RobotSim Manual v0.1

Kris Hauser, CS B659: Intelligent Robotics, Spring 2013

Document last updated: 5/27/2013

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# What is RobotSim?

RobotSim is a cross-platform software package for modeling, simulating, planning, and optimization for complex robots, particularly for manipulation and locomotion tasks. It has been developed at Indiana University since 2009 primarily as a research platform, and is being prototyped in 2013 for educational use.

This manual is meant to give **a high-level roadmap of the library’s functionality** and should not be considered a replacement for the detailed API documentation.

## Features

* Supports legged and fixed-based robots.
* Many sampling-based motion planners implemented.
* Fast trajectory optimization routines.
* Real-time motion planning routines.
* Forward and inverse kinematics, forward and inverse dynamics
* Contact mechanics computations (force closure, support polygons, stability of rigid bodies and actuated robots)
* Planning models are fully decoupled from simulation models, which helps model uncertainty.
* Robust rigid body simulation with triangle mesh / triangle mesh collisions.
* Simulation of PID controlled, torque controlled, and velocity controlled motors.
* Simulation of various sensors including gyroscopes, force/torque sensors, and accelerometers. (Vision / depth sensors not yet supported)

## Currently supported platforms

* \*nux environments
* Windows via Cygwin
* Windows via MS Visual Studio is possible with some effort to build dependencies and generate build files.
* MacOS, with some modifications.

Please let us know if you are able to compile on other platforms in order to help us support them in the future.

## Comparison to related packages

* **ROS (Robot Operating System)** is a large operating system designed for distributed control of physical robots. Although it does come with planning tools they are not as flexible as those in RobotSim. ROS has limited support for legged robots, and is poorly suited for prototyping high-rate feedback control systems. ROS is heavy-weight and not completely cross-platform (only Ubuntu is fully supported).
* **OpenRAVE (Robotics and Animation Virtual Environment)** is similar to RobotSim and was developed concurrently by a similar group at CMU. OpenRAVE has more sophisticated manipulation functionality. Does not support planning for legged robots, but simulation is possible with some effort. Simulation models are often conflated with planning models whereas in RobotSim they are fully decoupled. Heavy-weight.
* **Gazebo, Webots, V-REP, etc** are robot simulation packages built off of the same class of rigid body simulations as RobotSim. They have more sophisticated sensor simulation capabilities, cleaner APIs, and nicer visualizations but are typically built for mobile robots and have little to no functionality for modeling, planning, and optimization. RobotSim also has improved mesh-mesh collision handling that makes collision handling much more stable.

The main drawback of RobotSim is that it is very much an active research code base and much of the functionality is not fully documented or wrapped in convenient APIs. ROS also has many more wrappers for integration with hardware platforms and sensors.

# Downloading and Building RobotSim

RobotSim is publicly available via Github through <https://github.com/krishauser/RobotSim/>. The command

git clone https://github.com/krishauser/RobotSim

will download the required files.

You will also need to obtain the following dependencies, which may already be installed on your machine:

* GLUT
* GLPK, the GNU Linear Programming Kit
* Python, NumPy, and PyGL, if you wish to use the Python bindings. (Tested only on Python 2.6 & 2.7)

**Configuring for Python API.** To build the Python API…

* Set the LD\_LIBRARY\_PATH environment variable to include the locations of the TinyXML and ODE shared libraries, or move the .so files into your shared library path.

**Building dependencies.** First, the dependencies must be downloaded and built. GLUT and GLPK must first be installed in your library paths. KrisLibrary, TinyXML, GLUI, and ODE can be unpacked into the RobotSim/Library folder using the command ‘make unpack-deps’. After configuring the dependencies, they can be built using the command ‘make deps’.

To configure the dependencies, consider the following notes:

* KrisLibrary must be configured for your particular system by editing Makefile.config. See the KrisLibrary readme for more details.
* On Cygwin, KrisLibrary, GLUI, and RobotSim have been tested only using the W32API OpenGL implementation, NOT the X11 one. This requires, e.g., in GLUI, setting LIBGL=-lglu32 –lopengl32, LIBGLUT=-lglut32, and CPPFLAGS=-I/usr/include/w32api –DGLUT\_DISABLE\_ATEXIT\_HACK.
* During simulation, ODE will print many warning messages of the form “ODE Message 3: LCP internal error, s <= 0”. These can be safely ignored. The output can be made less verbose by commenting out the appropriate lines in ode/src/lcp.cpp (lines 1238 and 1658 in ODE 0.11.1).
* On some Linux systems, ODE becomes unstable in single floating-point precision and may crash with assertion failures. To enable double precision, configure ODE with --enable-double-precision and edit ‘-DdSINGLE’ to ‘-DdDOUBLE’ in RobotiSim/Makefile.config.

**Building documentation.** To build the documentation using Doxygen, type ‘make docs’.

**Building static library and apps.** The static library is built using ‘make lib’. The main apps to build are RobotTest, SimTest, and RobotPose. Typing ‘make [target]’ will build the target.

**Building Python bindings.** Once the RobotSim static library is built, the Python bindings in RobotSim/Python/robot can be built. After editing RobotSim/Python/robot/setup.py to point to the relevant directories, type ‘make python’ inside RobotSim/. ‘make python-docs’ will build the Python API documentation.

# Running RobotSim Apps

RobotTest helps inspect/debug robot files and is run from the command line as follows:



**Figure 1**. The RobotTest GUI.  
./RobotTest data/athlete.rob

./RobotTest robot\_file

SimTest performs physics / control simulation and is run from the command line as follows:

./SimTest [world, robot, environment, or object files]  
(e.g., ./SimTest data/athlete.rob data/plane.env or ./SimTest hubo\_files/hubo\_plane.xml)



**Figure 2**. The SimTest GUI. The transparent yellow robot is the “poser”.  
./SimTest hubo\_files/hubo\_plane.xml

RobotPose helps the designer create configurations, constraints, and motions, and is run similarly to SimTest.



**Figure 3**. The RobotPose GUI. The 3D coordinate frames are “widgets” for posing links of the robot in Cartesian space.  
./RobotPose hubo\_files/hubo\_plane.xml

## Interacting with 3D worlds

Each of the above apps follows a common camera navigation and robot posing interface.

