# The Baxter Simulator

Wyatt Newman

October, 2015

Our minimal robot illustrated the features of Gazebo, Rviz, a URDF file and joint controllers. Armed with this knowledge, we can begin to use a more realistically complex robot simulation. The example we will use is the Baxter simulator from Rethink Robotics, Inc.

On our systems, you will find a ROS subdirectory called “rethink.” This directory contains 4 repositories created by Rethink Robotics. Three of these are useful for interfacing to either the Baxter simulator or to the physical Baxter robot. The fourth repository, “baxter_simulator”, is currently a private repository. Direct access to this repository can be obtained on request from Rethink Robotics. It is anticipated that this restriction will go away before the end of 2015.

A second directory we will use is “cwru_baxter.” This directory contains a package called “cwru_baxter_sim”, which includes a modified version of the robot model, “cwru_baxter.urdf.” The modification is the addition of a Kinect sensor, beginning with the lines:

```
<gazebo reference="kinect_link">
   <sensor type="depth" name="openni_camera_camera">
```

and including the sensor library plug-in:

```
    <plugin name="camera_controller" filename="libgazebo_ros_openni_kinect.so">
```

With these additions, Baxter can be launched with a Kinect sensor. As with our minimal robot example, we will also need to start a static-transform publisher to broadcast the relationship between the sensor frame and the Kinect enclosure link. This publisher will be started within the Baxter simulator launch file.

## Starting the Baxter simulator:

When we start up the Baxter gazebo simulation, we will not need to start a roscore. This will be performed automatically as part of the Gazebo launch. To start up the simulator, enter:

```
roslaunch cwru_baxter_sim baxter_world.launch
```

The file “baxter_world.launch” starts up a default Gazebo “empty world”, it loads the robot model into the parameter server (thus making it available to Rviz), and it starts up the Baxter simulator with specified initial joint angles.

The default “empty world” Gazebo description is overridden with the argument:

```
<arg name="world_name" value="$(find cwru_baxter_sim)/baxter.world"/>
```

The file baxter.world makes the default world somewhat more interesting by introducing additional models, including a cafe table and a beer can. Specifications in this file describe where the models can be found, and where they should be placed in Gazebo, as follows:

(from baxter.world:)

```
   <include>
      <uri>model://cafe_table</uri>
      <pose>0.756237 -0.288636 0 0 -0 0</pose>
```

```
    </include>
    <include>
        <uri>model://beer</uri>
         <pose>0.69112 0 0.775 0 0 0</pose>
    </include>

  <param name="robot_description"
            command="cat '$(find cwru_baxter_sim)/cwru_baxter.urdf'" />
```

The file cwru_baxter.urdf is a modified version of Rethink's baxter.urdf, which includes a Kinect link, a fixed joint securing the Kinect link to the robot's (movable) head, and a gazebo plugin:

```
            <plugin name="camera_controller" filename="libgazebo_ros_openni_kinect.so">
```

