Open Source Solutions for Motion Planning

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This talk includes contributions from the entire ROS and PR2 development teams at Willow Garage (including several interns) and the PR2 Beta Program and ROS community in general.

External collaborators/contributors:
Maxim Likhachev, CMU
Lydia Kavraki, Rice University
Outline

• The PR2 robot

• ROS
  - tools for simulation
  - motion planning
    - navigation and manipulation
  - task execution
    - several examples and movies
  - applications

• Future directions
About Us

- Willow Garage - Menlo Park, CA, USA
  - 60 full-time employees

- Interns and visiting researchers - Freiburg, TUM, CMU, Penn, UNC, Stanford, GaTech.....

Picture courtesy: Armin Hornung, Freiburg
PR2

- PR2 - Personal Robotic System
PR2 Beta Program

- 11 robots to universities and industry
- 2 year program - research and develop state of the art techniques for personal robotics
PR2

Omnidirectional base

Telescopng spine

Pan and Tilt head
Sensing on the PR2

- Sensors for navigation
  - IMU
  - Laser scanner
    - base (planar)
    - tilting (3D scanner on head)
Sensing on the PR2

- Sensors for manipulation

Stereo cameras
Texture Projector
Tilting Laser Scanner
Forearm Camera
Computing power

- 2 servers
  - 8 cores each
  - 20 GB Memory
  - External hard drives for data storage
Outline

• The PR2 Robot

• ROS
  - tools for simulation
  - tools for motion planning
  - task execution
  - applications

• Future Directions
• Number of robots with ROS on them keeps growing

Resources: http://www.ros.org/wiki/robots
ROS

- Over 100 repositories
- Over 2000 packages!!
- Lots of code reuse
  - navigation
  - localization
  - mapping
  - motion planning
  - state machines
  - perception
  - drivers

1. wg-ros-pkg
2. prairie-dog (CU)
3. utexas-art-ros-pkg
4. ccny-ros-pkg
5. alufr-ros-pkg
6. ua-ros-pkg
7. umd-ros-pkg
8. dki-sks-ros-pkg
9. iheart-ros-pkg
10. gt-ros-pkg
11. openrobotino
12. bosch-ros-pkg
13. tum-ros-pkg
14. wu-ros-pkg
15. care-o-bot
16. kul-ros-pkg
17. berkeley-ros-pkg
18. brown-ros-pkg
19. sail-ros-pkg
20. cmu-ros-pkg
21. mit-ros-pkg
22. ros-engagement (WPI)
23. mod-ros-pkg (Penn)
24. usc-ros-pkg
25. cu-ros-pkg
26. amor-ros-pkg
27. rice-ros-pkg
28. sr-ros-interface
29. jsk-ros-pkg
30. isr-uc-ros-pkg
31. auburn-automow
32. RCPRG-ros-pkg
33. aptima-ros-pkg
34. ubc-ros-pkg
35. sue-ros-pkg
36. vanadium-ros-pkg
37. hwu-osl-ros-pkg
38. seabees3-ros-pkg
39. cwru-ros-pkg
40. flyatar
41. ethz-asl
42. vmi-ros-pkg
43. ais-bonn-ros-pkg
44. pi-robot
45. stanford-wbc
46. clearpath-ros-pkg
47. uusrc-ros-pkg
48. albany-ros-pkg
49. acin-tuwien
50. webots-ros-pkg
51. starmac-ros-pkg
52. wpi-ros-pkg
53. ssc-rovers-ros-pkg
54. csiro-asl-ros-pkg
55. tuc-ros-pkg
56. cornell-ros-pkg
ROS - Evolution

- Navigation
- Logging and playback (rosbag, rxbag)
- Image/laser pipelines
- OpenCV Integration
- Simulators (gazebo, stage)
- Visualizers (rviz, nav_view)
- Hardware drivers

- Arm navigation (initial release)
- Grasping pipeline (initial release)
- Task coordination (SMACH)
- Calibration
- Firewire drivers
- Nodelets
- Collada