**Navigating**

* Dragging with the left mouse button (left-drag) rotates the camera about a focal point.
* Alt+left-drag zooms the camera.
* Ctrl+left-drag pans the camera.
* Shift+left-drag moves the camera toward and away from the focal point.

**Posing robots**

* Right-clicking on a robot link and dragging up and down will set its desired joint value.
* The floating base of a robot is posed by right-dragging on the widget.
* *IK posing*
  + To switch to IK-posing mode, check the “Pose by IK” button.
  + In this mode, clicking on a point on the robot will add a new IK point constraint.
  + The widget can be right-dragged to move the robot around.
  + Typing ‘c’ while hovering over a link will add a new fixed position and rotation constraint.
  + Typing ‘d’ deletes an IK constraint.

**RobotTest commands**

* ‘h’ prints the full help.
* ‘p’ prints the posed configuration to the console.

**SimTest commands**

* *Command line options*
  + –config [.config file] loads a robot start configuration from disk. If more than one robot exist in the world file, multiple –config options may be specified to give their start configurations.
  + –milestones [.milestone file] loads a milestone path from disk.
  + –path [.xml or .path file] loads a MultiPath or piecewise linear trajectory from disk.
* ‘h’ prints the full help.
* Typing ‘ ‘ (space bar) or clicking the “Set Milestone” button will send the posed configuration to the controller.
* Typing ‘s’ or clicking the “Simulate” button toggles the simulation.
* Typing ‘a’ advances by one simulation step (1/100 s).
* Clicking “Save movie” will tell the simulator to start saving 640x480 frames to PPM files on disk at 30fps. These can be converted into a simulation-time (i.e., 1s of movie time = 1s of simulated time) movie using a utility such as mpeg\_encode.
* Typing ‘f’ toggles force application mode. In force application mode, right-clicking and dragging on the robot will apply a spring-like force between the robot and the cursor position.
* Typing ‘v’ (lowercase) saves the current viewport to disk, and ‘V’ (uppercase) loads the previously saved viewport. This is useful for creating side-by-side comparisons.

**RobotPose commands**

* *Command line options*
  + –l [resource\_library directory or XML file] loads a resource library from disk. Multiple libraries can be loaded in this way.
* Individual resources or resource libraries may be loaded from disk via the controls at the top.
* “Library -> Poser” sets the poser to use the currently selected configuration, stance, hold, or grasp from the resource library.
* “Poser -> Library” stores the current posed configuration, stance, or hold to the resource library. Selection is accomplished via the “Resource Type” selector.
* “Library Convert” converts the currently selected resource into a resource of the specified type in the “Resource Type” selector.
* “CreatePath” generates an interpolating path to the currently selected Config resource and saves it to the resource library.

## Example files

World files for different robots are available in the following subdirectories:

* hubo\_files: the KAIST Hubo humanoid.
* puma\_files: the Puma 760 industrial robot.
* tx90\_files: the Staubli TX90L industrial robot.

Other test robots, objects, and environments are available in the RobotSim/data/ subdirectory. Some files of interest may include:

* athlete.rob: the NASA ATHLETE hexapod (incomplete, missing wheel geometry).
* cartpole.rob: the cart-pole balancing control problem.
* footed\_2d\_biped.rob: a simple 2D biped mimicking a human’s forward motion.
* footed\_2d\_monoped.rob: a simple 2D monoped.
* hrp2.rob: the AIST HRP-2 humanoid
* simple\_2d\_biped.rob: a simple 2D biped mimicking a human’s lateral motion.
* swingup.rob: a simple pendulum swingup control problem.
* plane.env: a flat plane environment
* block.obj: a 40cm block
* block\_small.obj: an 8cm block

# Design Philosophy

The main philosophy behind the RobotSim design is to decouple Modeling, Planning, Control, and Simulation modules. This division provides a clear logical structure for developing large software systems for operating complex intelligent robots.

* *Modeling* refers to the underlying knowledge representation available to the robot, e.g., limb lengths, physical parameters, environment, and other objects in its vicinity. The Modeling module contains methods for representing this knowledge. It also includes the ubiquitous mathematical models, such as kinematics and dynamics, trajectory representations (e.g., splines), and contact mechanics that required for planning and control. Found in the RobotSim/Modeling/ and RobotSim/Contact/ directories.
* *Planning* refers to the computation of paths, trajectories, feedback control strategies, configurations, or contact points for a robot. Planning may be performed either offline or online. Found in the RobotSim/Planning/ directory and is based heavily on the KrisLibrary/planning and KrisLibrary/optimization packages.
* *Control* refers to the high-rate processing of sensor information into low-level robot controls (e.g., motor commands). This also includes state estimation. Note that the boundary between planning and control is fuzzy, because a fast planner can be used as a controller, or a planner can compute a feedback control strategy. Found in the RobotSim/Control/ directory.
* *Simulation* refers to a physical simulation of a virtual world that is meant *as a stand-in for the real world and robot*. The simulation module constructs a detailed physical rigid-body simulation and instantiates a controller and virtual sensors for a simulated robot. The controller then applies actuator commands that apply forces in the simulation. Found in the RobotSim/Simulation/ directory.

Planning, control, and simulation are related by the use of (largely) common models. However, the simulation model does not need to be the same as the planner or controller’s model. For example, an object’s position may be imperfectly sensed, or a free-floating robot like a humanoid may not know precisely where its torso lies in 3D space. Also, for computational practicality a planner might work on a simplified model of the robot (e.g., ignoring the arms during biped walking) while the controller must expand that information into the full robot representation.

**Behavior Scripting?** Many engineers and students tend to approach robots from a “scripting” approach, whereby a complex behavior is broken down into a state machine of painstakingly hand-tuned, heuristic behaviors. Unlike other packages, RobotSim does not try to make scripting convenient. This choice was made deliberately in order to discourage the use of heuristic behaviors. The philosophy is that *hand-tuned behaviors should be rare in intelligent robots*.

(If you really must know… To implement a behavior script in RobotSim, a controller should manually maintain and simulate the behavior of a state machine in its feedback loop.)

