

# libSOC

## Stochastic Optimal Control Library

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When using this library, please cite [1].

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## 1 Installation

The README file has more detailed installation instructions. The super quick way: on Ubuntu/Debian copy this to your console:

```
sudo apt-get install liblapack-dev freeglut3-dev libqhull-dev libf2c2-dev
wget http://user.cs.tu-berlin.de/mtoussai/source-code/soc.09.2.tgz
tar xvzf soc.09.2.tgz
cd libSOC
make
cd test/soc
./x.exe
```

## 2 Scope & overview

The *primary* scope of this lib is the implementation of Stochastic Optimal Control (SOC) methods (namespace `soc`) – that is, methods to compute (approximatively) optimal controllers and trajectories, typically in the context of robot motion. In particular, this includes

- *Approximate Inference Control* [1],
- iLQG (iterative Linear-Quadratic-Gaussian)
- gradient/spline trajectory optimization

- methods for 1-step control (optimal dynamic control, regularized/Bayesian motion rate control, etc)

The *secondary* scope of this lib is a robot simulator (namespace `ors`) that provides the necessary inputs to the methods above. Using this simulator is optional – it is provided only for completeness of the lib (and I use it in my work). But all the methods above can also be linked to your own simulation environment. My `ors` implementation tries to be minimalistic in its core, but can link to many convenient external libraries and engines: it defines basic data structures to describe robot configurations (trees/graphs of rigid bodies), implements the basic computation of kinematic/Jacobian/Hessian functions, and of course implements the `SocAbstraction`. It uses:

- SWIFT++ to compute shape distances/collisions
- Featherstone's Articulated Body Dynamics as an implementation of exact dynamics on articulated tree structures (much more precise than IBDS or ODE)
- IBDS (a rather robust impuls-based physical simulator)
- ODE (I don't like it)
- OpenGL for display
- read/write of file formats for robot configurations, shape/mesh files (e.g., obj files), etc

The interface between the SOC methods and the simulator is the `soc::SocAbstraction`: a class that defines functions that the SOC methods need access to and that need to be provided by the simulator. This `SocAbstraction` tries to be as close as possible to the typical mathematical notation used for Stochastic Optimal Control problems. If you're only interested in the SOC methods and not in the ORS simulator, you should start reading from section 3.2.

## 3 Programmer's guide

There are three headers which, in the end, you should understand:

- `array.h`
- `ors.h` and `ors_control.h`
- `soc.h`

They implement quite a lot – the following should give some orientation.

### 3.1 ORS data structures

- Check the `Array` class in `array.h` - it's yet another generic container class. There are many reasons why I decided reimplementing such a generic container (instead of using `std::vector`, `blast`, or whatever):
  - it's fully transparent
  - very robust range checking, easy debugging
  - direct linkage to LAPACK
  - tensor (multi-dimensional array) functions which are beyond most existing matrix implementations
  - etc

Anyway, the `Array` class is central in all my code. To get a first impression of its usage, check the `test/array`. In the context of SOC, we mainly use double arrays to represent vectors, matrices and do linear algebra, note the typedef

```
typedef MT::Array<double> arr;
```

- *Lists, Graphs, etc* In my convention a *List* is simply an array of pointers. Since arrays allow memmove operations, insertion, deletion etc are all  $O(1)$ . I also represent graph structures via lists: e.g. a list of nodes and a list of edges, a node may maintain a list of adjoint edges, etc.

For Lists (Arrays of pointers) it makes sense to have additional methods, like calling `delete` for all pointers, or writing the referenced objects to some output – at the bottom of `array.h` there are a number of template functions for lists and graphs.

- See the `ors.h` file. It defines a number of trivial data structures and methods that should be self-explanatory:
  - Vector
  - Matrix
  - Quaternion
  - Frame (a coordinate system)
  - Mesh (a triangulated surface)
  - Spline
- Given these types, a dynamic physical configuration is defined by lists of the following objects
  - *Body*: describes the physical (inertial) properties of a rigid body. This is mainly simply a *Frame* (position, orientation, velocities). Optionally (for dynamic physical simulation) this also includes inertial properties (mass etc) and forces.

- *Joint*: describes how two bodies are geometrically linked and what/where its degree of freedom is. The geometry of a *Joint* is given by a rigid transformation  $A$  (from body1 into the joint frame), a free transformation  $Q$  (the transformation of the degrees of freedom), and a rigid transformation  $B$  (from the joint frame to body2). Overall, the transformation from body1 to body2 is the concatenation  $B \circ Q \circ A$ .

- *Shape*: describes the collision and shape properties of a rigid body. To each rigid body we may associate multiple *Shapes*, like primitive shapes (box, sphere, etc) or *Meshes*; each shape has a relative transformation from its body.

