エージェントシステム第５講義

動作計画
OpenRAVE

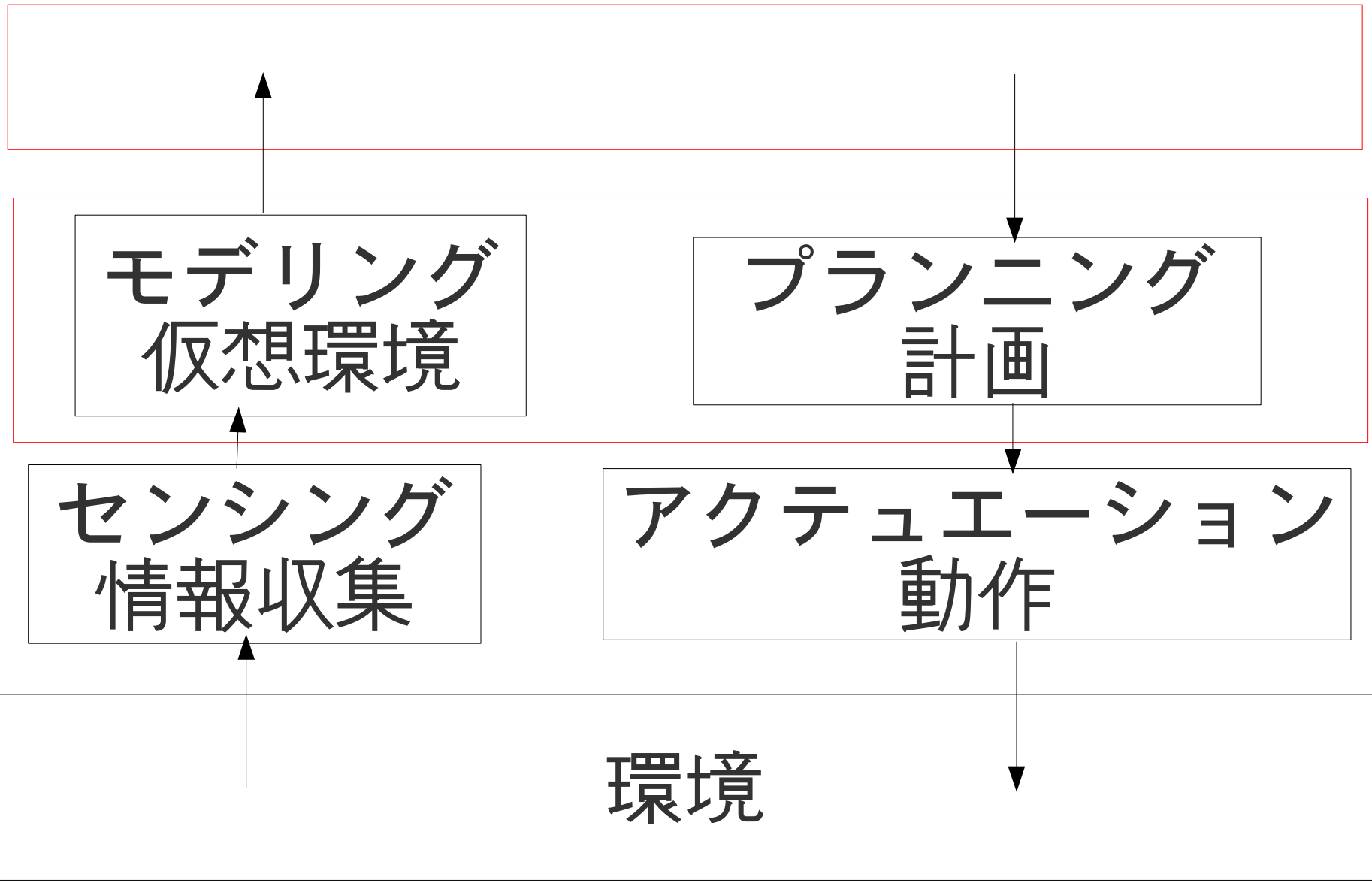
2011-05-25

出杏光　魯仙
であんこう　ろせん

内容

- 動作計画基礎
- 知的マニピュレーション
  - 自動化プロセスの概念
  - 動作計画用の知識ベース
  - 動作計画アルゴリズム
- OpenRAVE

エージェントシステムの基本像

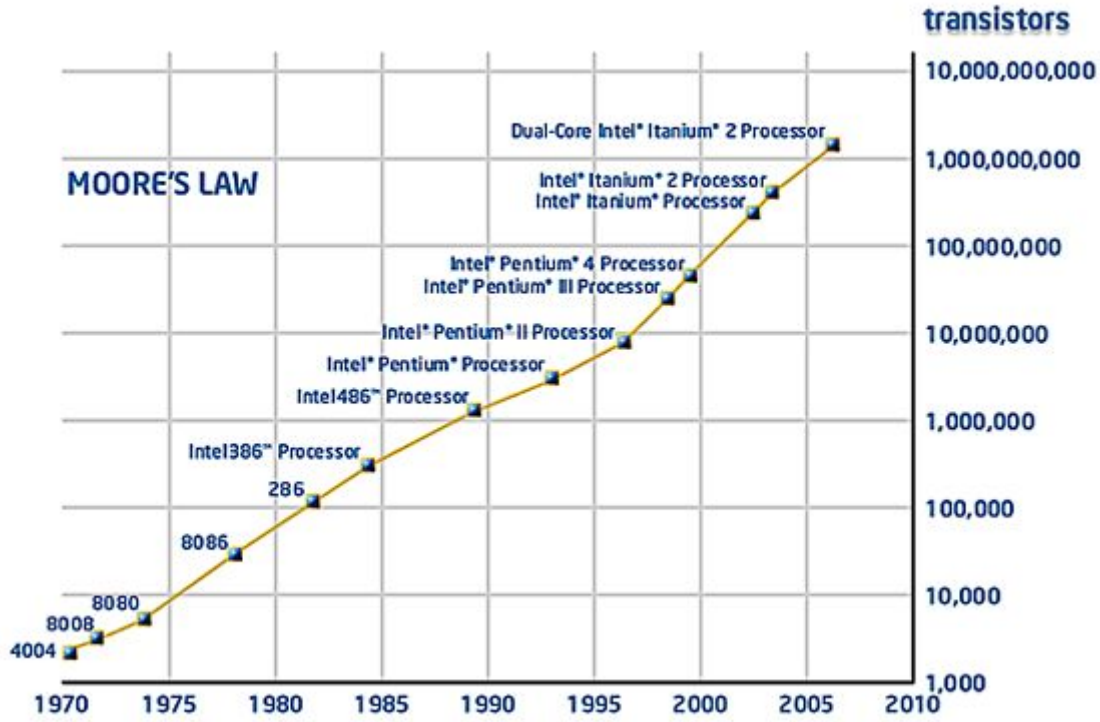


計画

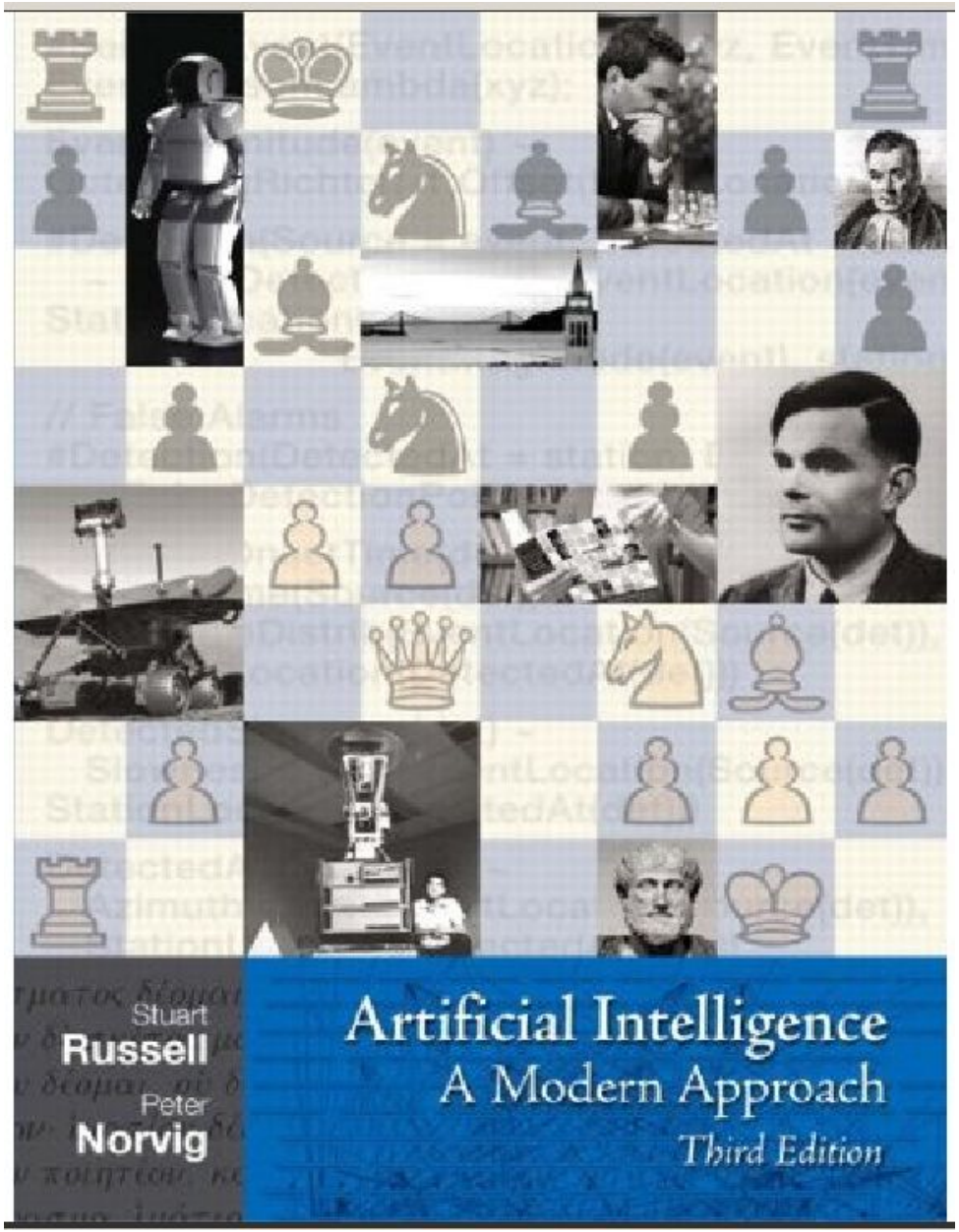
探索法の力

- 人工知能の基本
- 数多くの選択肢の考慮
- 毎年速くなっている

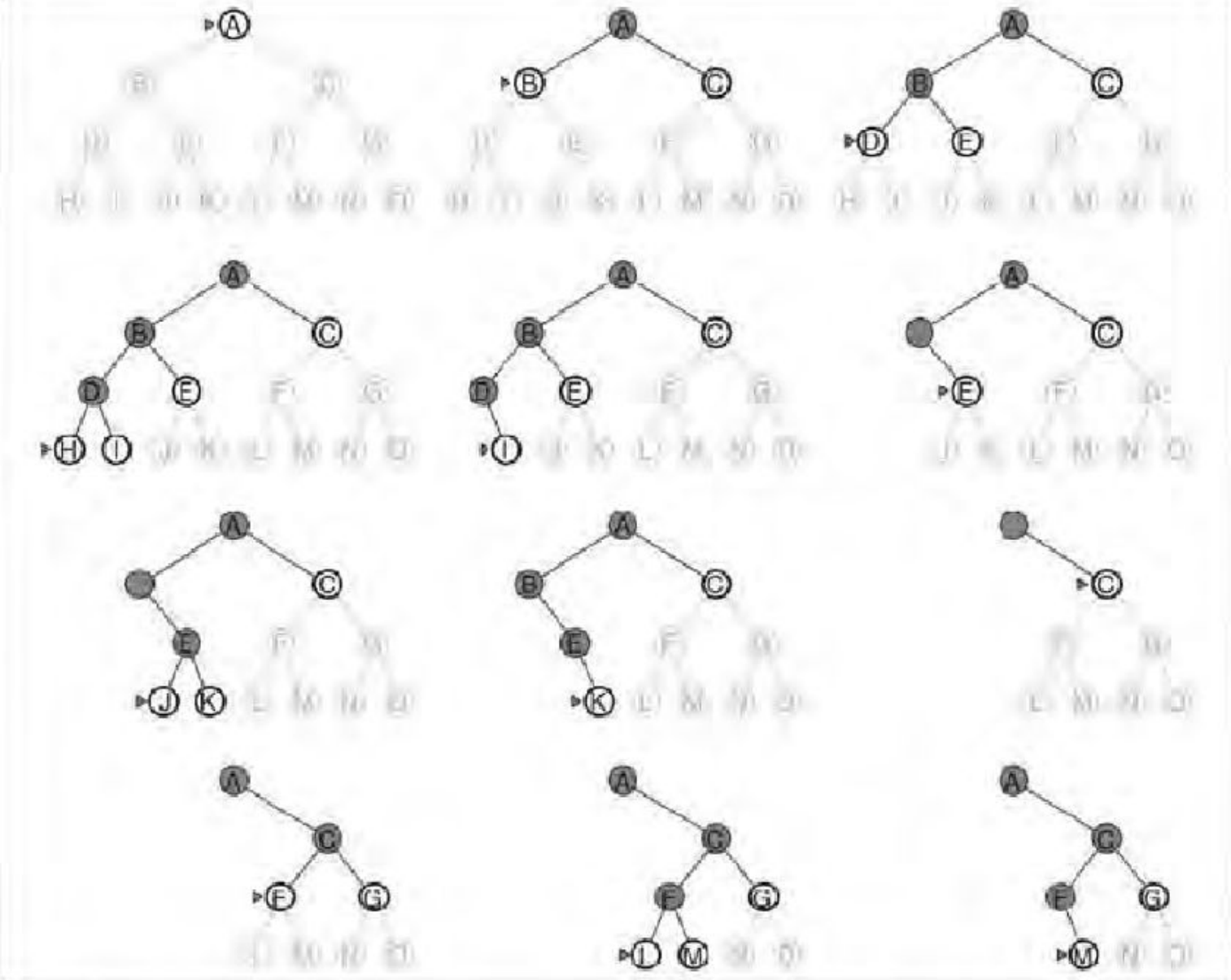
Gordon Moore, Intel Co-Founder