# Modeling

## 3-D Geometry

RobotSim uses the 3D geometry classes in KrisLibrary/math3d, KrisLibrary/geometry, and KrisLibrary/meshing for representing points, rotations, transformations, geometric primitives, and triangulated meshes. Mesh-mesh proximity testing (collision and distance computation) are handled by the open source PQP library developed by UNC Chapel Hill. These routines are heavily tested and fast.

Most users will be satisfied with definitions in the following files:

* KrisLibrary/math3d/primitives.h contains 2D and 3D mathematical primitives. The classes Vector2, Vector3, Matrix2, Matrix3, Matrix4, RigidTransform2D and RigidTransform are efficient implementations of 2D and 3D vector/matrix operations.
* KrisLibrary/math3d/rotation.h contains several representations of rigid 3D rotations, including euler angles, moments (aka exponential maps), angle-axis form, and quaternions. All representations can be transformed into one another. All routines are implemented to be numerically robust.
* KrisLibrary/geometry/CollisionMesh.h contains the CollisionMesh and CollisionMeshQuery data structures. CollisionMesh overloads the Meshing::TriMeshWithTopology class and represents a preprocessed triangle mesh for collision detection. It can be placed arbitrarily in space for making fast collision queries via the CollisionMeshQuery class.

## Robots

RobotSim is based heavily on the KrisLibrary/robotics package for defining articulated robot kinematics and dynamics. Robots are loaded from .rob files. The Robot class in RobotSim/Modeling/Robot.h has the following class hierarchy:

Robot -> RobotWithGeometry -> RobotDynamics3D -> RobotKinematics3D -> Chain

and provides the following functionality

* Describes a topologically sorted open linkage as a list of links with their parents (Chain).
* Stores most of the immutable kinematic characteristics common to all robots: link lengths, joint axis types, joint stops, inertial characteristics, and link geometry (RobotKinematics3D).
* Stores actuation limits (RobotDynamics3D)
* Stores a “current” robot configuration (RobotKinematics3D) and velocity (RobotDynamics3D). *Note: these should be thought of as temporary variables, see notes below.*
* Computes and stores the robot’s “current” link frames via forward kinematics (RobotKinematics3D).
* Computes the robot’s Lagrangian dynamics terms (RobotDynamics3D).
* Stores triangulated link geometry and performs collision detection (RobotWithGeometry).
* Stores information about which links can self-collide (RobotWithGeometry).
* Names each link and contains semantics of the how the degrees of freedom of the robot map to “joints” and actuators (Robot).
* Loads and saves robot descriptions from disk (Robot).

Note: The reasons for the class hierarchy are largely historical, but meaningful. For example, a protein backbone might be modeled as a RobotKinematics3D but not a RobotDynamics3D. For more transparent, flat access to the main Robot functionality, see the Python API.

**Configurations.** A robot configuration is described by a Config class, which is simply a typedef for Vector (see KrisLibrary/math/vector.h). A configuration is a nonredundant description of the positions of each link of the robot. The Robot.q member represents a “current” configuration. Note that Robot.q *is not the currently simulated robot configuration*, but is rather a temporary variable.

*Important*: to ensure consistency between the configuration and the link frames, the Robot.UpdateConfig(q) method should be called to change the robot’s configuration. UpdateConfig performs forward kinematics to compute the link frames, while Robot.q=q does not.

**Links.** Links represent rigid coordinate frames that are connected to either another link or the world coordinate frame via a movable *degree of freedom* (DOF). The data for each link in the robot is stored in RobotKinematics3D.links, which is a list of RobotLink3D’s. The parent index of each link is stored in Chain.parents which is a list of ints. -1 indicates that the link is attached to the world coordinate frame. Links may be prismatic or revolute and moves along or around the axis w. They also contain mass parameters (mass, inertia, com), the reference transformation to its parent (T0\_Parent), and the link’s “current” world transformation T\_World.

**Virtual links.** To represent free-floating bases, use a set of 5 massless *virtual links* and 1 physical link that represent the x, y, and z translations and rotations around the z, y, and x axes (roll-pitch-yaw convention). See RobotKinematics3D.InitializeRigidObject for an example of how to set up such a base. Likewise, a mobile robot may be represented by 2 virtual links + 1 physical link: two for x, y translations connected by prismatic joints, and the last for θ, connected to its parent by a revolute joint. A ball-and-socket joint may be represented by 2 virtual links + 1 physical link.

**Geometry.** The geometry of each link is a triangulated mesh, stored as a list of CollisionMeshs in the RobotWithGeometry.geometry member. The geometry may also be empty.

(So far we have no plans to officially support other types of geometry, but the MeshCollision and SelfCollision methods may potentially be overloaded to implement other geometric primitives in the future).

**Joints.** Superclasses of Robot consider all DOFs as generic variables that define the extents of the articulations between links. At the Robot level, RobotSim introduces the notion of *joints*, which introduce a notion of *semantics* to groups of DOFs. Most joints will be of the Normal type, which map directly to a single DOF in the normal way. However, free-floating bases and other special types of joints designate groups of DOFs that should be interpreted in special ways. These special joints include:

* Weld joints, which indicate that a DOF should not move.
* Spin joints, which are able to rotate freely and infinitely.
* Floating joints, which translate and rotate freely in 3D (e.g., free-floating bases)
* FloatingPlanar joints, which translate and rotate freely in 2D (e.g., mobile wheeled bases)
* BallAndSocket joints, which rotate freely in 3D.
* Closed joints, which indicate a closed kinematic loop. *Note: this is simply a placeholder for potential future capabilities; these are not yet handled in RobotSim.*

**Drivers.** Although many robots are driven by motors that transmit torques directly to single DOFs, the Robot class can represent other drive systems that apply forces to multiple DOFs. For example, a cable-driven finger may have a single cable actuating three links, a mobile base may only be able to move forward and turn, and a satellite may have thrusters. Free-floating bases may have no drive systems whatsoever.

A robot is set up with a list of drivers available to produce its torques. Normal drivers act as one would expect a motor to behave. Cable drives are supported through the Affine driver type. The other driver types are not fully tested and/or supported, although we hope to add some of this functionality in the future.

## Environments

An Environment (RobotSim/Modeling/Environment.h) is defined very simply as a CollisionMesh annotated with friction coefficients. They may be loaded from .env files or .tri files. In the latter case, some default friction value is assigned (set to 0.5).