- *Proxy*: describes a proximity between two shapes, i.e., when two shapes are close to each other. This includes information like the closest points on the two shapes and the normal. This information is computed from external libraries like *SWIFT*.

- The *Graph* data structure contains the lists of these objects and thereby describes the configuration of the whole physical system. It includes a number of low level routines, in particular for computing kinematics, Jacobians, dynamics etc. We don't describe these routines here – the SOC abstraction will provide a higher-level interface to such quantities which is closer to the mathematical notation of stochastic optimal control.

Use the `ors_editor` application to define your own physical configuration (described later in the user's guide). Learning to define a configuration should also give you sufficient understanding of the *Body*, *Joint*, and *Shape* data structures.

### 3.2 Stochastic Optimal Control

You should read this when you want to use your own simulator and thereby have to implement the `SocAbstraction`. Otherwise, when you use ORS, you may skip this section (although it's interesting in itself :-)).

We consider a discrete time stochastic controlled system of the form

$$P(x_{t+1} | u_t, x_t) = \mathcal{N}(x_{t+1} | f_t(x_t, u_t), Q_t) \quad (1)$$

with time step  $t$ , state  $x_t \in \mathbb{R}^n$ , control  $u_t \in \mathbb{R}^m$ , and Gaussian noise  $\xi$  of covariance  $Q$ ; where

$$\mathcal{N}(x|a, A) \propto \exp\left\{-\frac{1}{2}(x-a)^\top A^{-1}(x-a)\right\} \quad (2)$$

is a Gaussian over  $x$  with mean  $a$  and covariance  $A$ . For a given state-control sequence  $x_{0:T}, u_{0:T}$  we define the cost as

$$C(x_{0:T}, u_{0:T}) = \sum_{t=0}^T c_t(x_t, u_t). \quad (3)$$

The optimal value function  $J_t(x)$  gives the expected future cost when in state  $x$  at time  $t$  for the best controls and obeys the Bellman optimality equation

$$J_t(x) = \min_u \left[ c_t(x, u) + \int_{x'} P(x' | u, x) J_{t+1}(x') \right]. \quad (4)$$

The closed-loop (feedback) control problem is to find a control policy  $\pi_t^* : x_t \mapsto u_t$  (that uses the true state observation in each time step and maps it to a feedback control signal) that minimizes the expected cost.

The linear quadratic gaussian (LQG) case plays an important role as a local approximation model. LQG is a linear control process with Gaussian noise,

$$P(x_{t+1} | x_t, u_t) = \mathcal{N}(x_{t+1} | A_t x_t + a_t + B_t u_t, Q_t),$$

and quadratic costs,

$$c_t(x_t, u_t) = x_t^\top R_t x_t - 2r_t^\top x_t + u_t^\top H_t u_t. \quad (5)$$

The LQG process is defined by matrices and vectors  $A_{0:T}, a_{0:T}, B_{0:T}, Q_{0:T}, R_{0:T}, r_{0:T}, H_{0:T}$ . In the LQG case, the optimal controller can be computed exactly using the Ricatti equation – and the optimal controller will always be a linear controller in the form

$$u_t^*(x_t) = G_t (x_t - g_t) \quad (6)$$

and we can also compute the most likely trajectory  $x_{0:T}^*$ , which is also the optimal (cost minimal) trajectory in the zero-noise case  $Q = 0$ .

Robotic systems are typically non-LQG. Nevertheless, we can approximate the system locally (i.e., around a current robot state) as LQG. This is exactly what the robot simulator has to provide and what the SocAbstraction defines. In other terms, a simulator needs to provide a mapping

$$x_t \mapsto (A_t, a_t, B_t, Q_t, R_t, r_t, H_t) \quad (7)$$

which gives the approximate system matrices for a current robot state  $x_t$ .

(NOTE: future implementations will also provide non-Gaussian messages/approximations of task constraints...)

In the following we list how to compute these matrices for typical robot motion optimization scenarios:

**Kinematic motion rate control** The robot state is simply the posture  $x_t \equiv q_t \in \mathbb{R}^n$  (not velocities). We assume direct motion rate control. The process is simply

$$q_{t+1} = q_t + u_t + \xi \quad (8)$$

and therefore

$$A_t = 1, \quad B_t = 1, \quad a_t = 0 \quad (9)$$

**Dynamic torque control** The robot state is  $x_t \equiv \bar{q}_t = \begin{pmatrix} q_t \\ \dot{q}_t \end{pmatrix}$ . We assume torque control where the system process is given (approximately) in terms of the local mass matrix  $M$  and force vector  $F$ ,

$$P(q_{t+1} | \dot{q}_t, q_t) = \mathcal{N}(q_{t+1} | q_t + \tau \dot{q}_t, W^{-1}), \quad (10)$$

$$P(\dot{q}_{t+1} | \dot{q}_t, u_t) = \mathcal{N}(\dot{q}_{t+1} | \dot{q}_t + \tau M^{-1}(u_t + F), Q), \quad (11)$$

$$\begin{pmatrix} q_{t+1} \\ \dot{q}_{t+1} \end{pmatrix} = \begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix} \begin{pmatrix} q_t \\ \dot{q}_t \end{pmatrix} + \begin{pmatrix} \tau^2 \\ \tau \end{pmatrix} M^{-1}(u_t + F) + \xi$$

$$\langle d\xi d\xi^\top \rangle = \begin{pmatrix} W^{-1} & 0 \\ 0 & Q \end{pmatrix} \quad (12)$$

$$A = \begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} \tau^2 M^{-1} \\ \tau M^{-1} \end{pmatrix}, \quad a = \begin{pmatrix} \tau^2 M^{-1} F \\ \tau M^{-1} F \end{pmatrix} \quad (13)$$

**Pseudo-dynamic control** A simplification of dynamic control which still yields nice and dynamically smooth trajectories is this: The robot state is  $x_t \equiv \bar{q}_t = \begin{pmatrix} q_t \\ \dot{q}_t \end{pmatrix}$ . And we assume the control directly determines accelerations,

$$P(q_{t+1} | \dot{q}_t, q_t) = \mathcal{N}(q_{t+1} | q_t + \tau \dot{q}_t, W^{-1}), \quad (14)$$

$$P(\dot{q}_{t+1} | \dot{q}_t, u_t) = \mathcal{N}(\dot{q}_{t+1} | \dot{q}_t + \tau u_t, Q), \quad (15)$$

$$\begin{pmatrix} q_{t+1} \\ \dot{q}_{t+1} \end{pmatrix} = \begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix} \begin{pmatrix} q_t \\ \dot{q}_t \end{pmatrix} + \begin{pmatrix} \tau^2 \\ \tau \end{pmatrix} u_t + \xi$$

$$\langle d\xi d\xi^\top \rangle = \begin{pmatrix} W^{-1} & 0 \\ 0 & Q \end{pmatrix} \quad (16)$$

$$A = \begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} \tau^2 \\ 1 \end{pmatrix}, \quad a = 0 \quad (17)$$

**Kinematic task costs** The robot state  $x_t \equiv q_t \in \mathbb{R}^n$  is kinematic. We have  $m$  task variables  $y_i \in \mathbb{R}^{\dim(y_i)}$ . For instance, these could be the 3D endeffector position, the 2D horizontal balance, a 1D collision cost variable, a 1D joint limit cost variable, etc. For each we have a kinematic function  $\phi_i(q) = y_i$  and a Jacobian  $J_i(q) = \partial_q \phi_i(q)$ . We are given task targets  $y_{i,0:T}^*$  and want to follow them with (time-dependent) precisions  $\varrho_{i,0:T}$ . We have

$$c_t(q_t, u_t) = \sum_{i=1}^m \varrho_{i,t} [y_{i,t}^* - \phi_i(q_t)]^2 + u_t^\top H_t u_t$$

$$\approx \sum_{i=1}^m \varrho_{i,t} [y_{i,t}^* - \phi_i(\hat{q}_t) + J_i \hat{q}_t - J_i q_t]^2 + u_t^\top H_t u_t, \quad J_i = J_i(\hat{q}_t)$$

$$= \sum_{i=1}^m \varrho_{i,t} [q_t^\top J_i^\top J_i q_t - 2(y_{i,t}^* - \phi_i(\hat{q}_t) + J_i \hat{q}_t)^\top J_i q_t + \text{const}]$$

$$+ u_t^\top H_t u_t \quad (18)$$

$$R_t = \sum_{i=1}^m \varrho_{i,t} J_i^\top J_i \quad (19)$$

$$r_t = -2 \sum_{i=1}^m \varrho_{i,t} J_i^\top (y_{i,t}^* - \phi_i(\hat{q}_t) + J_i \hat{q}_t) \quad (20)$$

**Dynamic task costs** The robot state  $x_t \equiv \bar{q}_t = \begin{pmatrix} q_t \\ \dot{q}_t \end{pmatrix}$  is dynamic. We have  $m$  task variables  $y_i \in \mathbb{R}^{\dim(y_i)}$



date all ControlVariables by recomputing their state and their Jacobian w.r.t. the current state. After we've set the state using `setq`, we can easily access all necessary information from the SocAbstraction. For instance, `soc::OrsSocImplementation::getJtJ` simply accesses the Jacobian of a particular ControlVariable – the algorithm behind the SocAbstraction doesn't need to know any semantics or meaning of that ControlVariable, it only needs to know its current state, target/precision, and the Jacobian. For instance, an easy algorithm for motion computation is the `soc::bayesianIKControl` – have a look at its code: it simply loops through all existing ControlVariables, queries their state, target/precision, and Jacobian, adds things up (following equations (19,20), which implicitly computes a task constraints message), and returns the maximum a posteriori step  $dq$  in joint space.

