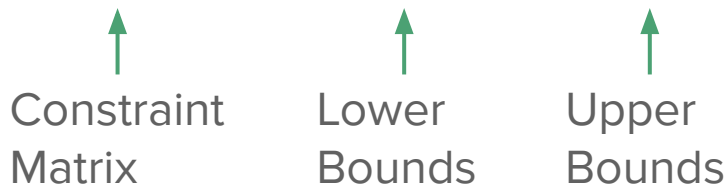
$$\mathcal{F}_3 = \sum_{i=1}^2 \left[\|\mathbf{A}_i \mathbf{x} - \mathbf{b}_i\|_{\mathbf{W}_i}^2 + \mathbf{c}_i^T \mathbf{x} \right]$$

a weighted sum of cost functions associated to each task.

Constraints

A **Constraint** is an atomic element denoted by:

$$\mathcal{C}_1 = \{ \mathbf{C}_1 \in \mathbb{R}^{l \times n}, \mathbf{l}_1 \in \mathbb{R}^l, \mathbf{u}_1 \in \mathbb{R}^l \}$$


Constraint Matrix Lower Bounds Upper Bounds

which defines the inequality constraint: $\mathbf{l}_1 \leq \mathbf{C}_1 \mathbf{x} \leq \mathbf{u}_1$,

or the equality constraint: $\mathbf{C}_1 \mathbf{x} = \mathbf{u}_1 = \mathbf{l}_1$

Stacks

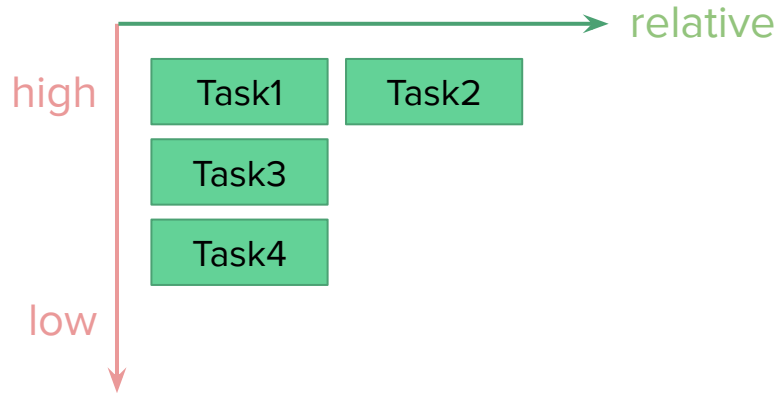
A **Stack** consists in one or more tasks and constraints, and their relations.

Tasks can be in **soft** or **hard** priority relations:

In **hard priorities**,
low level tasks
can not change
optimality of high
level tasks.



Implemented
through solver
strategies.



In **soft priorities**,
tasks are at same
level, optimality can
change according
to relative weights.



Implemented
through sum of
tasks.