Future implementations may support other geometry representations, e.g., point cloud environments, or richer semantic models.

## Rigid Objects

A RigidObject (Modeling/RigidObject.h) is a collision mesh associated with a RigidTransform and other dynamic parameters. RigidObjects may be loaded from .obj files or .tri files. In the latter case, the dynamic parameters are set to default values (e.g., mass = 1).

## Worlds

The RobotWorld class (Modeling/World.h) stores multiple named robots, environments, and rigid objects, along with associated visualization information. Each entity in the world, including each robot link, can be addressed via a common ID number. Worlds are loaded from .xml files.

## Paths and Trajectories

RobotSim distinguishes between *paths* and *trajectories*: paths are geometric, time-free curves, while trajectories are paths with an explicit time parameterization. Mathematically, paths are expressed as a continuous curve while trajectories are expressed as continuous curves where is the configuration space and are the initial and final times of the trajectory, respectively.

Classical motion planners compute paths because time is essentially irrelevant for fully actuated robots in static environments. However, a robot must ultimately execute trajectories. Various methods are available in RobotSim to convert paths into trajectories.

RobotSim handles two path types.

* *Milestone lists*. The simplest path type is simply a list of *milestones* that should be piecewise linearly interpolated. These are typically simply given as vector<Config>. *Note: to properly handle rotational joints, milestones should be interpolated via the functions in* RobotSim/Modeling/Interpolate.h*. Cartesian linear interpolation does not correctly handle floating and spin joints.*
* *Cubic splines*. RobotSim also has partial support for cubic Bezier curves. Routines for interpolating configuration lists are found in RobotSim/Modeling/SplineInterpolation.h.

RobotSim handles three trajectory types.

* *Piecewise linear*. These trajectories are given by a list of times and milestones that should be piecewise linearly interpolated. These are typically simply given as two arrays: vector<Real> and vector<Config>. [*See note above regarding interpolation*.]
* *DynamicPath (piecewise parabolic curves).* These are time-optimal bounded-acceleration trajectories that include both configuration, velocity, and time. Routines in RobotSim/Modeling/DynamicPath.h are available to quickly compute DynamicPaths from milestone lists, milestone+velocity lists, and milestone+time lists given velocity and acceleration bounds.
* *Timed cubic splines.* Found inthe TimeScaledBezierCurveclass in RobotSim/Planning/TimeScaling.h.

Especially for legged robots, the preferred path type is MultiPath, which allows storing both untimed paths and timed trajectories. It can also store multiple path sections with inverse kinematics constraints on each section. Conversions to/from piecewise linear paths, DynamicPath’s, and cubic splines are supported.

## Inverse Kinematics

Inverse kinematics (IK) constraints are defined in KrisLibrary/robotics/IK.h, and numerical IK solvers are defined in KrisLibrary/robotics/IKFunctions.h. IK constraints may attach any number of transformation variables of a link to fixed values relative to the world coordinate system or the coordinate system of any other link.

The IKGoal class defines a constraint on a single link. The link and destLink members must be filled out prior to use.

**Easy setup.** For convenience, the SetFromPoints method is provided to map a list of local points to a list of world space points. This function covers most typical IK constraints. If there is a single point, the constraint is a fixed point constraint. If the points are collinear, the constraint is an edge constraint. If the points span a plane, the constraint is a fixed constraint.

**Detailed setup.** Position constraints are defined by the localPosition, endPosition, and optionally the direction members. There are four types of position constraint available.

* Free: no constraint
* Planar: the point is constrained in one dimension, i.e., to lie on a plane. Here endPosition refers to a point on the plane and direction refers to the plane normal.
* Linear: the point is constrained in two dimensions, i.e., to lie on a line. Here endPosition refers to a point on the line and direction refers to the line direction.
* Fixed: the point is constrained to a fixed point. Here endPosition refers to that point and direction is ignored.

Rotation constraints are defined by the endRotation and optionally the localAxis members. There are three types of rotation constraint available.

* Free: no constraint
* Axis: rotation is constrained about an axis. The direction localAxis maps to the endRotation direction. These must be unit vectors.
* Fixed: rotation is fixed. The endRotation member is a MomentRotation that represents the fixed orientation. To convert to a 3x3 matrix, call the GetFixedGoalRotation method. To convert from a 3x3 matrix, call the SetFixedRotation method.

**Numerical solvers**. Numerical inverse kinematics solvers are extremely flexible and can solve for arbitrary combinations of IK constraints. The SolveIK() functions in KrisLibrary/robotics/IKFunctions.h are the easiest way to do so. They take the robot’s current configuration as a starting point and run a Newton-Raphson technique to (hopefully) solve all constraints simultaneously. These routines automatically try to optimize only over the relevant variables, e.g., if the only constraint is on the robot’s right foot, then the arms, head, and left leg will not be included as optimization variables.

For richer functionality, use the RobotIKFunction and RobotIKSolver classes and Get\*Dofs() functions directly.

**Analytical solvers.** There arehooks for analytical solvers in KrisLibrary/robotics/AnalyticIK.h but these are not used yet in RobotSim. Future versions may support them.

## Dynamics

The fundamental Langrangian mechanics equation is

|  |  |  |
| --- | --- | --- |
|  |  |  |

Where is configuration is velocity,is acceleration, is the positive semidefinite *mass matrix*, is the *Coriolis force*, is the *generalized gravity*, is the link torque, are *external forces*, and are the Jacobians of the points at which the points are applied. A robot’s motion under given torques and external forces can be computed by multiplying both sides by B-1 and integrating the equation forward in time.

RobotSim has several methods for calculating and manipulating these terms. The first set of methods is found in RobotKinematics3D and RobotDynamics3D. These use the “classic” method that expands the terms mathematically in terms of Jacobians and Jacobian derivatives, and runs in O(n3). The CalcAcceleration method is used to convert the RHS to accelerations (*forward dynamics*). CalcTorques is used to convert from accelerations to the RHS (*inverse dynamics*).