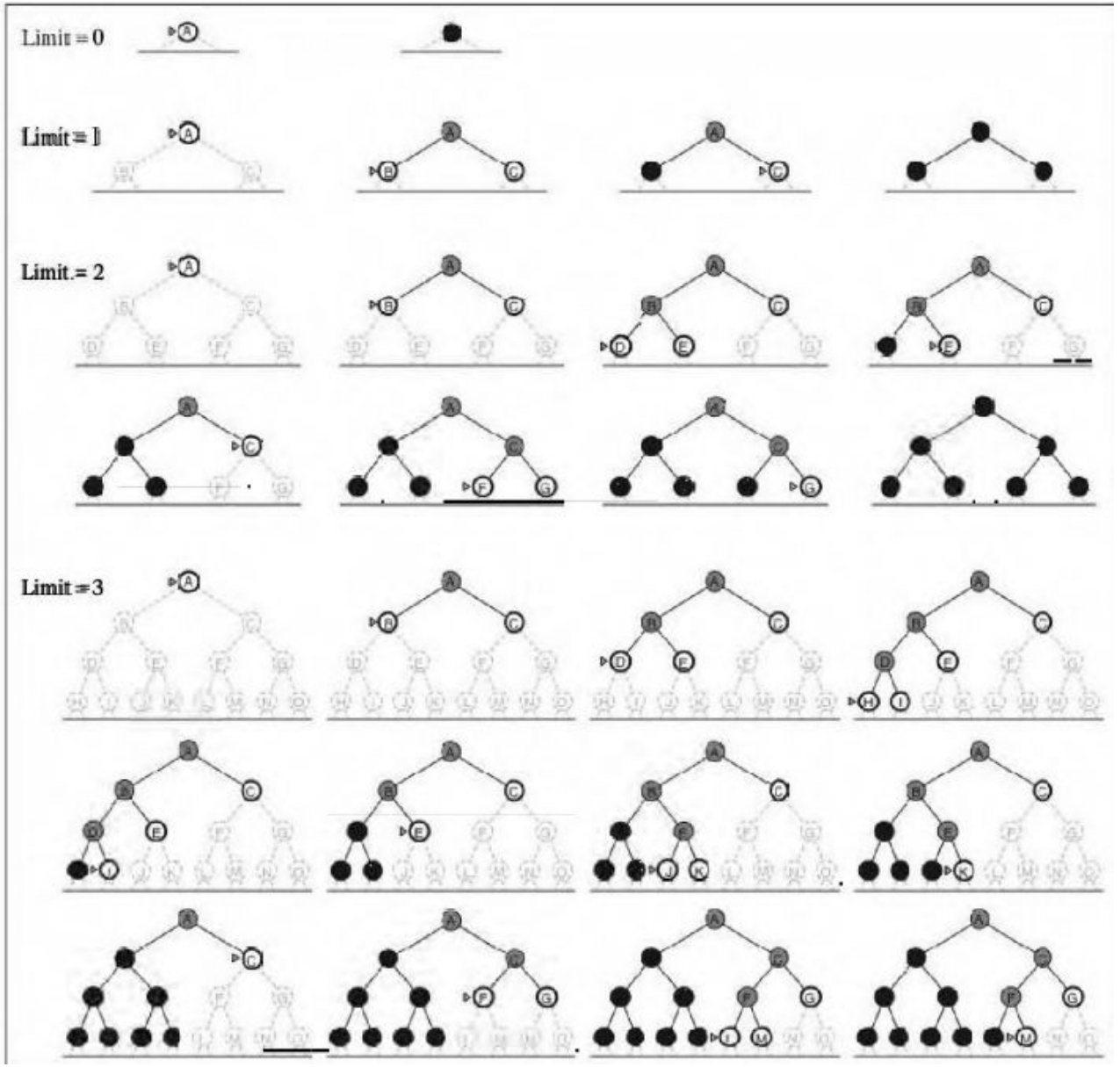
一般計画アルゴリズム


Stuart
Russell
Peter
Norvig
Artificial Intelligence
A Modern Approach
Third Edition

Depth First Search (DFS)



Iterative Deepening DFS



A*探索：最短の距離

$$f(n) = g(n) + h(n)$$

- f(n) – nを通る最短距離のコスト
- g(n) – 初期値からのnまでのコスト
- h(n) – nから目的地までのコスト

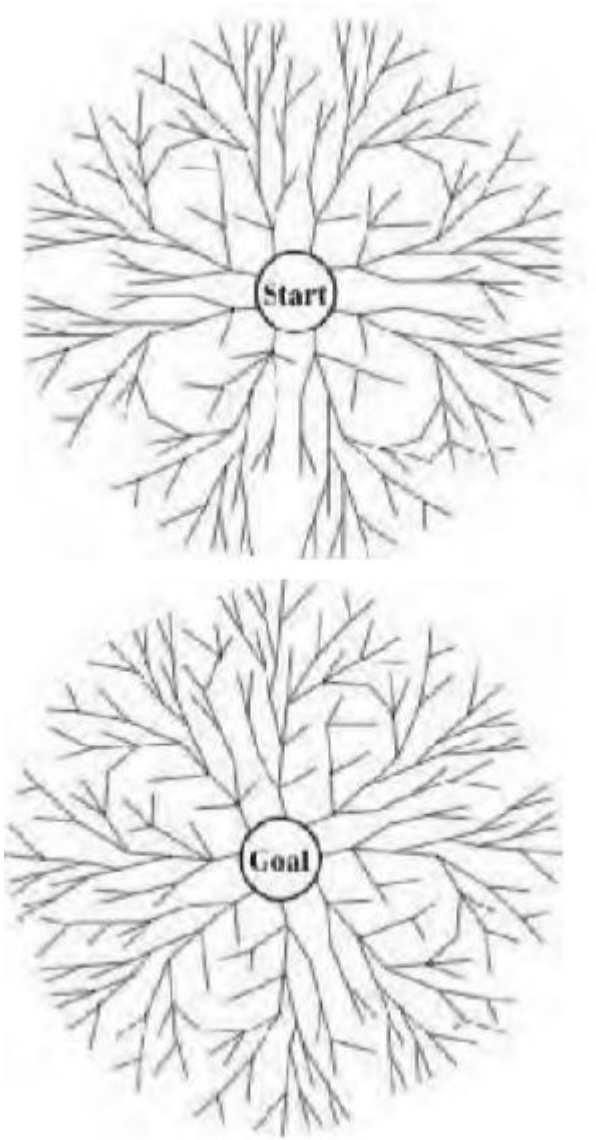
条件：$h(x) \leq d(x,y) + h(y)$

一般的な前進探索アルゴリズム

```
FORWARD_SEARCH
 1    Q.Insert(x_I) and mark x_I as visited
 2    while Q not empty do
 3        x ← Q.GetFirst()
 4        if x ∈ X_G
 5            return SUCCESS
 6        forall u ∈ U(x)
 7            x' ← f(x, u)
 8            if x' not visited
 9                Mark x' as visited
10                Q.Insert(x')
11            else
12                Resolve duplicate x'
13   return FAILURE
```

