Tool Use as a *constraint satisfaction* problem, with high-dimensional continuous variables

Choose a grasp $G$ such that:
1. Kinematically Suitable
2. Reachable
3. Force Suitable

**Kinematic Suitability**
Goal: Enables Tool Path while respecting torque limits

$$\tau_{\text{lim}} > J^T(q) \tau_{\text{ext}}$$

**Reachability**
Goal: Exists collision-free path to grasp

**Force Suitability**
Goal: Frictional Joint "maintained" under external forces

Model grasp with planar patch contacts

$$f_x^c (N\mu)^2 + f_z^c (N\mu)^2 + (N\mu)^2(r_{\text{FL}})^2 < 1$$

**How Difficult are the Tasks?**

<table>
<thead>
<tr>
<th>Task</th>
<th>$C_0$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_0 \cap C_2$</th>
<th>$C_0 \cap C_1 \cap C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>screw_driving</td>
<td>500</td>
<td>398</td>
<td>162</td>
<td>162</td>
<td>162</td>
</tr>
<tr>
<td>wrench_turning</td>
<td>52</td>
<td>369</td>
<td>220</td>
<td>219</td>
<td>27</td>
</tr>
<tr>
<td>knife_cutting</td>
<td>56</td>
<td>382</td>
<td>329</td>
<td>333</td>
<td>26</td>
</tr>
<tr>
<td>hammer_pulling</td>
<td>36</td>
<td>359</td>
<td>116</td>
<td>116</td>
<td>1</td>
</tr>
</tbody>
</table>

*Easy*, *Medium*, *Hard*

**Experimental Force/Torque Profiles**

- *knife_cutting*
  - $f_x$ vs. Time Steps
  - $f_z$ vs. Time Steps

- *wrench_turning*
  - $f_x$ vs. Time Steps
  - $f_z$ vs. Time Steps

Rachel Holladay$^{1,2}$, Tomás Lozano-Pérez$^2$ and Alberto Rodriguez$^1$

$^1$Manipulation & Mechanisms @ MIT, $^2$Learning & Intelligent Systems

Massachusetts Institute of Technology