The second set of methods uses the Newton-Euler rigid body equations and the Featherstone algorithm (KrisLibrary/robotics/NewtonEuler.h). These equations are O(n) for sparsely branched chains and are typically faster than the classic methods for modestly sized robots (e.g., n>6). Although NewtonEuler is designed particularly for the CalcAccel and CalcTorques methods for forward and inverse dynamics, it is also possible to use it to calculate the C+G term in O(n) time, and it can calculate the B or B-1matrices in O(n2) time.

## Contacts

Several operations for working with contacts can be found in KrisLibrary/robotics, in particular Contact.h, Stability.h, and TorqueSolver.h. Currently these support legged locomotion better than object manipulation

* The ContactPoint class allows for frictionless and frictional point contacts to be defined. Consist of a position, normal, and coefficient of friction.
* The ContactFormation defines a set of contacts on multiple links of a robot. Consists of a list of links and a list of lists of contacts. For all indices i, contacts[i] is the set of contacts that affect links[i]. Whether the contact quantities are given world space or in link-local coordinates is application-defined.
* The TestCOMEquilibrium functions test whether the center of mass of a rigid body can be stably supported against gravity by valid contact forces at the given contact list.
* The EquilibriumTester class provides richer functionality than TestCOMEquilibrium, such as force limiting and adding robustness factors. It may also save some memory allocations when testing multiple centers of mass with the same contact list.
* The SupportPolygon class explicitly computes a support polygon for a given contact list, and provides even faster testing than EquilibriumTester for testing large numbers of centers of mass (typically around 10-20).
* The TorqueSolver class solves for equilibrium of an articulated robot under gravity and torque constraints. It can handle both statically balanced and dynamically moving robots.

## Holds and stances

Holds (RobotSim/Contact/Hold.h) are defined as a set of contacts (the contacts member) and the associated IK constraint (the ikConstraint member) that keeps a link on the robot placed at those contacts. Holds may be saved and loaded from disk. They also contain convenience setup routines in the Setup\* methods.

Stances (RobotSim/Contact/Stance.h) define all contact constraints of a robot. They are defined simply as a map from links to Holds.

## MultiPaths

A MultiPath (RobotSim/Modeling/MultiPath.h) is a rich path representation for legged robot motion. They contain one or more path(or trajectory) *sections* along with a set of IK constraints and holds that should be satisfied during each of the sections. This information can be used to interpolate between milestones more intelligently, or for controllers to compute feedforward torques more intelligently than a raw path. They are loaded and saved to XML files.

Each MultiPath section maintains a list of IK constraints in the ikObjectives member, and a list of Holds in the holds member. There is also support for storing common holds in the MultiPath’s holdSet member, and referencing them through a section’s holdNames or holdIndices lists (keyed via string or integer index, respectively). This functionality helps determine which constraints are shared between sections, and also saves a bit of storage space.

MultiPaths also contain arbitrary application-specific settings, which are stored in a string-keyed dictionary member settings. Common settings include:

* resolution, which indicates the resolution to which a path has been discretized. If resolution has not been set or is too large for the given application, a program should use IK to interpolate the path.
* program, the name of the procedure used to generate the path.
* command\_line, the shell command used to invoke the program.

Sections may also have settings. No common settings have yet been defined for sections.

## Resources and Resource Libraries

Most of the types mentioned in this section can be saved and loaded from disk conveniently through the RobotSim resource management mechanism. When working on a large project, it is recommended that configurations, paths, holds, etc. be stored in dedicated sub-project folders to avoid polluting the main RobotSim folder.

A sub-project folder can be loaded all at once through the ResourceLibrary class (KrisLibrary/utils/ResourceLibrary.h). After initializing a ResourceLibrary instance with the MakeRobotResourceLibrary function in (RobotSim/Modeling/Resources.h) to make it RobotSim-aware, the LoadAll/SaveAll() methods can load an entire folder of resources. These resources can be accessed by name or type using the Get\*() methods.

Currently supported types include:

* Config (.config)
* Hold (.hold)
* Stance (.stance)
* Configuration lists (.configs)
* TriMesh (.tri)
* Robot (.rob)
* World (.xml)
* Linear paths (.path) (Note that the data must be extracted from the LinearPathResource)
* MultiPath (.xml)

Alternatively, resource libraries can be saved to XML files via the LoadXml/SaveXml() methods. This mechanism may be useful in the future, for example to send complex robot data across a network. These also support the following additional types which do not have a dedicated file extension:

* Vector3
* Matrix3
* RigidTransform
* Matrix
* IKGoal

## File Types

The following standard file types are used in RobotSim.

* World files (.xml)
* Robot files (.rob)
* Triangle mesh files (.tri)
* Rigid object files (.obj)
* Configuration files (.config)
* Configuration set files (.configs)
* Simple linear path files (.path)
* Multi-path files (.xml)
* Hold files (.hold)
* Stance files (.stance)

TODO: describe file formats.

# Planning

## Basic Kinematic Motion PlanniNG

Basic kinematic motion planning generates collision-free paths for fixed-base robots in free space (i.e., not in contact with the environment or objects). The general way to plan a path connecting configurations qstart and qgoal is as follows:

Initialize a WorldPlannerSettings object for a RobotWorld with the InitializeDefault method.

Create a SingleRobotCSpace (RobotSim/Planning/RobotCSpace.h) with the RobotWorld, the index of the robot (typically 0), and the initialized WorldPlannerSettings object.

Then, a MotionPlannerFactory (KrisLibrary/planning/AnyMotionPlanner.h) should be initialized with your desired planning algorithm. The SBL type is recommended as a good first choice.

Construct a MotionPlanningInterface\* with the MotionPlannerFactory.Create() method. Call MotionPlanningInterface.AddConfig(qstart) and MotionPlanningInterface.AddConfig(qgoal)

Call MotionPlanningInterface.PlanMore(N) to plan for N iterations, or call PlanMore() until a time limit is reached. Terminate when IsConnected(0,1) returns true, and call GetPath(0,1,path) to retrieve the path.

Delete the MotionPlanningInterface\*.

Example code is as follows.