Qが整頓されている

両進探索




```
BIDIRECTIONAL_SEARCH
 1   Q_I.Insert(x_I) and mark x_I as visited
 2   Q_G.Insert(x_G) and mark x_G as visited
 3   while Q_I not empty and Q_G not empty do
 4       if Q_I not empty
 5           x ← Q_I.GetFirst()
 6           if x = x_G or x ∈ Q_G
 7               return SUCCESS
 8           forall u ∈ U(x)
 9               x' ← f(x, u)
10               if x' not visited
11                   Mark x' as visited
12                   Q_I.Insert(x')
13               else
14                   Resolve duplicate x'
15       if Q_G not empty
16           x' ← Q_G.GetFirst()
17           if x' = x_I or x' ∈ Q_I
18               return SUCCESS
19           forall u^-1 ∈ U^-1(x')
20               x ← f^-1(x', u^-1)
21               if x not visited
22                   Mark x as visited
23                   Q_G.Insert(x)
24               else
25                   Resolve duplicate x
26   return FAILURE
```

エージェント用探索アルゴリズム

- 後進探索の重要性
  - 一歩進んで計画どおりに行かなければ再計画の速さ
- D* Lite（火星探索ロボット利用）
  - g(s) = 目的地からsへのコスト
  - v(s) = sからのベストコスト
  - 状態の優先 $k(s) = [k_1(s), k_2(s)]$

$$= [min(v(s), g(s)) + h(s_{start}, s), min(v(s), g(s))]$$

Anthony Stentz, Dave Ferguson, Likachev
カーネギーメロン大学

D* Lite

ComputePath()

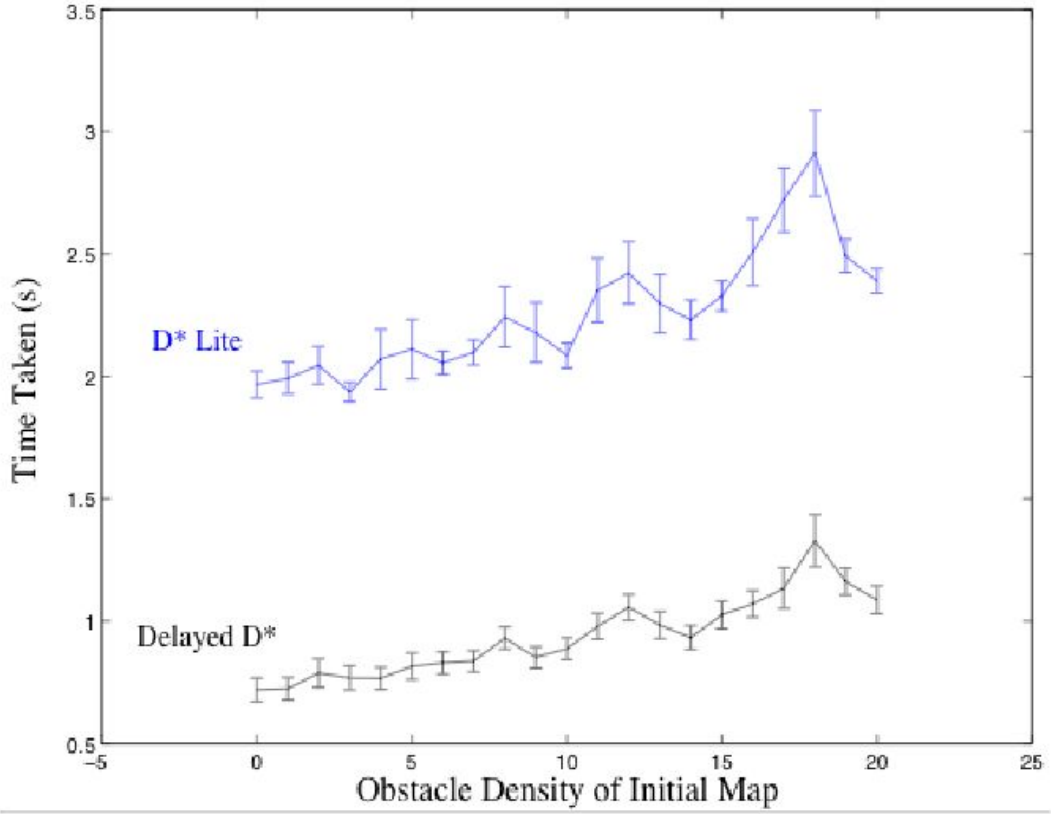
5 while(key(s_{start}) > $\min_{s \in OPEN}$(key(s)) OR $v(s_{start}) < g(s_{start})$)
6 remove s with the smallest key(s) from $OPEN$;
7 if $(v(s) > g(s))$
8 $v(s) = g(s)$;
9 for each predecessor s' of s
10 if s' was never visited before
11 $v(s') = g(s') = \infty; bp(s') =$ **null**;
12 if $(g(s') > c(s', s) + v(s))$
13 $bp(s') = s$;
14 $g(s') = c(s', bp(s')) + v(bp(s'))$; UpdateSetMembership($s'$);
15 else
16 $v(s) = \infty$; UpdateSetMembership(s);
17 for each predecessor s' of s
18 if s' was never visited before
19 $v(s') = g(s') = \infty; bp(s') =$ **null**;
20 if $(bp(s') = s)$
21 $bp(s') = \text{argmin}_{s'' \in Succ(s')} c(s', s'') + v(s'')$;
22 $g(s') = c(s', bp(s')) + v(bp(s'))$; UpdateSetMembership($s'$);

UpdateSetMembership(s)