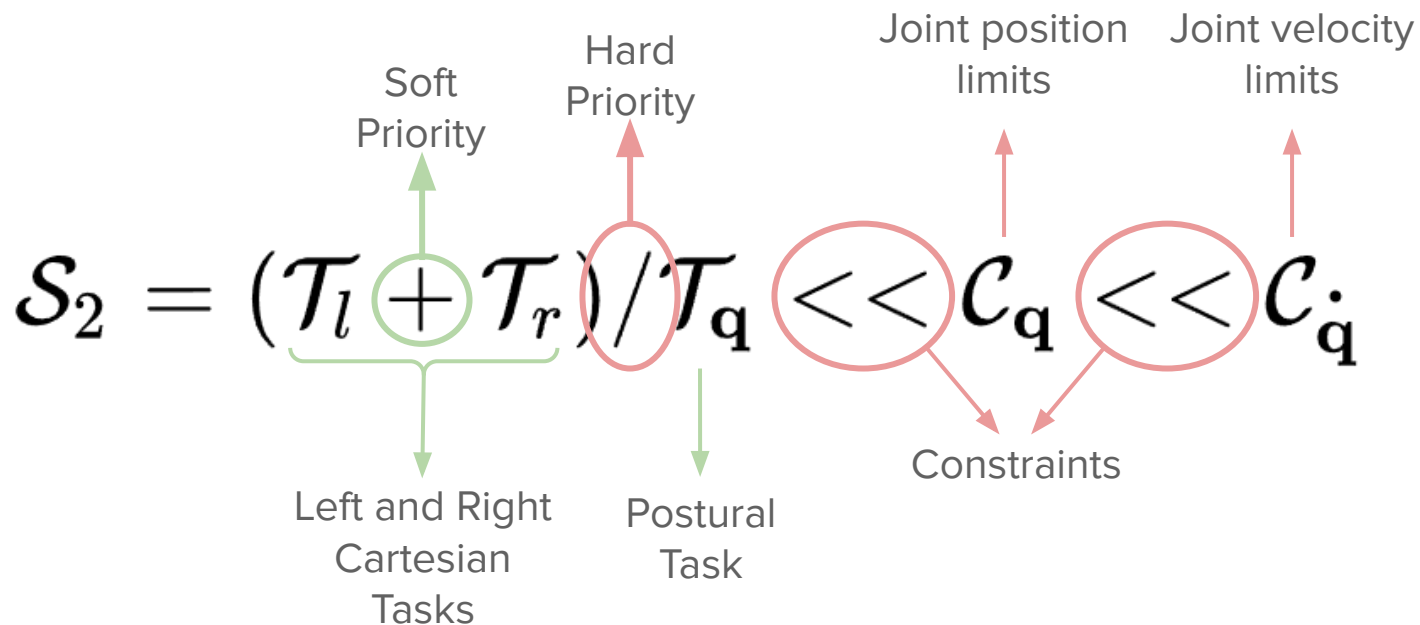
Stacks

Example of Stack:

$$\mathcal{S}_2 = (\mathcal{T}_l + \mathcal{T}_r) / \mathcal{T}_q \ll \mathcal{C}_q \ll \mathcal{C}_{\dot{q}}$$

Stacks

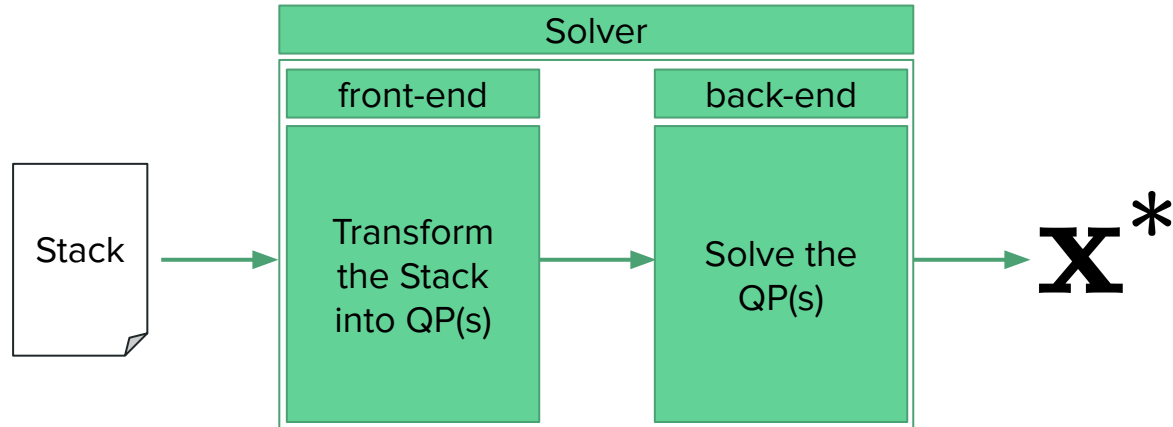
Example of Stack:



Solvers

A **solver** implements a mathematical method to resolve a Stack, i.e. one or more QP/LP problems.

IMPORTANT: Solvers implements hard priorities between tasks.



Solvers

Example: inequality Hierarchical QP (iHQP) [1]

$$(\mathcal{T}_l + \mathcal{T}_r) / \mathcal{T}_q \ll \mathcal{C}_q \ll \mathcal{C}_{\dot{q}}$$



$$\begin{aligned} \dot{\mathbf{q}}_1^* &= \underset{\dot{\mathbf{q}}}{\operatorname{argmin}} \|\mathbf{J}_{l+r} \dot{\mathbf{q}} - \mathbf{v}_{d,l+r}\|_{\mathbf{W}_{l+r}}^2 + \epsilon \|\dot{\mathbf{q}}\|^2 \\ \text{s.t.} \quad & \mathbf{l}_{q+\dot{q}} \leq \mathbf{C}_{q+\dot{q}} \leq \mathbf{u}_{q+\dot{q}} \end{aligned}$$

1st priority is resolved in 1st QP

$$\begin{aligned} \dot{\mathbf{q}}_0^* &= \underset{\dot{\mathbf{q}}}{\operatorname{argmin}} \|\dot{\mathbf{q}} - \dot{\mathbf{q}}_d\|^2 \\ \text{s.t.} \quad & \mathbf{l}_{q+\dot{q}} \leq \mathbf{C}_{q+\dot{q}} \leq \mathbf{u}_{q+\dot{q}} \\ & \mathbf{J}_{l+r} \dot{\mathbf{q}}_1^* = \mathbf{J}_{l+r} \dot{\mathbf{q}} \end{aligned}$$