#include “Planning/SingleRobotCSpace.h”  
#include <planning/AnyMotionPlanner.h>  
  
//TODO: setup world  
WorldPlannerSettings settings;  
settings.InitializeDefault(world);  
//do more constraint setup here if desired, e.g., add collision margins  
SingleRobotCSpace cspace(world,0,&settings); //plan for robot 0  
MotionPlannerFactory factory;  
factory.type = MotionPlannerFactory::SBL;  
//do more planner setup here if desired, e.g., change perturbation size  
MotionPlanningInterface\* planner = factory.Create(&cspace);  
int istart=planner->AddConfig(qstart); //should be 0  
int igoal=planner->AddConfig(qgoal); //should be 1  
int maxIters=1000;  
bool solved=false;  
MilestonePath path;  
for(int i=0;i<maxIters;i++) {  
 planner->PlanMore();  
 if(planner->IsConnected(0,1)) {  
 planner->GetPath(0,1,path);  
 solved=true;  
 break;  
 }  
}  
delete planner;

The default settings in WorldPlannerSettings (RobotSim/Planning/PlannerSettings.h) and MotionPlannerFactory should be sufficient for basic testing purposes, but many users will want to tune them for better performance.

To plan for part of a robot (e.g., the arm of a legged robot), the SingleRobotCSpace2 class can be used instead. Be sure to configure the fixedDofs and fixedValues members before using it.

Note: although RobotCSpace.h contains multi-robot planning classes, they are not yet well-tested. Use at your own risk.

## Time-Optimal Acceleration-Bounded Trajectories

The result of kinematic planning is a sequence of milestones, which ought to be converted to a time-parameterized trajectory to be executed. The standard “path controllers” (see Section 9.3) do accept milestone lists and will do this automatically. Occasionally you may want to do this manually, for example, to perform path smoothing before execution.

This functionality is contained within the DynamicPath class in the RobotSim/Modeling/DynamicPath.h file, which builds on the classes in RobotSim/Modeling/ParabolicRamp.h. To shortcut a path, the following procedure is used:

1. Set the velocity and acceleration constraints, and optionally, the joint limits in the DynamicPath.
2. Call DynamicPath.SetMilestones(). The trajectory will now interpolate linearly and start and stop at each milestone.
3. Subclass the FeasibilityCheckerBase class with the appropriate kinematic constraint checkers overriding ConfigFeasible and SegmentFeasible. Construct an instance of this checker.
4. Construct a RampFeasibilityChecker with a pointer to the FeasibilityCheckerBase instance and an appropriate checking resolution.
5. Call DynamicPath.Shortcut(N,checker) where N is the desired number of shortcuts.

The resulting trajectory will be smoothed, satisfy velocity and acceleration bounds, and feasible.

Warning: free-rotational joints will not be interpolated correctly. Spin joints are not automatically handled correctly at step 3 and must be “unwrapped” manually; step 5 must be replaced with the WrappedShortcut method.

For more details, please see: *K. Hauser and V. Ng-Thow-Hing. Fast Smoothing of Manipulator Trajectories using Optimal Bounded-Acceleration Shortcuts. In proceedings of IEEE Int'l Conference on Robotics and Automation (ICRA), 2010.*

## Planning with Closed-Chain Constraints

To plan for motions that satisfy closed chain constraints (e.g., that a robot’s hands and feet touch a support surface), the ContactCSpace class (RobotSim/Planning/ContactCSpace.h) should be used in the place of SingleRobotCSpace. Fill out the contactIK member, optionally using the Add\*() convenience routines. The kinematic planning approach can then be used as usual.

Note that the milestones outputted by the planner should NOT be interpolated linearly because the motion lies on a lower-dimensional, nonlinear constraint manifold in configuration space. Rather, the path should be discretized finely on the constraint manifold before sending it to any function that assumes a configuration-space path. There are two methods for doing so: first, using MilestonePath.Eval() with a fine discretization, or the methods in RobotSim/Planning/RobotConstrainedInterpolator.h. This latter approach guarantees that the resulting path is sufficiently close to the constraint manifold.

To use RobotConstrainedInterpolator, construct an instance with the robot and its IK constraints. Then, calling RobotConstrainedInterpolator.Make() with two consecutive configurations will produce a list of finely-discretized milestones up to the tolerance RobotConstrainedInterpolator.xtol. Alternatively, the RobotSmoothConstrainedInterpolator class and the MultiSmoothInterpolate function can be used to construct a smoothed cubic path.

## Time-Scaling Optimization

TODO

## Real-Time Motion Planning

TODO

# Control

Controllers provide the “glue” between the physical robot’s actuators, sensors, and planners. They are very similar to planners in that they generate controls for the robot, but the main difference is that a controller is expected to work online and synchronously within a fixed, small time budget. As a result, they can only perform relatively light computations.

To **connect a controller to a simulated robot**, simply construct the controller and call the WorldSimulation.SetController() method. Or, the controller type can be specified in the world XML file as described in Section 9.3.

To **connect a controller to a physical robot**, slightly more work is needed to write a wrapper loop that repeatedly fills in the controller’s sensor data from the physical data, and write’s the controller’s actuator commands to the physical motors.

To **connect a planner to a controller**, there are two options. The first is to *externally instantiate* a planning thread that communicates periodically with the controller through some well-defined interface (for example, the SendCommand() API). The second is to *internally instantiate* a planning thread inside the controller, and the controller can read data from the planner whenever it is available. Both methods are suitable, so the choice is simply a matter of taste.

## Actuators

At the lowest level, a robot is controlled by *actuators*. The RobotMotorCommand (RobotSim/Control/Command.h) structure contains a list of ActuatorCommands , which receive instructions from the controller and produce link torques that are used by the simulator.

RobotSim supports three types of actuator:

* *Torque control* accepts torques and feeds them directly to links.
* *PID control* accepts a desired joint value and velocity and uses a PID control loop to compute link torques servo to the desired position. Gain constants kP, kI, and kD should be tuned for behavior similar to those of the physical robot. PID controllers may also accept *feedforward torques*.
* *Locked velocity* *control* drives a link at a fixed velocity. *Experimental*. (Note: this is different from “soft” velocity control which feeds a piecewise linear path to a PID controller)

Note that the PID control and locked velocity control loops are performed as fast as possible with the simulation time step. This rate is typically faster than that of the robot controller. Hence a PID controlled actuator typically performs better (rejects disturbances faster, is less prone to instability) than a torque controlled actuator with a simulated PID loop at the controller level.