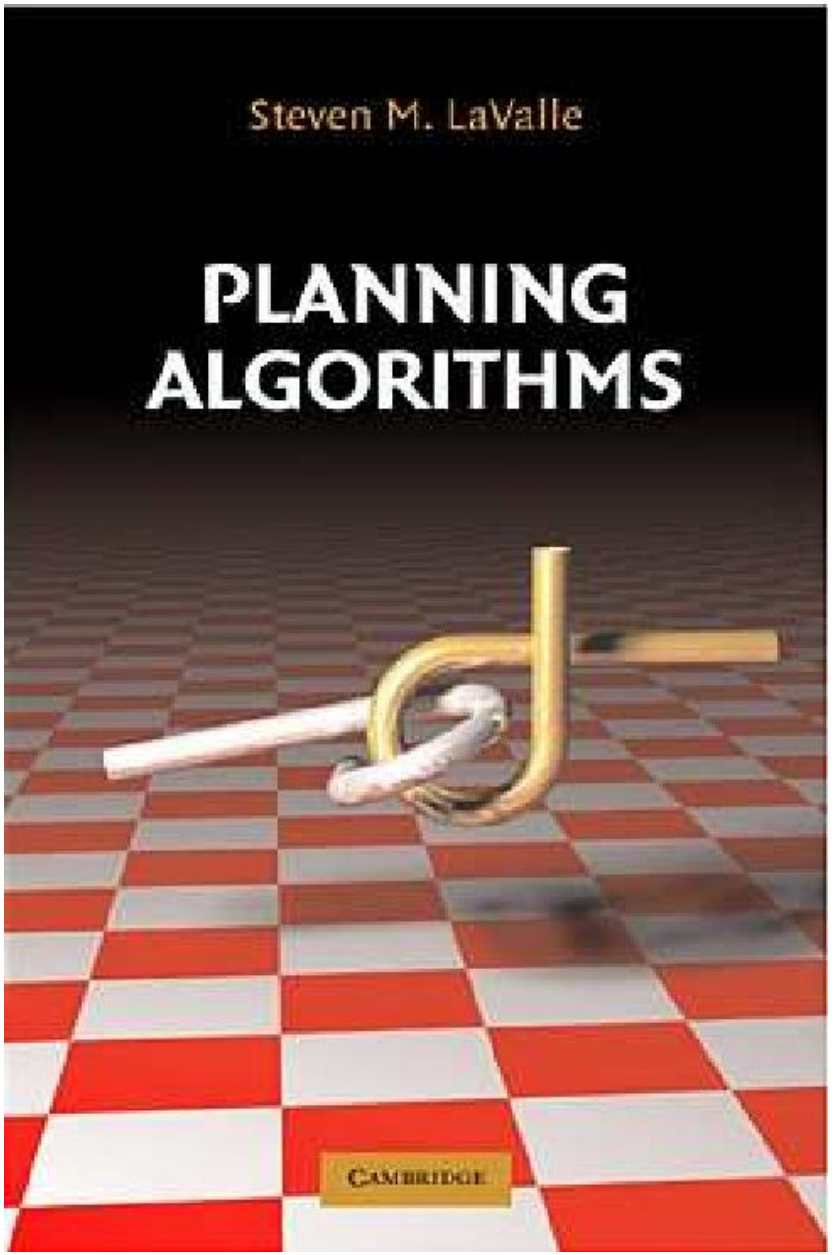
1 if $(v(s) \neq g(s))$
2 insert/update s in $OPEN$ with key(s);
3 else
4 if $(s \in OPEN)$ remove s from $OPEN$;

Delayed D*

- 状態を調べる際
  - 経路に影響を与えないものを省く

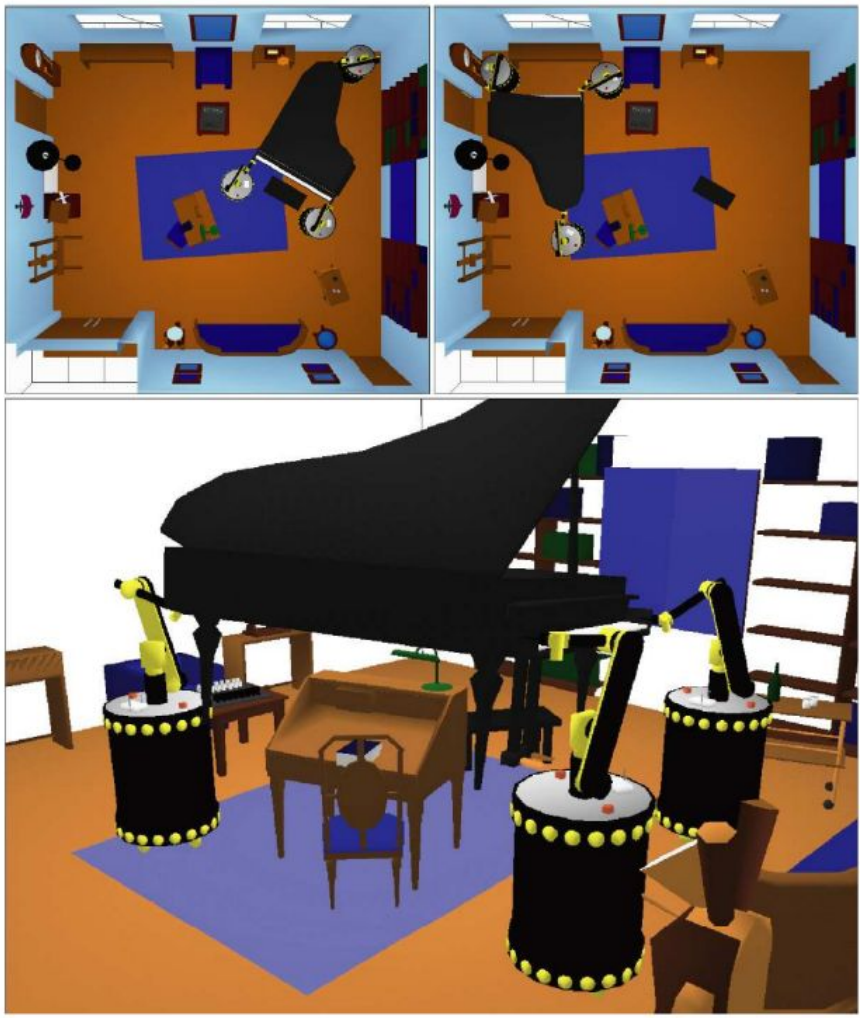


動作計画
アルゴリズム



Configuration Space
コンフィグレーションスペース
状態空間

- 3D位置
- 3D姿勢
- 関節の値



Steven LaValle. Planning Algorithms. Cambridge University, 2006

状態空間：C-Space

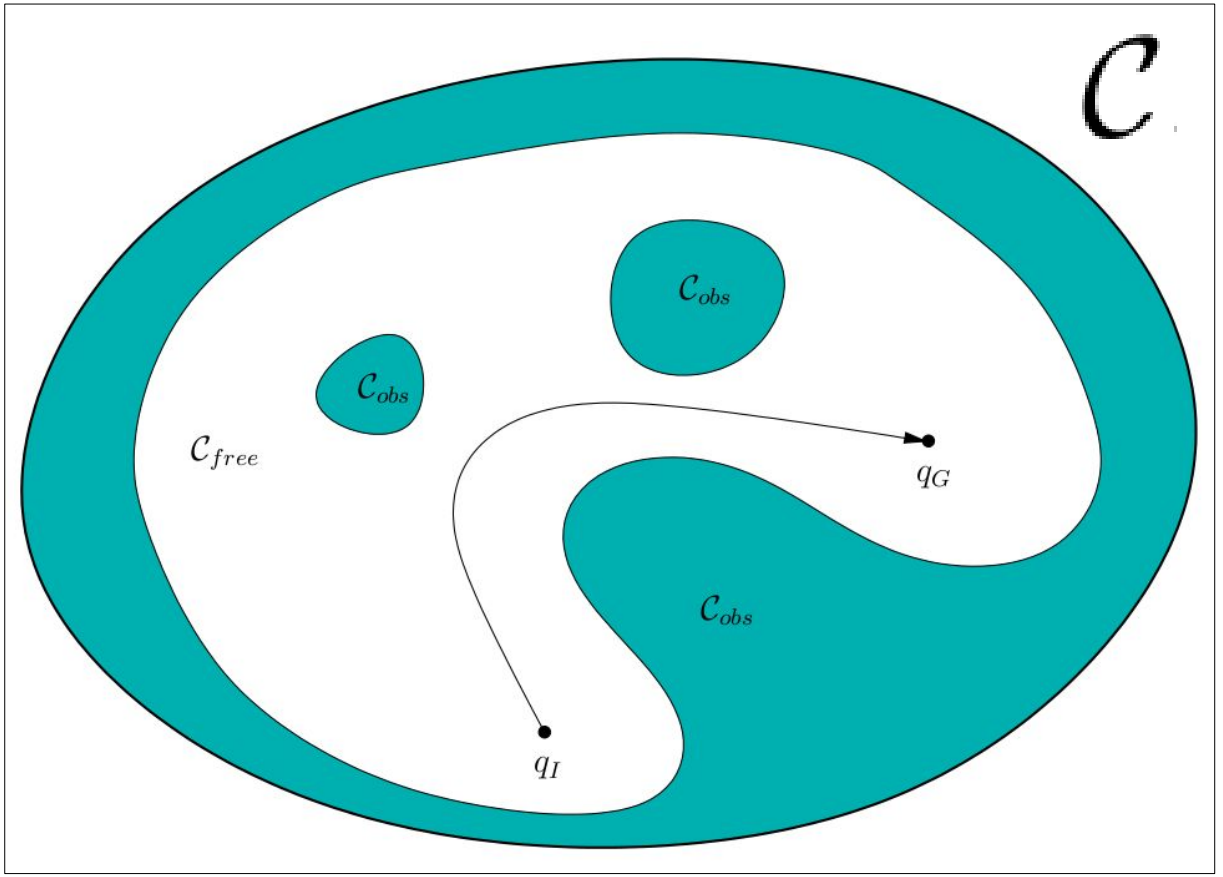
$$\mathcal{C}_{obs} = \{q \in \mathcal{C} \mid \mathcal{A}(q) \cap \mathcal{O} \neq \emptyset\}$$