- Lightweight ROS
- Point Cloud Library
- SMACH (1.0)
- OpenNI/Kinect
ROS

• Transport infrastructure/framework

• Tools
  - navigation
  - control
  - sensing
  - perception
  - motion planning
  - simulation

How can you start using ROS for motion planning?
Robot Description

- URDF (Universal Robot Description Format)
  - serial manipulators
  - URDFs already available for different robots

```xml
<robot name="test_robot">
  <link name="link1" />
  <link name="link2" />
  <link name="link3" />
  <link name="link4" />
  
  <joint name="joint1" type="continuous">
    <parent link="link1"/>
    <child link="link2"/>
    <origin xyz="5 3 0" rpy="0 0 0" />
    <axis xyz="-0.9 0.15 0" />
  </joint>

  <joint name="joint2" type="continuous">
    <parent link="link1"/>
    <child link="link3"/>
    <origin xyz="-2 5 0" rpy="0 0 1.57" />
    <axis xyz="-0.707 0.707 0" />
  </joint>

  <joint name="joint3" type="continuous">
    <parent link="link3"/>
    <child link="link4"/>
    <origin xyz="5 0 0" rpy="0 0 -1.57" />
    <axis xyz="0.707 -0.707 0" />
  </joint>

</robot>
```

1. [www.ros.org/wiki/urdf](http://www.ros.org/wiki/urdf)
2. [www.ros.org/wiki/robots](http://www.ros.org/wiki/robots)
Simulator

- Gazebo
  - now maintained actively by Willow Garage
  - using the URDF and ROS or through config files
    - add robots
    - add objects
    - add sensors
    - add maps

http://www.ros.org/wiki/simulator_gazebo
Simulator

http://www.ros.org/wiki/pr2_gazebo
Outline

• The PR2 robot

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  - tools for simulation
  - tools for motion planning
     navigation
  - task execution
  - applications

• Future Directions
Navigation

• Need
  - representation of robot
    ✓ footprint - 2D projection of robot onto ground plane
  - representation of environment
  - global motion planner
  - local motion planner
  - controller
Navigation

- Environment Representation
  - Dealing with 3D obstacles
  - Voxel grid (stored compactly)

- Global planner
  - Djikstra’s, A*
  - plans in x,y space
  - assumes circular robot

- Local planner
  - trajectory rollout
  - lays out full footprint of the robot

2D costmap - http://www.ros.org/wiki/costmap_2d
3D voxel grid - http://www.ros.org/wiki/voxel_grid
Lattice based planner

- 2D global planner can produce infeasible paths
  - nice to have better paths for local controller to follow
  - take into account constraints/dynamics in global planning as well

![Diagram of lattice based planner](image)

motion primitives

construct the graph:

search the graph for solution:

[M. Likhachev]
Navigation

- Discretize orientation as well
  - ability to plan in orientation as well as x,y
  - better trajectories that are easier to follow for local planner

Lattice planner - [http://www.ros.org/wiki/sbpl_lattice_planner](http://www.ros.org/wiki/sbpl_lattice_planner)
Search based planning library - [http://www.ros.org/wiki/sbpl](http://www.ros.org/wiki/sbpl)
- developed by Maxim Likhachev’s group at CMU in collaboration with Willow Garage
Navigation - extension

• Used 3D data projected onto a 2D costmap
 ❖ problems with tables, overhangs etc. in environment
 ❖ inability to plan with arms not tucked

• Collision checking of 3D robot model against 3D model of environment
 ❖ need compact representation of environment
Octomap

- Octree-based representation of the environment
  - Probabilistic, flexible, and compact 3D mapping
  - Optimized for online operation
“3D” Navigation

- Octomap + lattice based planner
  - full 3D collision checking only when necessary
  - allows general navigation in unstructured environments (even with arms outstretched)
Applications - Long term autonomy

- 13 days, 2 hours
- 138.9 km
- 2 manual interventions
  - robot emails for help
    - get around a chair
    - re-localization
    - (both issues resolved over the web)
Applications

- Navigation with moveable objects
  - need to move large objects around
  - robots limited in their payload capacity
    - e.g. PR2 has a maximum 5 lb. payload
    - can carry only one object in each hand