*Important*: When using RobotSim to prototype behaviors for a physical robot, the RobotSim actuator properties should be calibrated to mimic the robot’s true low-level motor behavior as closely as possible. It is also the responsibility of the user to ensure that the controller uses the simulated actuators in the same fashion as it would use the robot’s physical actuators. For example, for a PID controlled robot with no feedforward torque capabilities, it would not be appropriate to use torque control in RobotSim. If a robot does not allow changing the PID gains, then it would not be appropriate to do so in RobotSim. RobotSim will not automatically configure your controller for compatibility with the physical actuators, nor will it complain if such errors are made.

## Sensors

RobotSim can emulate of several types of sensors typically found on robots. At the user’s level of abstraction they generically provide streaming numerical-valued measurements. It is up to the user to process these raw measurements into meaningful information. The following sensors are natively supported:

* JointPositionSensor: Standard joint encoders.
* JointVelocitySensor: Velocity sensors. Here velocities are treated raw measurements, not differenced from a position encoder, and hence they are rarely found in real life. However, these will be good approximations of differenced velocity estimates from high-rate encoders.
* DriverTorqueSensor: Torques fed back from a robot’s motors.
* ContactSensor: A contact switch, not currently functional.
* ForceTorqueSensor: A force/torque sensor at a robot’s joint. Can be configured to report values from 1 to 6DOF.
* Accelerometer: An accelerometer. Can be configured to report values from 1 to 3 channels.
* TiltSensor: A tilt sensor. Can be configured to report values from 1 to 2 axes, and optionally tilt rates.
* GyroSensor: A gyroscope. Can be configured to report accelerations, velocities, or absolute rotations.
* IMUSensor: An inertial measurement unit that uses an accelerometer and/or gyroscope to provide estimates of a link’s transformation and its derivatives. It will fill in the gaps that are not provided by the accelerometer / gyro using either integration or differencing.
* FilteredSensor: A “virtual sensor” that simply filters the measurements provided by another sensor.

Sensors can be dynamically configured from world XML files under the <simulation> and <robot> elements via a statement of the form <sensor type=”TheSensorType” name=”some\_name” attr1=”value” … />. Each of the attribute/value pairs is fed to the sensor’s SetSetting method, and details on sensor-specific settings are found in the documentation in Control/Sensor.h.

## Controllers

The number of ways in which a robot may be controlled is infinite, and can range from extremely simple methods, e.g., a linear gain, to extremely complex ones, e.g. an operational space controller or a learned policy. Yet, all controllers are structured as a simple callback loop: repeatedly read off sensor data from a RobotSensors structure, perform some processing, and write commands to a RobotMotorCommands structure. The implementation of the internal processing is open to the user.

Any controller must subclass the RobotController class (RobotSim/Control/Controller.h) and overload the Update method. The members sensors and command are available for the subclass to use.

**Dynamically loadable controllers.** Controllers can be dynamically and automatically loaded from world XML files via a statement of the form <controller type=”TheControllerType” attr1=”value” … /> under the <simulation> and <robot> elements. The following controllers are supported:

* *JointTrackingController* (RobotSim/Control/JointTrackingController.h): a simple open-loop controller that accepts a desired setpoint.
* *MilestonePathController* (RobotSim/Control/PathController.h): an open-loop controller based on a DynamicPath trajectory queue.
* *PolynomialPathController* (RobotSim/Control/PathController.h): an open-loop controller based on a PiecewisePolynomialSpline trajectory queue. Somewhat more flexible than MilestonePathController.
* *FeedforwardJointTrackingController* (RobotSim/Control/FeedforwardController.h): a controller that additionally computes feedforward torques for gravity compensation and acceleration compensation. Works properly only with fixed-based robots. Otherwise works exactly like JointTrackingController.
* *FeedforwardMilestonePathController*: see above.
* *FeedforwardPolynomialPathController*: see above.

New controller types can also be defined for dynamic loading in world XML files using the RobotControllerFactory::Register(name,ptr) function. This hook must be called before the world file is loaded. Afterward, the specified controller type will be instantiated whenever the registered type appears in the world file.

**Generic external interfaces.** Optionally, controllers may expose various configuration settings to be loaded from XML files by implementing the \*Settings methods. (These may also be manipulated by GUI programs and higher-level controllers/planners). They may also accept arbitrary external commands by overloading the \*Command\* methods.

## State estimation

Controllers may or may not perform state estimation internally. If so, it is good practice to define the state estimator as independent of the controller, such as via a subclass of RobotStateEstimator. The RobotStateEstimator interface is fairly sparse, but the calling convention helps standardize their use in controllers.

**Using state estimators.** Controllers should instantiate a state estimator explicitly on construction. Inside the Update callback, the controller should:

1. Call RobotStateEstimator.ReadSensors(\*sensors), then UpdateModel() to update the robot’s model.
2. Read off the estimated state of the robot model (and potentially other information computed by the state estimator, such as uncertainty levels) and compute its command as usual.
3. Just before returning, call the ReadCommand(\*command) and Advance(dt) methods on the RobotStateEstimator object.

A few experimental state estimators are available. OmniscientStateEstimator gives the entire actual robot state to the controller, regardless of the sensors available to the robot. IntegratedStateEstimator augments accelerometers and gyros with an integrator that tries to track true position. These integrators are then merged (in a rather simple-minded way) to produce the final model.

# Simulation

TODO: describe simulation geometry, surface parameters, PID constants.

# C++ Programming

RobotSim is written in C++, and using C++ will give you full access to its functionality. But, it does require comfort with large code bases and moderate-to-advanced C++ programming abilities. Here are some conventions and suggestions for programming C++ apps that use RobotSim.

* Use STL and smart pointers (KrisLibrary/utils/SmartPointer.h) rather than managing memory yourself.
* Use a debugger (e.g., GDB) to debug crashes.
* KrisLibrary contains a lot of functionality, including linear algebra routines, 3D math, optimization, geometric routines, OpenGL drawing, statistics, and graph structures. Browse KrisLibrary before you reinvent the wheel.
* Avoid hard-coding. A much better practice is to place all settings into a class (e.g., with a robotLeftHandXOffsetAmount member) that gets initialized to a default value in the class’ constructor. If you need to hard-code values, define them as const static variables or #defines at the top of your file. Name them descriptively, e.g., gRobotLeftHandXOffsetAmount is much better than shift or (God forbid) thatStupidVariable, when you come back to the file a month from now.
* The main() function in RobotSim/Main/simtest.cpp is a good reference for setting up a world and a simulation from command-line arguments.