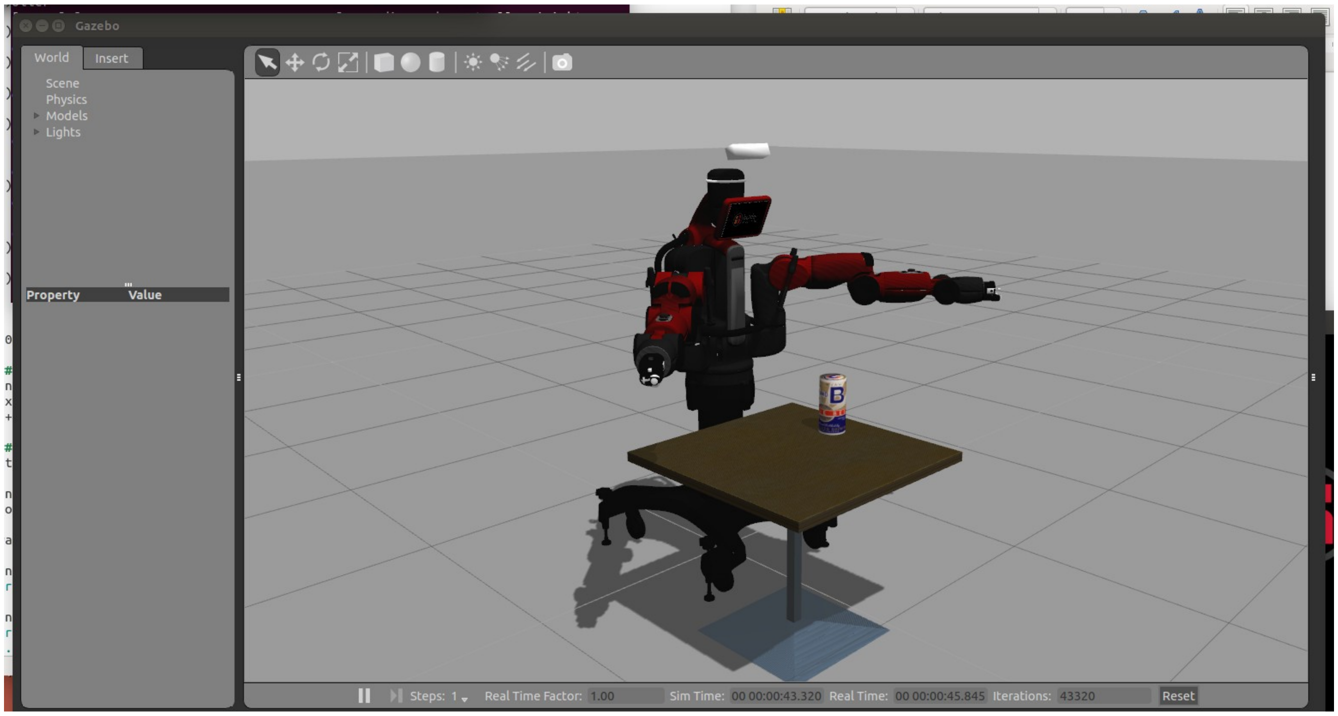
to emulate a Kinect sensor.

The baxter_world launch file also includes the following launch file:

```
  <!-- ros_control baxter launch file -->
  <include file="$(find baxter_sim_hardware)/launch/baxter_sdk_control.launch" />
```

This launch file is responsible for bringing up Rethink code for a set of joint controllers.  We will not need a version of “minimal_joint_controller” for Baxter (neither in simulation nor with the physical robot), since the joint controllers are provided as part of the simulator and as part of the robot controller.

Once the Baxter simulator is launched, it will appear in Gazebo as below:



**Getting Baxter joint and sensor states:**
With the Baxter simulator (or physical Baxter) running, executing:

```
rostopic list
```

reveals that approximately 300 topics are being used.  There are nearly 40 topics under “cameras” (Baxter has 3 built-in cameras), several “gazebo” topics, 16 “kinect” topics, nearly 250 “robot” topics, tf, tf_static and two “laserscan” sensor topics.  One of the most useful topics is the /robot/joint_states topic, which is described further below.

Running:

```
rosnode list
```

we see that a robot_state_publisher is running.  We thus will not need to start this node for Rviz visualization of joint poses.  However, the robot_state_publisher needs access to a robot model and to robot joint states.  We can see from a

```
rosparam list
```

that our “robot_description” is loaded on the parameter server.  We can further examine the topic “/robot/joint_states” with:

```
rostopic info /robot/joint_states
```

which shows that this topic carries messages of type “sensor_msgs/JointState”, which is a standard ROS means of publishing robot joint states.  The JointState message type can be examined by running:

```
rosmsg show sensor_msgs/JointState
```

which shows that this message is comprised of the following fields:

```
std_msgs/Header header
  uint32 seq
  time stamp
  string frame_id
string[] name
float64[] position
float64[] velocity
float64[] effort
```

