Motion Planning and Proximity Computations for Industrial Robots

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- Jamie Snape (UNC/Kitware)
- Jur Van Den Berg (UNC/Utah/Google)
- Sachin Chitta (Willow Garage/SRI)
- Ioan Sucan (Willow Garage/Google)
Motion Planning

- Widely studied in academic for 40+ years
- Good algorithms and software tools
- Technology transfer (CAD/CAM, games, simulation)
- Limited use for industrial robots
Planning tools for Industrial Robotics: Challenges

- Limited capabilities
- Limited development tools
- Lack of portability and flexibility
- Slow technology adoption
Collision & Proximity Queries

**Geometric reasoning of spatial relationships among objects (in a dynamic environment)**

- **Collision Detection**
- **Closest Points & Separation Distance**
- **Contact Points & Normals**
- **Penetration Depth**
Collision & Proximity Computations

• A key component of motion planning algorithms (90% of total time)

• Widely used in CAD/CAM, simulation and virtual prototyping

• Studied in academia for 30+ years

• Supported in robot simulation and CAD systems
Our work on Proximity Computations

- Fast algorithms for convex polytopes (1991 onwards)
- Bounding volume hierarchies for general polygonal models (1995 onwards)
- Deformable models & self-collisions (2000 onwards)
- Use of GPUs and multi-core hardware (2005 onwards)
- Multi-robot planning and coordination (2008 onwards)
Prior work on Proximity Computations

Multiple software systems

- I-Collide, RAPID, PQP, DEEP, SWIFT, SWIFT++, DeformCD, PIVOT, Self-CCD, RVO, HRVO
- http://gamma.cs.unc.edu/software/#collision

- More than 120,000 downloads from 1995 onwards

- Issued more than 55 commercial licenses (Kawasaki, MSC Software, Ford, Honda, Sensable, Siemens, BMW, Phillips, Intel, Boeing, etc.)
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Widely used, but not on industrial robots
Recent Work: FCL

- A new collision and proximity computation library
  - Flexible: different object types/queries
  - Extensible: adding new algorithms is easy
  - Efficiency: similar performance with the best libraries
- Provide many functions from state-of-the-art research, more in future
<table>
<thead>
<tr>
<th></th>
<th>Rigid Objects</th>
<th>Point Clouds</th>
<th>Deformable Objects</th>
<th>Articulated Objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Discrete) Collision Detection</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Continuous Collision Detection</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Self Collision Detection</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Penetration Estimation</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Distance Computation</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Broad-phase Collision</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
FCL: Usage

- Independent code, but ROS interface is provided

- Available at http://gamma.cs.unc.edu/FCL

- Part of MoveIt:
  http://moveit.ros.org/wiki/MoveIt!
FCL Application: Optimal Inverse Kinematics for Complex Path Planning

http://rosindustrial.org/
Robot Sensors: Data Collection

Cameras
Robot Sensors: Data Collection

Laser Scanners
Handling Sensor Data

- Human environments
  - Clutter, dynamic obstacles
- Data from 3D sensors
  - Large number of points (~10k for laser scans, ~20k for stereo)
- Real-time computation important for fast online reactive grasping, motion planning
- Proximity computation important for many useful heuristics in robotics

*Efficient collision and proximity computation is essential for any online robot operations in human environments*
Sensor Data

• Point cloud
  • Output from laser/Kinect, etc.
  • Cannot encode unknown regions
  • Very large

• Octree (octomap)
  • Store point cloud in a compact manner
  • Support multi-resolution
  • Encode occupied/free/unknown regions
Accelerated Pipeline: Point-Cloud Data

- Directly collide with sensor data represented by octree

- We eliminate construction time in this pipeline

http://gamma.cs.unc.edu/POINTC/
Proximity & Planning with Industrial Robots

http://rosindustrial.org/
Task Executions of Robots

• Advances in technology allow robots to perform complex tasks

<PR2: fetching a beer from the fridge>  <Baxter: $22k robot needs no programming>
Task Execution with Multiple Components

• A task is decomposed into many primitive subtasks

1. Move the body to the fridge.
2. Move the left arm to the handle.
3. Move the body to open the fridge door.
4. Move the body to in front of the fridge.
5. Move the left arm to hold the door.
6. Move the right arm to the beer.
7. Grasp the bottle.
8. Move the right arm to the basket.
9. Release the bottle.

<PR2: taking out a beer from the fridge>
(From Willow Garage)

Most of the subtasks are moving the robot to the next desired pose
Subtask Execution

• ‘Move the body to the fridge’ subtask
  – Use sensors to recognize the objects and obstacles in the environment
  – Compute a collision-free path to the pose close to the fridge
  – Control motors to execute the computed motion
Motion Planning: RRT Algorithm

• Serial RRT tree expansion
Motion Planning: Challenges

• How to perform motion planning computation in realtime?