2nd priority is resolved in 2nd QP,
constrained by solution of 1st QP

$$\dot{\mathbf{q}}_0^*$$

solution

Variables

An affine variable is defined as:

$$\mathbf{y} = \mathbf{M}\mathbf{x} + \mathbf{p}$$

which can be used to:

- select variables in complex problems:

$$\mathbf{f} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{v}} \\ \mathbf{f} \end{bmatrix}$$

\downarrow \mathbf{M} \downarrow \mathbf{x}

- derive complex variables: $\ddot{\mathbf{x}} = \underbrace{\mathbf{J}\ddot{\mathbf{q}}}_{\mathbf{M}\mathbf{x}} + \underbrace{\mathbf{J}\dot{\mathbf{q}}}_{\mathbf{p}}$

API (C++)

- **Tasks/Constraints:**
 - base classes to write new components
 - library of out-of-the-box components (velocity/acceleration/force/wrench formulations)
- **Variables:**
 - API to simplify the writing of complex problems, i.e. floating-base ID
- **Operators:**
 - creation of stacks using mathematical operators applied to tasks and constraints
- **Solvers:**
 - base classes to write new solvers and front-/back-ends
 - library of out-of-the-box front-ends and back-ends with SoA QP/LP solvers

Library of Tasks, Constraints, and Solvers

Task	Formulation
Cartesian	Velocity/Acceleration
Postural	Velocity/Acceleration
CoM	Velocity/Acceleration
Angular Momentum	Velocity/Acceleration
Gaze	Velocity
Pure Rolling*	Velocity
Floating-Base Dynamics*	Acceleration + Force
Min Effort	Velocity
Manipulability	Velocity

Constraint	Formulation	Type
Joint Pos./Vel./Acc. Limits	Velocity/Acceleration	Inequality
Torque Limits	Acceleration + Force	Inequality
CoP Limits	Wrench	Inequality
Friction Cone Limits	Force	Inequality
Normal Torque Limits	Wrench	Inequality
Collision Avoidance	Velocity	Inequality
OmniWheels	Velocity	Equality

Solver	Constraints Type	Use Back-end
eHQP	equality only	×
iHQP	equality/inequality	✓
nHQP	equality/inequality	✓
HCOD	equality/inequality	×

Solver	Type
qpOASES	QP/LP
OSQP	QP/LP
proxQP	QP/LP
qpSWIFT	QP
eiQuadProg	QP
GLPK	LP/MIP

* Mostly used as equality constraints

Operators (Math of Tasks)

Operator	Symbol	Stack	Task	Constraint	Properties
<i>soft priority</i>	+		$\mathcal{T}_c = \mathcal{T}_a + \mathcal{T}_b$		<i>commutative</i> $\mathcal{T}_a + \mathcal{T}_b = \mathcal{T}_b + \mathcal{T}_a$ <i>associative</i> $\mathcal{T}_a + (\mathcal{T}_b + \mathcal{T}_c) = (\mathcal{T}_a + \mathcal{T}_b) + \mathcal{T}_c$
<i>sub-task</i>	%		$\mathcal{T}^{[i,j,k]} = \mathcal{T}\%[i, j, k]$		<i>(indices) commutative</i> $\mathcal{T}^{[i,j,k]} = \mathcal{T}^{[j,k,i]}$ <i>NOT distributive</i> $(\mathcal{T}_a + \mathcal{T}_b)^{[1,2,3]} \neq \mathcal{T}_a^{[1,2,3]} + \mathcal{T}_b^{[1,2,3]}$
<i>multiplication</i>	.		$a\mathcal{T} \rightarrow \mathbf{W} = \text{diag}(a), \quad a > 0$ $\mathbf{E}\mathcal{T} \rightarrow \mathbf{W} = \mathbf{E}, \quad \mathbf{x}^T \mathbf{E}\mathbf{x} > 0, \forall \mathbf{x}$		<i>(scalar) distributive</i> $a(\mathcal{T}_a + \mathcal{T}_b) = a\mathcal{T}_a + a\mathcal{T}_b$
<i>hard priority</i>	/	$S_{i+j} = S_i/S_j$	$S_{i+1} = S_i/\mathcal{T}$		<i>NOT commutative</i> $\mathcal{T}_a/\mathcal{T}_b \neq \mathcal{T}_b/\mathcal{T}_a$ <i>associative</i> $\mathcal{T}_a/(\mathcal{T}_b/\mathcal{T}_c) = (\mathcal{T}_a/\mathcal{T}_b)/\mathcal{T}_c$
<i>local constraint</i>	\ll	$S_a/\mathcal{T}_b \ll \mathcal{C} \neq (S_a/\mathcal{T}_b) \ll \mathcal{C}$	$\mathcal{T} \ll \mathcal{C}$	$\mathcal{C}_c = \mathcal{C}_a \ll \mathcal{C}_b$	<i>distributive</i> $\mathcal{T}_a \ll \mathcal{C} + \mathcal{T}_b \ll \mathcal{C} = (\mathcal{T}_a + \mathcal{T}_b) \ll \mathcal{C}$ <i>minor precedence</i> $\mathcal{T}_a + \mathcal{T}_b \ll \mathcal{C} = (\mathcal{T}_a + \mathcal{T}_b) \ll \mathcal{C}$
<i>global constraint</i>	\ll	$S \ll \mathcal{C}$	$S_a \ll \mathcal{C}/\mathcal{T}_b = (S_a/\mathcal{T}_b) \ll \mathcal{C}$	$\mathcal{C}_c = \mathcal{C}_a \ll \mathcal{C}_b$	<i>distributive</i> $S_a \ll \mathcal{C}/S_b \ll \mathcal{C} = (S_a/S_b) \ll \mathcal{C}$ <i>minor precedence</i> $S_a/S_b \ll \mathcal{C} = (S_a/S_b) \ll \mathcal{C}$