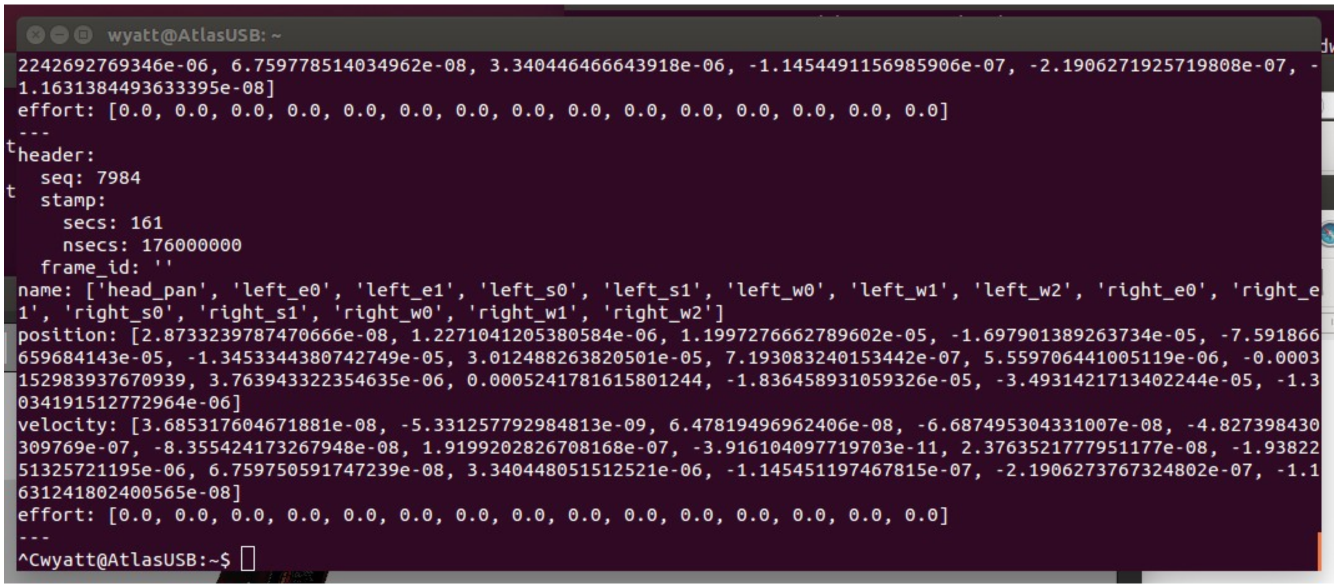
Running:

```
rostopic hz /robot/joint_states
```

shows that messages on this topic are being updated at 50Hz.   To get a glimpse of the data being published on this topic, run:

```
rostopic echo /robot/joint_states
```

A screenfull of this output is shown below.



```
wyatt@AtlasUSB: ~
2242692769346e-06, 6.759778514034962e-08, 3.340446466643918e-06, -1.1454491156985906e-07, -2.1906271925719808e-07, -
1.1631384493633395e-08]
effort: [0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0]
---
header:
  seq: 7984
  stamp:
    secs: 161
    nsecs: 176000000
  frame_id: ''
name: ['head_pan', 'left_e0', 'left_e1', 'left_s0', 'left_s1', 'left_w0', 'left_w1', 'left_w2', 'right_e0', 'right_e
1', 'right_s0', 'right_s1', 'right_w0', 'right_w1', 'right_w2']
position: [2.8733239787470666e-08, 1.2271041205380584e-06, 1.1997276662789602e-05, -1.697901389263734e-05, -7.591866
659684143e-05, -1.3453344380742749e-05, 3.012488263820501e-05, 7.193083240153442e-07, 5.559706441005119e-06, -0.0003
152983937670939, 3.763943322354635e-06, 0.0005241781615801244, -1.836458931059326e-05, -3.4931421713402244e-05, -1.3
034191512772964e-06]
velocity: [3.685317604671881e-08, -5.331257792984813e-09, 6.47819496962406e-08, -6.687495304331007e-08, -4.827398430
309769e-07, -8.355424173267948e-08, 1.9199202826708168e-07, -3.916104097719703e-11, 2.3763521777951177e-08, -1.93822
51325721195e-06, 6.759750591747239e-08, 3.340448051512521e-06, -1.145451197467815e-07, -2.1906273767324802e-07, -1.1
631241802400565e-08]
effort: [0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0]
---
^Cwyatt@AtlasUSB:~$
```

From our echo of the joint_states topic, we see the following joint names:

name: ['head_pan', 'left_e0', 'left_e1', 'left_s0', 'left_s1', 'left_w0', 'left_w1', 'left_w2', 'right_e0', 'right_e1', 'right_s0', 'right_s1', 'right_w0', 'right_w1', 'right_w2']

The joint states are reported in the same order as this listing of joint names. The order used by Baxter is somewhat odd; conventionally, joints are reported in order of the chain they describe, from torso to tip. ROS, however, is generally indifferent to the order of joints, either for reporting states or accepting commands; the order used in the "name" list is the order ROS will use, and this may change from iteration to iteration. For joint_states reporting, we can assume that the same order will be used every iteration.