### 3.5 Motion algorithms

See the documentation of `soc.h` for a list of all motion algorithms. All of them are implemented on the basis of the SocAbstraction.

## 4 User's guide

### 4.1 ors.editor and the ors-file format

- `ors.editor` is a very simple program that helps editing ors-files. ors-files contain the definition of a physical configuration. See the directory `test/ors_editor`, the binary program is `test/ors.editor/x.exe`, a symbolic link `bin/ors_editor` exists. It works like this:

```
> emacs test.ors &
> ./ors_editor test.ors &
```

Then you edit the `test.ors` file in your standard text editor (here, `emacs`). Whenever you like, you press enter within the OpenGL window to update the display – when you made mistakes in the syntax, error messages will be output to the console.

- The general syntax of the ors-file is very simple: it lists elements in the syntax

```
elem_type elem_name (list of parents) { attribute list }
```

(This is a general hypergraph syntax, which I also use in other contexts (factor graphs), where elements may connect an arbitrary number of parent elements; nodes are special case in that they connect no parents, edges are special case in that they connect exactly two parents, etc)

In our case we have three possible types: `body`, `joint`, `shape`. This is a simple example:

```
#any comment after a # sign
body torso (){
```

```
  X=<t(0 0 1)>          #coordinate system of this body
}
body arm {}

shape some_shape_name (torso) {
  rel=<d(90 0 1 0)>      #rel. transf. torso -> shape
  type=3
  meshfile='filename.tri'
}

joint some_joint_name (torso arm){
  A=<t(0 0 .5) d(90 0 1 0)> #rel. transf. torso -> joint
  B=<t(0 0 .5)>           #rel. transf. joint -> arm
}
```

The attribute list is simply a list of `tag=something` declarations. The 'something' can be a single double number, an array [1 2 3 4] of numbers, a string in quotes, a transformation  $\langle \dots \rangle$ , or a list of strings in parenthesis (`string1 string2` etc). Generally, you can set any attributes you like. But only some special tags have effects right now – the most important ones are explained in the example. See the routines `ors::Body::read`, `ors::Joint::read`, `ors::Shape::read` for details on which attributes have actually effects. The routine `ors::Graph::read` parses a whole ors-file and creates the respective data structures.

- We need to explain coordinate systems and how to specify transformations. A transformation is given as a sequence of primitive transformations enclosed in brackets  $\langle \dots \rangle$ . The most important primitive transformations are a translation  $t(x\ yz)$ , a rotation  $d(\text{degrees axis}_x\ \text{axis}_y\ \text{axis}_z)$ . Concatenating them you can generate any transformation. See the `ors::Frame::read` routine to learn about all primitive transformations.

Every body has its own coordinate system (position and rotation in world coordinates), which you can specify with  $X=\langle \dots \rangle$ . Also every joint has its own coordinate system – we assume that the x-axis is always the rotation axis of the joint. One can specify the coordinate system of a joint directly with  $X=\langle \dots \rangle$  (in world coordinates), or the relative transformations from parent  $\rightarrow$  joint  $\rightarrow$  child with  $A=\langle \dots \rangle$  and  $B=\langle \dots \rangle$ , respectively. Specifying all these transformation at the same time is redundant, of course. Whatever transformations you do not specify (including body coordinates), the parser tries to compute from the given absolute or relative transformations and the tree structure of the kinematics. [[This doesn't work fully automatically in the current version!]]

### 4.2 ors.fileConverter

To view, convert, resize, and cleanup meshfiles, there is a little application `test/ors_fileConverter/x.exe`

(and a symbolic link `bin/ors.fileConverter`). It simply provides an application interface to the functionalities of the `ors::Mesh` data structure. Please see the `test/ors_fileConverter/main.cpp` to learn about all functionalities. Test something like

```
> ./ors_fileConverter filename.obj -view -box  
> ./ors_fileConverter filename.stl -view -box -center -qhull -save
```

## References

- [1] M. Toussaint. Robot trajectory optimization using approximate inference. In *Proc. of the 26rd Int. Conf. on Machine Learning (ICML 2009)*, 2009.