# Python Programming

The RobotSim/Python folder contains a Python API for RobotSim that is much cleaner and easier to work with than the C++ API. It is, however, not as fully functional.

## The robot module

The core modeling and simulation RobotSim functionality is found in the robot module. Users will typically load a WorldModel, construct a Simulator, and implement a robot controller by interacting with the SimRobotController. They may also wish to use the RobotModel to compute IK solutions (via the IKObjective and IKSolver classes), or do other kinds of planning tasks. A simple example file is found in RobotSim/Python/gltest.py.

**Motion queue control**. By default, the SimRobotController class implements a FeedforwardMilestonePathController, which is a motion-queued controller with optional feedforward torques. The setMilestone and addMilestone methods set and append a new destination milestone, respectively.

**Custom control**. It is possible to completely override the controller’s behavior to implement a custom control loop by calling the setPIDCommand or setTorqueCommand methods at every simulation time step.

Sub-modules of robot:

* contact: allows querying contact maps from a simulator and computing wrench matrices. *Stability testing not supported yet.*
* ik: convenience routines for setting up and solving IK constraints. *We do not yet allow solving across multiple robots and objects but this functionality may be supported in the future.*
* loading: methods for loading/saving objects to disk.
* map: convenient object-oriented interface for accessing worlds, robots, objects, links, etc. For example, you can write

wm = map.map(world)  
wm.robots[0].links[4].transform

instead of

world.robot(0).getLink(4).getTransform().

* robotcollide: defines a WorldCollider class that enables querying the collision status of the world and subsets of bodies in the world. Requires the geometry module.
* robotcspace: defines a configuration space for a robot in a world to be used in kinematic motion planning. Requires the motionplanning module.

The robot module does not (yet) contain interfaces to state estimators. Instead these must be implemented in the user’s own Python code.

## The geometry module

The geometry module defines basic vector operations (vectorops.py), rotations (so3.py), rigid transformations (se3.py), and collision detection between geometric primitives and triangle meshes (the collide submodule, with prototypes defined in collide.h).

## The motionplanning module

The motionplanning module defines configuration space prototype base classes (CSpace) and planners (MotionPlan). The most convenient interface is found in cspace.py.

To define a custom CSpace, subclasses will need to override (\* indicates that the method is optional):

* feasible(x): returns true if the vector x is in the feasible space
* \*sample(): returns a new vector x from a superset of the feasible space. If this is not overridden, then subclasses should set CSpace.bound to be a list of pairs defining an axis-aligned bounding box.
* \*sampleneighborhood(c,r): returns a new vector x from a neighborhood of c with radius r
* \*visible(a,b): returns true if the path between a and b is feasible. If this is not overridden, then paths are checked by subdivision, with the collision tolerance CSpace.eps.
* \*distance(a,b): return a distance between a and b
* \*interpolate(a,b,u): interpolate between a, b with parameter u

cspaceutils.py contains helpers for constructing composite CSpaces and slices of CSpaces.

# General recommendations

* Ask questions and report issues/bugs. This will help us make improvements to the RobotSim. If you write a piece of code that you think will be useful to others, consider making it a contribution to the library.
* Practice self-documenting code. Name files, functions, classes, and variables descriptively. Comment as you go.
* Use *visual debugging* to debug your algorithms. For example, output intermediate configurations or paths to disk and inspect them with the RobotPose program.
* *Think statefully*. Decompose your programs into algorithms, state, parameters, and data. State is what the algorithm changes during its running. Parameters are values that are given as input to the algorithm when it begins (arguments and settings), and they do not change during execution. Data is the knowledge available to the algorithm and the information logged as a side effect of its execution.
* When prototyping long action sequences, build in functionality to save the state of your system at intermediate points, and restore it.

# Wish List

RobotSim is a constantly evolving project and we hope to grow and refine it in the future with the help of others. Future development of RobotSim will focus on the following items (in no particular order):

* Tutorials for common tasks, instructional exercises
* Comprehensive GUI redesign with a better GUI package, e.g., Qt
* Better manipulation support in contact mechanics
* Convenience routines for easier motion planning
* Unification of locomotion and manipulation planning
* Specifying and solving optimization and optimal control problems
* Refinement of sensors and state estimators
* Expansion of the Python API (e.g., to handle contacts)
* Binding with the Python Task and Motion Library (PyTAMP)

# Papers/Projects using RobotSim

* TeamHubo in the DARPA Robotics Challenge: <http://dasl.mem.drexel.edu/DRC/>
* K. Hauser. *Fast Interpolation and Time-Optimization on Implicit Contact Submanifolds*. Robotics: Science and Systems, 2013.
* K. Hauser. *On Responsiveness, Safety, and Completeness in Real-Time Motion Planning*. Autonomous Robots, 32(1):35-48, 2012.
* Y. Zhang, J. Luo, and K. Hauser. *Sampling-based Motion Planning with Dynamic Intermediate State Objectives: Application to Throwing*. In proceedings of IEEE Int'l Conference on Robotics and Automation (ICRA), May 2012.
* E. You and K. Hauser. *Assisted Teleoperation Strategies for Aggressively Controlling a Robot Arm with 2D Input*. In proceedings of Robotics: Science and Systems (RSS), Los Angeles, USA, June 2011. (24.6% acceptance rate)
* K. Hauser. *Adaptive Time Stepping in Real-Time Motion Planning*. In Algorithmic Foundations of Robotics IX, Springer Tracts in Advanced Robotics (STAR), Springer Berlin / Heidelberg, vol 68, p215-230, 2010.
* K. Hauser. *Recognition, Prediction, and Planning for Assisted Teleoperation with Freeform Tasks*. In proceedings of Robotics: Science and Systems, July 2012.
* K. Hauser. *The Minimum Constraint Removal Problem with Three Robotics Applications*. In proceedings of Workshop on the Algorithmic Foundations of Robotics, June 2012.