障害物

ロボット領域

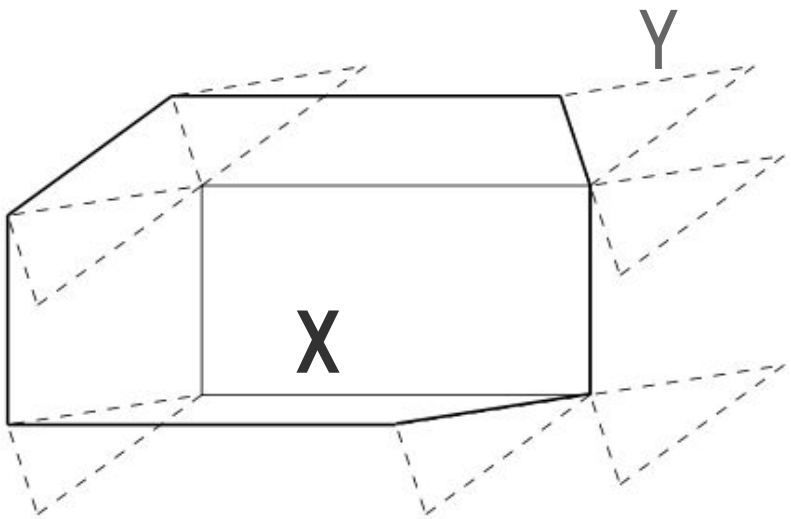
$$\mathcal{C}_{obs} \subseteq \mathcal{C}$$

$$\mathcal{C}_{free} = \mathcal{C} \setminus \mathcal{C}_{obs}$$

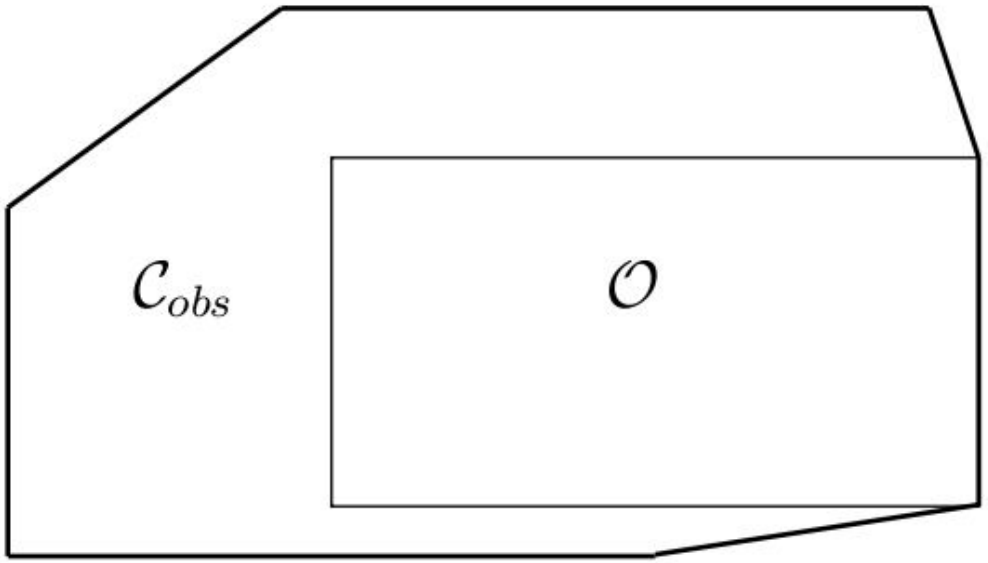


Minkowski引算

$$X \ominus Y = \{x - y \in \mathbb{R}^n \mid x \in X \text{ and } y \in Y\}$$



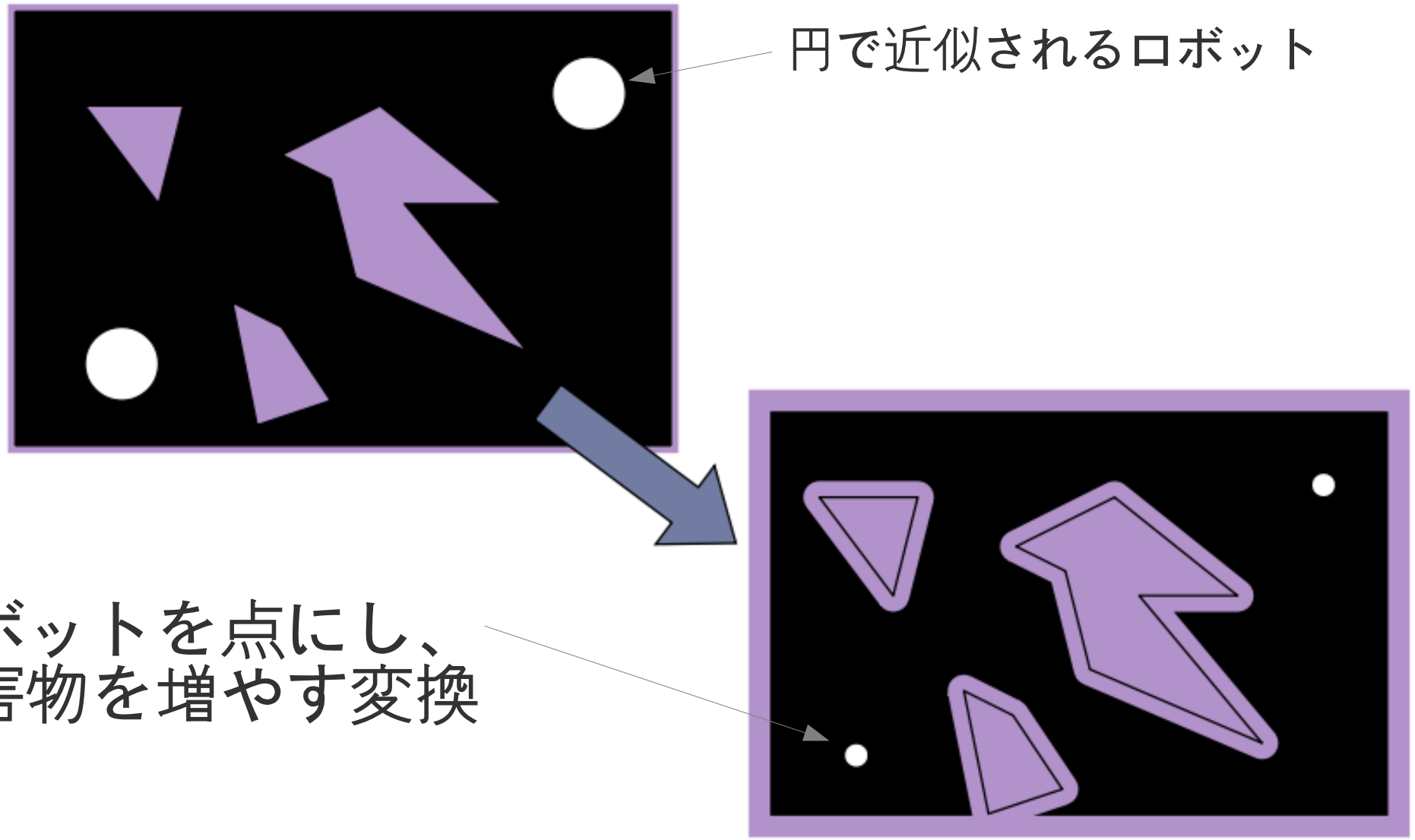
(a)