- Example tasks
  - carry a set of dishes to the kitchen
  - arrange chairs in a room
Motion Planning

- Given a start and goal, generate a collision free path that takes the robot (and cart) from start to goal

  - State representation
    - whole body planning too expensive
    - choose to work in lower-dimensional space
      - x,y position of the robot base
      - orientation of the base
      - articulated angle for the cart (relative to robot)

  - cart motion restricted to pivoting about a center of rotation in front of robot
Motion Primitives

- Rotation, forward, sideways (a), (b), (c)
- Articulated motion primitive (d)
  - designed for going around 90 degree corners
  - cart angle starts and ends at 0 degrees
Experiments

- Run the robot + cart in Willow Garage office building
  - plan continuously between multiple waypoints on the map
  - map generated offline (a priori)
Experiments
Environment Uncertainty
Some surprises along the way!!
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  - tools for motion planning
    ✷ manipulation
  - task execution
  - applications

• Future Directions
Manipulation

• Motion planning
  - sensing for motion planning
    - semantic perception
  - collision environment
  - system architecture
  - motion planners
    - applications
  - safer control
Manipulation

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Manipulation

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    ✷ semantic perception
  - collision environment
  - kinematics
  - motion planners
  - smoothers
  - monitoring and control
Manipulation

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Sensing

• Essential for operation in unstructured environments

• Sensor input
  - point cloud (from stereo, lasers, etc.)
    - collection of 3D points
    - can annotate other information
      - RGB color, intensity values
    - stereo (20-25,000 points)
    - laser sensor (5-7,000 points)
Sensing

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Semantic Perception

Extracting semantic information from point clouds
Semantic Perception

Extracting semantic information from point clouds
Semantic Perception

Extracting semantic information from point clouds

Point Cloud Library - http://pointclouds.org
Semantic Perception

- Helps in
  - object recognition
  - object representation for collision checking
  - place recognition
  - task planning
    - place/pickup locations for objects
    - constrained planning
Manipulation

• Motion planning
  - sensing for motion planning
    ❖ semantic perception
  - collision environment
  - kinematics
  - motion planners
  - smoothers
  - monitoring and control
Collision Environment

- From point clouds to collision representation
  - meshes for known objects
  - each point represented as box/sphere primitive
Collision Environment

- Sensor data -> Collision map
  - 3D Occupancy grid
  - Filter robot parts out of sensor streams
Collision Environment

- Collision map
  - account for self-occlusion
Collision Environment

Collision map - http://www.ros.org/wiki/collision_map
Collision space - http://www.ros.org/wiki/collision_space
Collision Environment

- You can create your own environment by adding objects into the space as a
  - mesh
  - geometric primitive - boxes, cylinders, spheres

```c++
// add the cylinder into the collision space
mapping_msgs::CollisionObject cylinder_object;
cylinder_object.id = "pole";
cylinder_object.operation.operation = mapping_msgs::CollisionObjectOperation::ADD;
cylinder_object.header.frame_id = "base_link";
cylinder_object.header.stamp = ros::Time::now();
geometric_shapes_msgs::Shape object;
object.type = geometric_shapes_msgs::Shape::CYLINDER;
object.dimensions.resize(2);
object.dimensions[0] = .1;
object.dimensions[1] = .75;
geometry_msgs::Pose pose;
pose.position.x = .6;
pose.position.y = -.6;
pose.position.z = .375;
pose.orientation.x = 0;
pose.orientation.y = 0;
pose.orientation.z = 0;
pose.orientation.w = 1;
cylinder_object.shapes.push_back(object);
cylinder_object.poses.push_back(pose);
```
Collider

• Generate collision map for manipulation using Octomap
  ❖ future plans to use notion of uncertainty in sensing
  ❖ probabilistic representation possibly more robust to sensor noise, errors

Octomap - [http://octomap.sf.net](http://octomap.sf.net)
Collider - [http://www.ros.org/wiki/collider](http://www.ros.org/wiki/collider)
Armin Hornung, Kai Wurm, et. al., Freiburg
Manipulation