• How to handle high DOF robots
<table>
<thead>
<tr>
<th>Processor</th>
<th>Single Tflops</th>
<th>Double Gflops</th>
<th>Stream/CUDA Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMD Radeon 7970</td>
<td>3.79</td>
<td>947</td>
<td>2048</td>
</tr>
<tr>
<td>NVIDIA GTX 680</td>
<td>3.09</td>
<td>1.1</td>
<td>1536</td>
</tr>
</tbody>
</table>

Commodity Tera-Flop Processor (peak performance)
Heterogeneous Processing

3rd Generation Intel® Core™ Processor: 22nm Process

New architecture with shared cache delivering more performance and energy efficiency

CPU + GPU on the same chip
Parallel Poisson-RRT Algorithm

AND Parallel RRT Tree

Poisson-RRT Tree

No nodes which are too close to each other
GPU-based RRT Planner

OMPL Benchmarks

<table>
<thead>
<tr>
<th>Absolute planning time for GPU Poisson-RRT</th>
<th>Easy 0.028s</th>
<th>Cubicle 0.361s</th>
<th>AlphaPuzzle 1.314s</th>
<th>Apartment 11.877s</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRT (Single CPU core)</td>
<td>8.3x</td>
<td>4.2x</td>
<td>24.9x</td>
<td>12.8x</td>
</tr>
<tr>
<td>GPU AND Parallel RRT</td>
<td>12.1x</td>
<td>6.4x</td>
<td>18.6x</td>
<td>16.1x</td>
</tr>
<tr>
<td>GPU Poisson-RRT</td>
<td>16.1x</td>
<td>8.3x</td>
<td>12.8x</td>
<td>16.1x</td>
</tr>
</tbody>
</table>
High-DOF Realtime RRT Planning

http://gamma.cs.unc.edu/PoissonRRT/
Real-Time Planning: High DOF Robots

• High-DOF robots (40 DOF for humanoids)

• Generate collision-free and smooth paths

• Dynamics constraints (e.g. dynamic stability)

• Moving obstacles (e.g. humans)
Motion Planning Algorithms

- Random sampling-based algorithms
- Optimization-based algorithms
Real-Time Planning

- Use optimization-based techniques
- Formulate constraints
- Parallel computation on multi-core CPUs and many-core GPUs
Parallel Trajectory Optimization

- Parallel optimization of multiple trajectories
  - Use Multiple threads
    - Start from different initial trajectories
    - Trajectories are generated by quasi-random sampling
  - Exploits the multiple CPU cores (multi-cores) or GPU-based cores (many-cores)

http://gamma.cs.unc.edu/ITOMP/ITOMP_ROS/
Real-Time High DOF Planning

http://gamma.cs.unc.edu/ITOMP
Parallel Trajectory Optimization

Performance improvement with number of cores

Multi-core CPU
- 1 core: 26.357
- 2 cores: 51.463
- 4 cores: 97.473

Mani-core GPU
- 1 trajectory: 522.739
- 10 trajectories: 1,012.881

Iteration / sec
Multi-Robot Planning

• Reciprocal Velocity Obstacles (RVOs)

\[ \text{RVO}_B^A(v_B, v_A) = \{v'_A \mid 2v'_A - v_A \not\in \text{VO}_B^A(v_B)\} \] [Berg et al. 2008]
MULTI-AGENT COLLISION AVOIDANCE (ORCA)

[Berg. Guy et al. 2010]
Multi-Robot Navigation

• Reciprocal velocity-space planning on robots
• Challenges for robots
  – Sensor Uncertainty
  – Motion Uncertainty
  – Kineodynamic Constraints
• Implementation on iRobot Create
• ROS Library implementation available

[[Snape et al. 2009, 2011]]

Independent Navigation of Multiple Mobile Robots with Hybrid Reciprocal Velocity Obstacles

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Jur van den Berg
Stephen J. Guy
Dinesh Manocha

University of North Carolina at Chapel Hill

http://gamma.cs.unc.edu/HRVO
Multi-Robot Navigation: ROS Integration

[ Claes et al., 2011, Willow Garage ]
RVO2 Library

• Publically available Library: http://gamma.cs.unc.edu/RVO2
• 6,500+ Downloads
• Licensed to Relic Entertainment, EA, GameLoft ...
• Widely used in game engines (Unity, UDK)
• Integrated into ROS
• Ports
  – ORCA – C++
  – ORCA – C#
  – ORCA3D – C++
Multi Human-Like Robots

http://gamma.cs.unc.edu/ITOMP
Going Forward

• Significant recent progress in algorithmic technology for motion planning and proximity computations

• Good software tools: FCL, ROS, MoveIT, OpenRAVE, etc.

• Applications
  – Advanced manipulation
  – Advanced perception
  – Flexible automation

• Major Challenge: Interface with robot devices and industrial use
Acknowledgements

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