To clarify Baxter's joint ordering and naming, the joints defined sequentially from torso to wrist for right arm are:

    right_s0, right_s1, right_e0, right_e1, right_w0, right_w1, right_w2.

For the left arm, the naming sequence is the same, but substitute "left" for "right."

All of position[], velocity[] and effort[] are reported in the order listed by order of names (as seen from the rostopic echo).

The camera topics, kinect topics, and laserscan topics will all be useful for perceptual processing. If more sensors are added to Baxter, the sensor values should be published on topics as well to be made available for interpretation.

**Controlling the Baxter Robot:** The Baxter simulator (and actual Baxter robot) subscribes to the topic:

    /robot/limb/right/joint_command

which carries messages of type baxter_core_msgs/JointCommand. We can examine this message type with:

```
rosmsg show baxter_core_msgs/JointCommand

int32 POSITION_MODE=1
int32 VELOCITY_MODE=2
int32 TORQUE_MODE=3
int32 RAW_POSITION_MODE=4
int32 mode
float64[] command
string[] names
```

The code snippet below illustrates how to command joint angles to joints of Baxter's right arm in position-control mode:

Here is an instantiation of the proper message type:

```
baxter_core_msgs::JointCommand right_cmd;
```

Assuming we have desired joint angles in the array vector qvec[], we can fill the command message with:

```
right_cmd.mode = 1; // position-command mode
```

Define the ordering of joints to be commanded as follows:

```
   // define the joint angles 0-6 to be right arm, from shoulder to wrist;
   // we only need to do this part once—and we can subsequently re-use this message, changing only
   // the position-command data
   right_cmd.names.push_back("right_s0");
   right_cmd.names.push_back("right_s1");
   right_cmd.names.push_back("right_e0");
   right_cmd.names.push_back("right_e1");
   right_cmd.names.push_back("right_w0");
   right_cmd.names.push_back("right_w1");
   right_cmd.names.push_back("right_w2");
```

Note: in the above, we have created room for 7 joint names. The “push_back()” command should not be repeated, else the list of names will grow with every iteration. The joint-command object can be retained, and this ordering of joint names can be persistent, so this step can be treated as an initialization. Within a control loop, only the desired joint values would need to be changed within this command message.

We can specify the right-arm joint-angle commands (in radians) with:

```
   for (int i = 0; i < 7; i++) {
      right_cmd.command[i] = qvec[i];
   }
```

and publish this command as:

```
   joint_cmd_pub_right.publish(right_cmd);
```

Where the publisher is defined as:

```
   joint_cmd_pub_right =
nh.advertise<baxter_core_msgs::JointCommand>("/robot/limb/right/joint_command", 1);
```

Joint-angle commands should be published as a rapidly-updated stream of incrementally changing joint values to produce a smooth trajectory. However, the joint controller will only respond to a limited update rate of commands. Likely, the joint controller accepts commands at the same rate that joint_states messages are published, i.e. 50Hz.