(b)

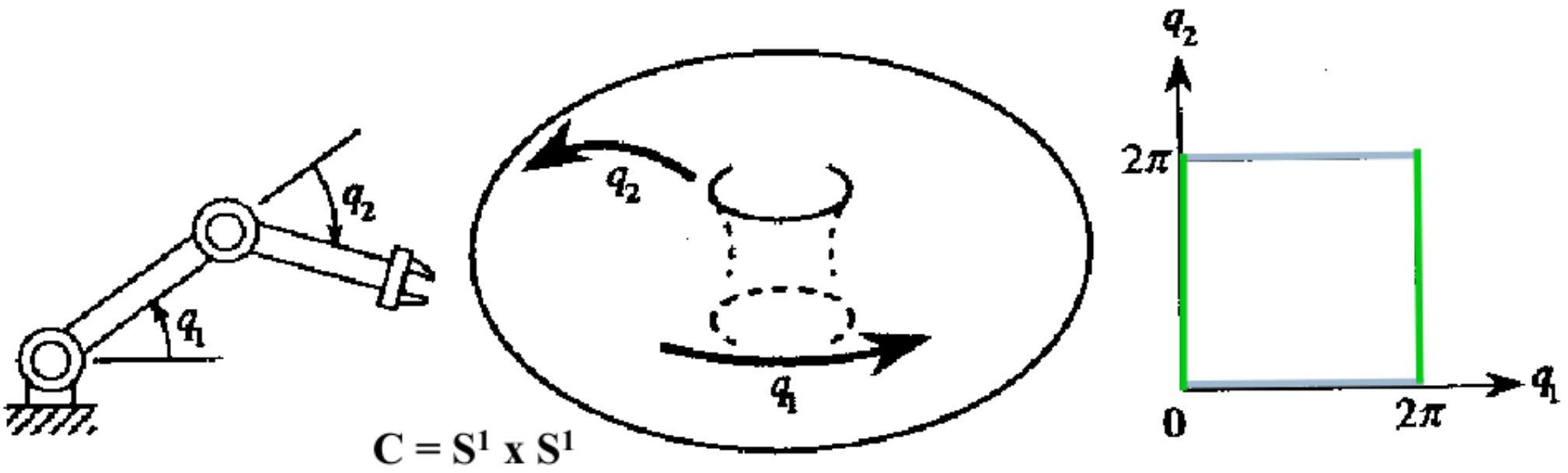
$$\mathcal{C}_{obs} = \{q \in \mathcal{C} \mid \mathcal{A}(q) \cap \mathcal{O} \neq \emptyset\} \longrightarrow \mathcal{C}_{obs} = \mathcal{O} \ominus \mathcal{A}(0)$$