• Motion planning
  - sensing for motion planning
    - semantic perception
  - collision environment
  - kinematics
  - motion planners
  - smoothers
  - monitoring and control
Kinematics

• Robot specific kinematics
  ❖ e.g. pr2_kinematics package - fast custom solvers

• Constraint, collision aware kinematics
  ❖ search for collision free configurations that satisfy constraints for general arms

PR2 custom kinematics - http://www.ros.org/wiki/pr2_arm_kinematics
General kinematics solvers - http://www.ros.org/wiki/arm_kinematics_constraint_aware
Kinematics

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ROS - Motion Planners

• Sampling based planners (OMPL)
  - developed by Lydia Kavraki’s group at Rice University in collaboration with Willow Garage

• CHOMP*

• Search based planners (SBPL)
  - developed by Maxim Likhachev’s group (now at CMU) in collaboration with Willow Garage


http://www.ros.org/wiki/ompl
http://www.ros.org/wiki/ompl_ros_interface
http://www.ros.org/wiki/chomp_motion_planner
http://www.ros.org/wiki/sbpl
OMPL

- Sampling-based planners
  - RRT, RRT-Connect, EST, KPIECE, SBL and more
  - coming soon - RRT *
- Very fast planning times
- Extensive documentation
- ROS interface
  - easily go from robot description to complete planners
  - configure task space planners

OMPL - http://www.ros.org/wiki/ompl
ROS interface to OMPL - http://www.ros.org/wiki/ompl_ros_interface
Smoothers

- Sampling based planners generate jerky paths
  - smoothing required before plans can be sent to controllers
  - cubic spline shortcuts used to smoothen paths

Cubic spline smoother - [http://www.ros.org/wiki/constraint_aware_spline_smoker](http://www.ros.org/wiki/constraint_aware_spline_smoker)
CHOMP

- Covariant descent based approach - generates smoother trajectories
- Uses signed distance field to move robot away from obstacles

CHOMP - http://www.ros.org/wiki/chomp_motion_planner
Applications for CHOMP

- Planning out of contact
  - noisy sensor data, noisy models, actual contact
  - typically achieved by jittering start state
System Architecture

User Input → Move arm → Arm Joint Trajectory

Pose goal

Perform IK?

Yes → IK → Joint space goal

No → Sensing

Motion Planner → Path

Smoother → Trajectory

Safe Controller

Abort?

Yes
System Architecture

User Input → Move arm → Arm Joint Trajectory

Pose goal → Perform IK? → Yes → IK → Motion Planner → Path 
No → Sensing

Joint space goal → Motion Planner → Smoother → Trajectory 
Abort? → Yes 

Safe Controller
System Architecture

• Input
  ❖ specify goal as regions in space
    ✓ joint space goal - nominal joint angle + tolerance
    ✓ position goal - nominal position + region of space
    ✓ orientation goal - nominal orientation + tolerance (in roll, pitch and yaw)

Move arm -http://www.ros.org/wiki/move_arm
Interface definition -http://www.ros.org/wiki/move_arm_msgs
System Architecture

• Constraints
  ❖ keep the glass of water level - less freedom in roll and pitch space
  ❖ constraint specification:

```cpp
orientation_constraint.header.frame_id = "torso_lift_link";
orientation_constraint.header.stamp = ros::Time::now();
orientation_constraint.link_name = "r_wrist_roll_link";
orientation_constraint.orientation.x = 0.0;
orientation_constraint.orientation.y = 0.0;
orientation_constraint.orientation.z = 0.0;
orientation_constraint.orientation.w = 1.0;
orientation_constraint.type = motion_planning_msgs::OrientationConstraint::HEADER_FRAME;
orientation_constraint.absolute_roll_tolerance = 0.1;
orientation_constraint.absolute_pitch_tolerance = 0.1;
orientation_constraint.absolute_yaw_tolerance = M_PI;
```
Dealing with constraints