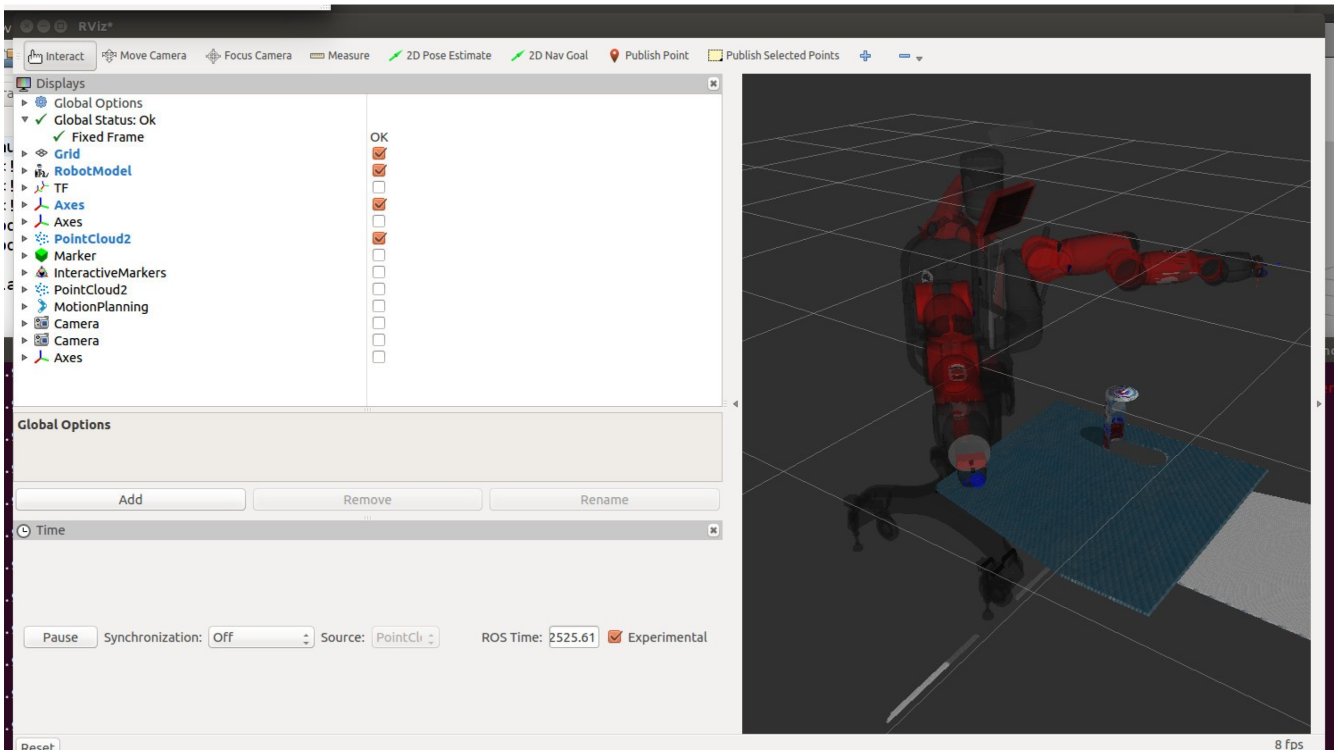
The topic /tf publishes large number of link-to-link transforms. All link-to-link relationships described by a connecting joint are updated rapidly. Some of these can be viewed by running:

```
rostopic echo tf
```

With the Baxter simulator launch, we have provided all of the necessary information (robot model on parameter server, publication of joint_states and execution of robot_state_publisher) for Rviz to correctly display all robot-model links. Starting up:

```
rosrun rviz rviz
```

we can add a "robot model" item to view Baxter in Rviz. An example view is shown below. In the view below, we have included a "pointCloud2" topic, which subscribes to the kinect/depth/points topic. The resulting display shows what the Kinect sensor would see, given the Gazebo objects present in the virtual world. If the physical Baxter robot were running, and if a Kinect were added to the robot, and if the Kinect driver were streaming its data, and if the Kinect transform relative to the robot's head were being published, Rviz would be able to display the Kinect data similarly, only with reference to the physical rather than the virtual world.



**A Trajectory Action Server for Baxter:**
As we saw with the minimal robot, it is useful to have an action server that can interpolate joint commands to smoothly execute trajectories—as described in a trajectory message. A primitive joint-space interpolation action server is in the package "baxter_traj_streamer" (within the cwru_baxter

repository). The source code of the action server is “traj_interpolator_as.cpp.” An action message is defined in this package, called “traj.action.” The key component of this action message is that the goal message contains:

```
    trajectory_msgs/JointTrajectory trajectory
```

This is essentially identical to the earlier introduction to trajectory messages in the package “example_trajectory.” Requested (goal) trajectories are linearly interpolated (in joint space) between specified joint poses with a fixed time step (currently set to 10ms in baxter_traj_streamer.h). This action server has a number of limitations. Its interpolation is only linear between desired joint poses, and thus large accelerations can occur at the start of each segment of the trajectory, unless the user has carefully crafted the trajectory to account for this (and has provided a sufficiently high-resolution trajectory specification). The interpolation action server also does not check for feasibility—either of joint limits or of joint velocity limits. It is up to the user to make sure a desired trajectory is feasible. This action server also does not check that the first point of a goal trajectory agrees (within some tolerance) with the actual pose of the robot. Violating this condition can result in large, potentially dangerous jumps. Finally, this interpolator is restrictive, in that it only commands the right-arm joints, and it requires that *all* right-arm joint angles be specified, and that these angles are listed in a required order—from torso to tool flange. All of these limitations could be relieved, but the present example at least offers a minimal illustration of a joint-interpolation action server for a realistic robot arm.