Example: Whole-Body Inverse Dynamics (Python)

- Imports, model creation and update

```
from xbot2_interface import pyxbot2_interface as xbi
from pyopensot.tasks.acceleration import Cartesian, CoM, DynamicFeasibility, Postural
from pyopensot.constraints.acceleration import JointLimits, VelocityLimits
from pyopensot.constraints.force import FrictionCone
import pyopensot as pysot

...
model = xbi.ModelInterface2(urdf)
...
model.setJointPosition(q)
model.setJointVelocity(dq)
model.update()
```

Example: Whole-Body Inverse Dynamics (Python)

- Variables creation

```
contact_frames = ["left_foot_upper_right", "left_foot_lower_right",  
                 "left_foot_upper_left",  "left_foot_lower_left",  
                 "right_foot_upper_right", "right_foot_lower_right",  
                 "right_foot_upper_left",  "right_foot_lower_left"]  
  
variables_vec = dict()  
variables_vec["qddot"] = model.nv  
for contact_frame in contact_frames:  
    variables_vec[contact_frame] = 3  
variables = pysot.OptvarHelper(variables_vec)
```

Example: Whole-Body Inverse Dynamics (Python)

- Tasks & Constraints creation

```
# Tasks
com = CoM(model, variables.getVariable("qddot"))
...
base = Cartesian("base", model, "world", "base_link", variables.getVariable("qddot"))
...

# Constraints
force_variables = list()
for c in contact_frames:
    force_variables.append(variables.getVariable(c))
fb = DynamicFeasibility("floating_base_dynamics", model, variables.getVariable("qddot"),
force_variables, contact_frames)
...
jlims = JointLimits(model, variables.getVariable("qddot"), qmax, qmin, dqmax, dt)
...
```


Example: Whole-Body Inverse Dynamics (Python)

- Stack & Solver creation

```
# Creates 1st priority level
lv1 = (0.1*com + 0.1*(base%[3, 4, 5]))
for i in range(len(cartesian_contact_tasks_frames)):
    lv1 = lv1 + 10.*contact_tasks[i]

# Creates Stack
stack = (lv1/posture) << fb << jlims << VelocityLimits(model,
variables.getVariable("qddot"), dqmax, dt)
...

# Creates Solver
solver = pysot.iHQP(stack, be_solver=OpenSoT::solvers::solver_back_ends::qpOASES)
```

Example: Whole-Body Inverse Dynamics (Python)

- Control loop

```
while ok():
    model.setJointPosition(q)
    model.setJointVelocity(dq)
    model.update()

    com.setReference(com_ref)
    ...
    stack.update()

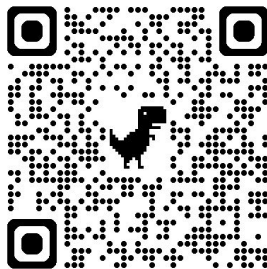
    x = solver.solve()
    qddot= variables.getVariable("qddot").getValue(x)
    ...
```


Tele-Operation w/ Self-Collision Avoidance



Conclusions

- OpenSoT is a mature library for Whole-Body Control based on optimization
- Add-ons:
 - Cartesi/O for high-level interfaces based on ROS (ROS2 is coming...)
 - Visual Servoing based on Visp
 - ...
- Try it on Docker!



https://github.com/hucebot/opensot_docker

Thank You!

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