- In joint space - the constraint manifold is complicated
- Sampling based planners sample in joint space
  - Far away from constrained manifold
  - Need to project samples back onto constraint manifold

Dealing with constraints

❖ In joint space - the constraint manifold is complicated
❖ sampling based planners sample in joint space
 ✓ far away from constrained manifold
 ✓ need to project samples back onto constraint manifold

❖ Most constraints are expressed more naturally in cartesian space
 ✓ e.g. holding water level => restricting roll and pitch of the end-effector

Constrained Planning

- Exploit geometry of the PR2
  - joint limits imply only 1 IK solution branch exists most of the time
  - plan in cartesian end-effector coordinates + redundancy (shoulder roll joint angle)
  - no need to do constraint projections in joint space
  ✓ just shrink region available for sampling!
Application - Grasping

- Collision Map Generation
- Scene Interpreter
- Object Model Registration
- 3D Perception
- Grasp Planning for unknown objects
- Grasp Planning for known objects
- Grasp Selection
- Motion Planning
- Grasp Execution
- Tactile Feedback
- Object Model Database
Arm Navigation and Manipulation

[Images of robotic arms engaged in tasks]

http://www.ros.org/wiki/arm_navigation
http://www.ros.org/wiki/object_manipulation
http://www.ros.org/wiki/pr2_object_manipulation
Towards a safer robot

- Detect impacts
  - accelerometer and joint signals

Joe Romano (Intern at Willow Garage, Summer 2010), Kaijen Hsiao, Gunter Neimeyer, Sachin Chitta, Katherine Kuchenbecker (Penn)

http://www.ros.org/wiki/pr2_gripper_sensor_action
Towards a safer robot

- Actively monitor motion
  - abort on possible collision
“Stochastic Trajectory Optimization for Motion Planning”, Mrinal Kalakrishnan, Sachin Chitta, Evangelos Theodorus, Peter Pastor, Stefan Schaal, ICRA 2011
Outline

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• ROS
  - tools for simulation
  - tools for motion planning
    - task execution
  - applications
• Future Directions
Task Execution

- SMACH
  - Task-level state machine architecture
  - State machine architecture
    ✓ concurrence
    ✓ synchronization
    ✓ failure recovery
    ✓ pre-emption

SMACH - http://www.ros.org/wiki/smach
Meta-programming on top of Python

```python
def construct_sm():
    open_door_sm =StateMachine(['succeeded','aborted','preempted'])
    with open_door_sm:
        cs0 = Concurrence(['succeeded','aborted'],'aborted')
       StateMachine.add('PREP_FOR_NAV',cs0,['succeeded':'NAVIGATE_TO_FRIDGE'])
        with cs0:
            Concurrence.add('TUCK_FOR_NAV',
                SimpleActionState('tuck_arms',TuckArmsAction,
                goal = TuckArmsGoal(False,True,True))
            Concurrence.add('LOWER_SPINE',
                SimpleActionState('torso_controller/position_joint_action', SingleJointPositionAction,
                goal = SingleJointPositionGoal(position=0.07))
            Concurrence.add_outcome_map('succeeded',{'TUCK_FOR_NAV':'succeeded','LOWER_SPINE':'succeeded'})
```
SMACH

- Visualize updates in real-time
Application - Beverage Retrieval
Applications - Pool

- specialized hardware
- hackathon - 1 week effort
- no motion planning for the arm
- pre-determined waypoints around table for base
Application - Pool

- Simulation based planning*

*Open source simulator FastFiz by Alon Altman at Stanford University
http://billiards2.stanford.edu/FastFiz/main.html
Application - Pool
Application - Busbot
What’s coming?

• Better tools
  - go from URDF to complete planning in a few quick steps
  - visualize everything along the way
  - interactive GUI to test out planning
Thank you!

More resources:

2. http://answers.ros.org
3. ros-users mailing lists
Thank you!

Email: sachinc@willowgarage.com

This talk included contributions from the entire ROS and PR2 development teams at Willow Garage, the PR2 Beta Program and the ROS community.

External collaborators/contributors:
Lydia Kavraki, Rice University
Maxim Likhachev, CMU