Within the baxter_traj_streamer package, there is an example client program, which helps illustrate use of the trajectory action server. The program, “traj_action_client_pre_pose.cpp,” makes use of a custom library, “baxter_traj_streamer.” The header file “baxter_traj_streamer.h” defines a class, “Baxter_traj_streamer”, and this class is compiled into a library, “baxter_traj_streamer.” Some of the useful member functions of Baxter_traj_streamer are:

Vectorq7x1 Baxter_traj_streamer::get_qvec_right_arm(): this returns an Eigen-type vector, 7x1, containing the right-arm joint angles, ordered from torso to tool flange. This function is useful for constructing trajectories that start at the robot's current pose, which is necessary for safe trajectories.

double Baxter_traj_streamer::transition_time(Eigen::VectorXd dqvec): This function computes the minimum time possible to move all of the joints by dqvec, subject to joint velocity constraints. This does not account for acceleration times. The velocity constraints are hard-coded in the baxter_traj_streamer.h header file, and these values have not been tuned experimentally. An additional scale factor, SPEED_SCALE_FACTOR, de-rates these values to a lower value (currently, 50% of the hard-coded velocity limits) for the purpose of experimental tuning.

void Baxter_traj_streamer::stuff_trajectory( std::vector<Vectorq7x1> qvecs, trajectory_msgs::JointTrajectory &new_trajectory): This function takes a C++ vector of Eigen-type vectors of 7-DOF joint poses as a path specification (in joint space). The desired path is converted to a trajectory with the addition of arrival times. The arrival times are computed based on velocity limits (and a speed scale factor), so as to define a feasible trajectory.

The example trajectory-interpolator action client program, “traj_action_client_pre_pose”, uses the baxter_traj_streamer library. It instantiates an object of the class Baxter_traj_streamer. It then uses this object to get the current arm pose, via:

```
   q_vec_right_arm =  baxter_traj_streamer.get_qvec_right_arm();
```

The example client uses the current arm pose as its first point in specifying a path, via the command:

```
 des_path.push_back(q_in_vecxd);
```

A second pose has been hard coded as:

```
    q_pre_pose<< -0.907528, -0.111813,   2.06622,    1.8737,    -1.295,   2.00164,  -2.87179;
```

This second pose is pushed onto the path description as a second point:

```
    q_in_vecxd = q_pre_pose; //
    des_path.push_back(q_in_vecxd);
```

This defines a joint-space path consisting of only 2 poses, and the initial pose is consistent with the current actual pose of the robot. The path is converted to a trajectory with:

```
            baxter_traj_streamer.stuff_trajectory(des_path, des_trajectory);
```

In using this baxter_traj_streamer library function, an appropriate (feasible) arrival times are assigned to each specified "knot" point (7-DOF joint-space sub-goal) along the path. For this simple example, there is only an initial knot point (the current are pose) and a final knot point (the destination pose).

The trajectory thus constructed is feasible, in that it starts from the current pose and it does not violate any joint velocity constraints. It should be tested, however, if start and end goal angles might send the robot through unreachable angles in attempting to move a shortest distance to the goal pose.

Having constructed a goal trajectory, the client connects to the action server, which is called "trajActionServer." The client transmits its goal trajectory with:

```
   action_client.sendGoal(goal,&doneCb);
```

The client waits a maximum of 5 seconds for a response, then gives up (with a warning message) if it has not heard back "success" from the action server. For this simple program, sending this single, hard-coded destination completes the task, and the client terminates.

This client program could be emulated and enhanced to create more interesting moves. The baxter_traj_streamer library and the trajectory interpolation action server could continue to be used as-is, or these could be further enhanced or replaced.

To run these example programs, do the following (in separate terminals):

roslaunch cwru_baxter_sim baxter_world.launch   (brings up Baxter in Gazebo with custom world)

roslaunch cwru_baxter_sim kinect_xform.launch  (this is only needed if want to see Kinect data in rviz)
(optionally, rosrun rviz rviz   to view the robot and Kinect data in rviz).

rosrun baxter_traj_streamer traj_interpolator_as  (brings up the trajectory-interpolation action server)

rosrun baxter_tools enable_robot.py -e  (enable the joint controllers)

rosrun baxter_traj_streamer traj_action_client_pre_pose (will move the right arm, then terminate)

Although "traj_action_client_pre_pose" runs to completion, the trajectory action server is still running and available to accept new commands.