2Dの状態空間



2関節ロボットの状態空間

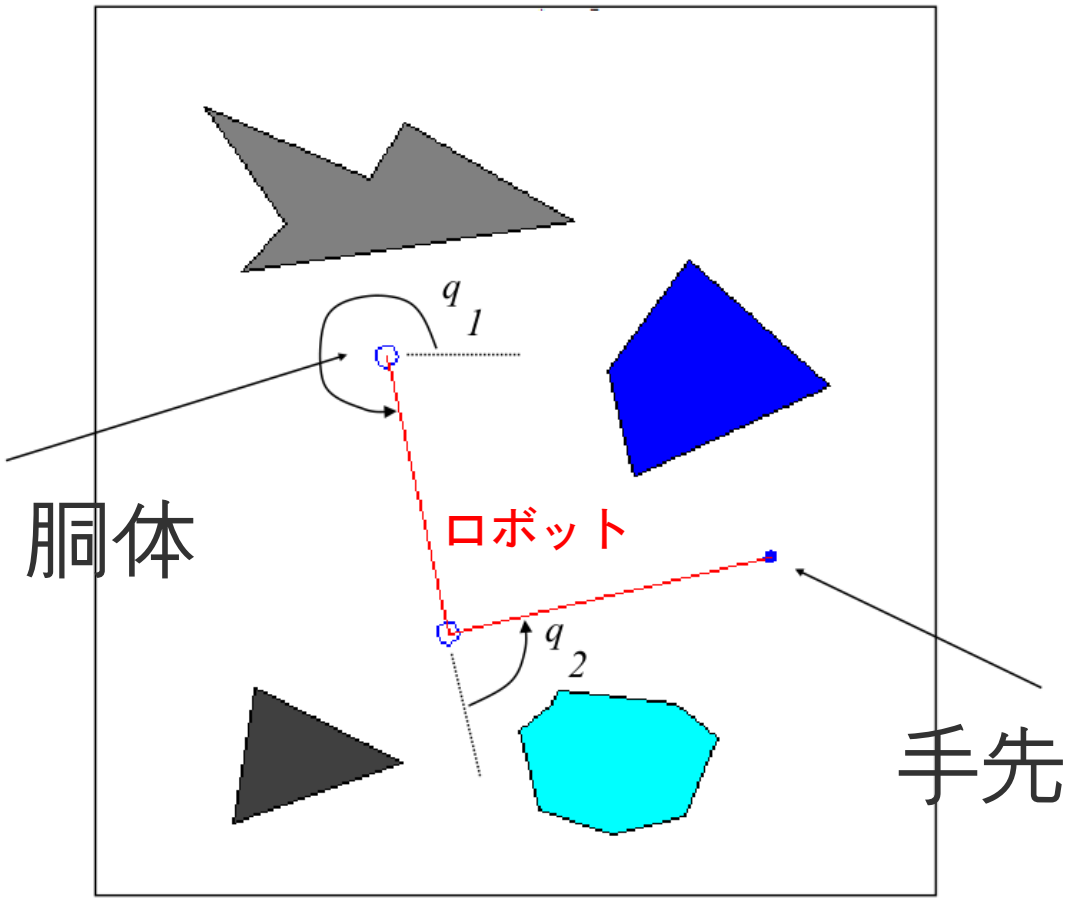
- 二つの関節は円環面（torus）の表面を描く



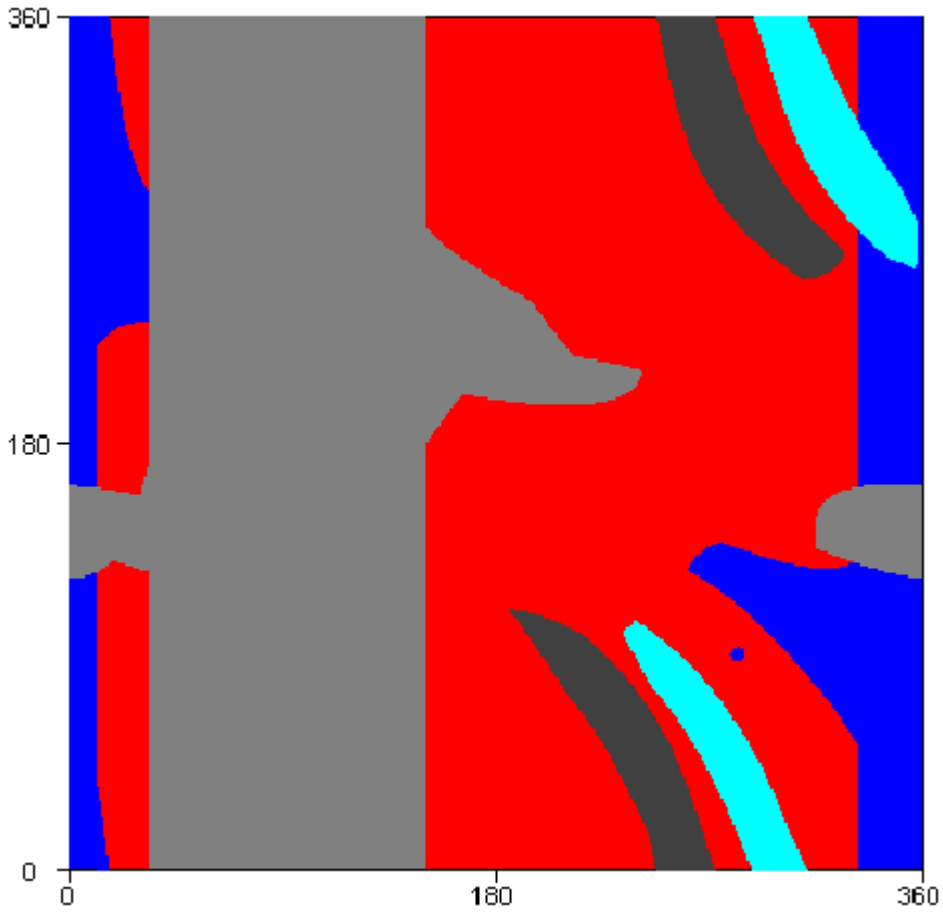
2D作業空間、2関節ロボット

http://ford.ieor.berkeley.edu/cspace/

作業空間

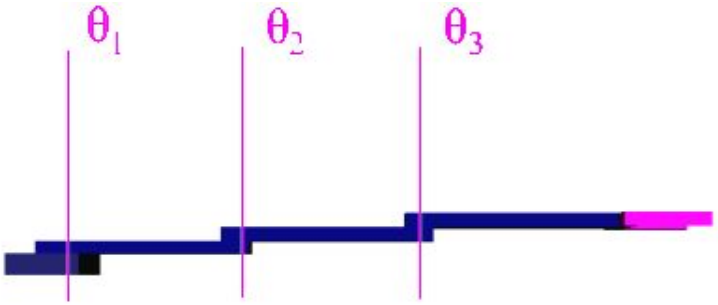


状態空間



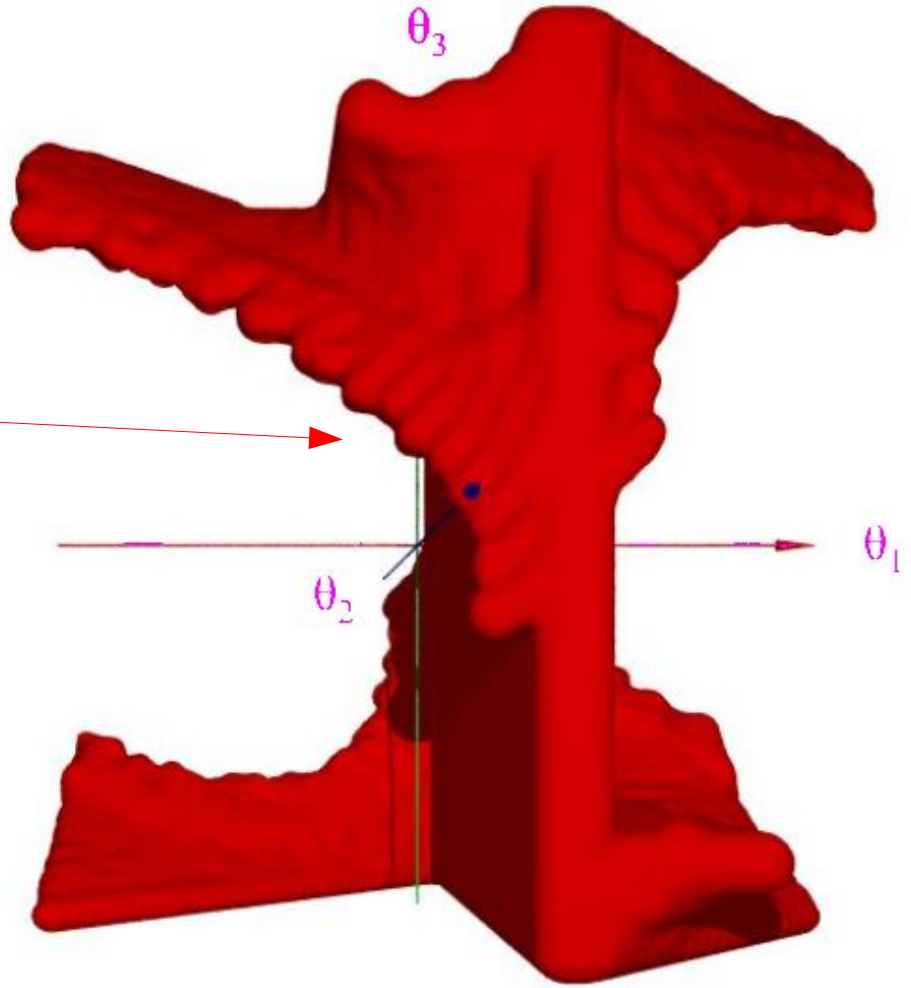
2D作業空間、３関節ロボット

作業空間

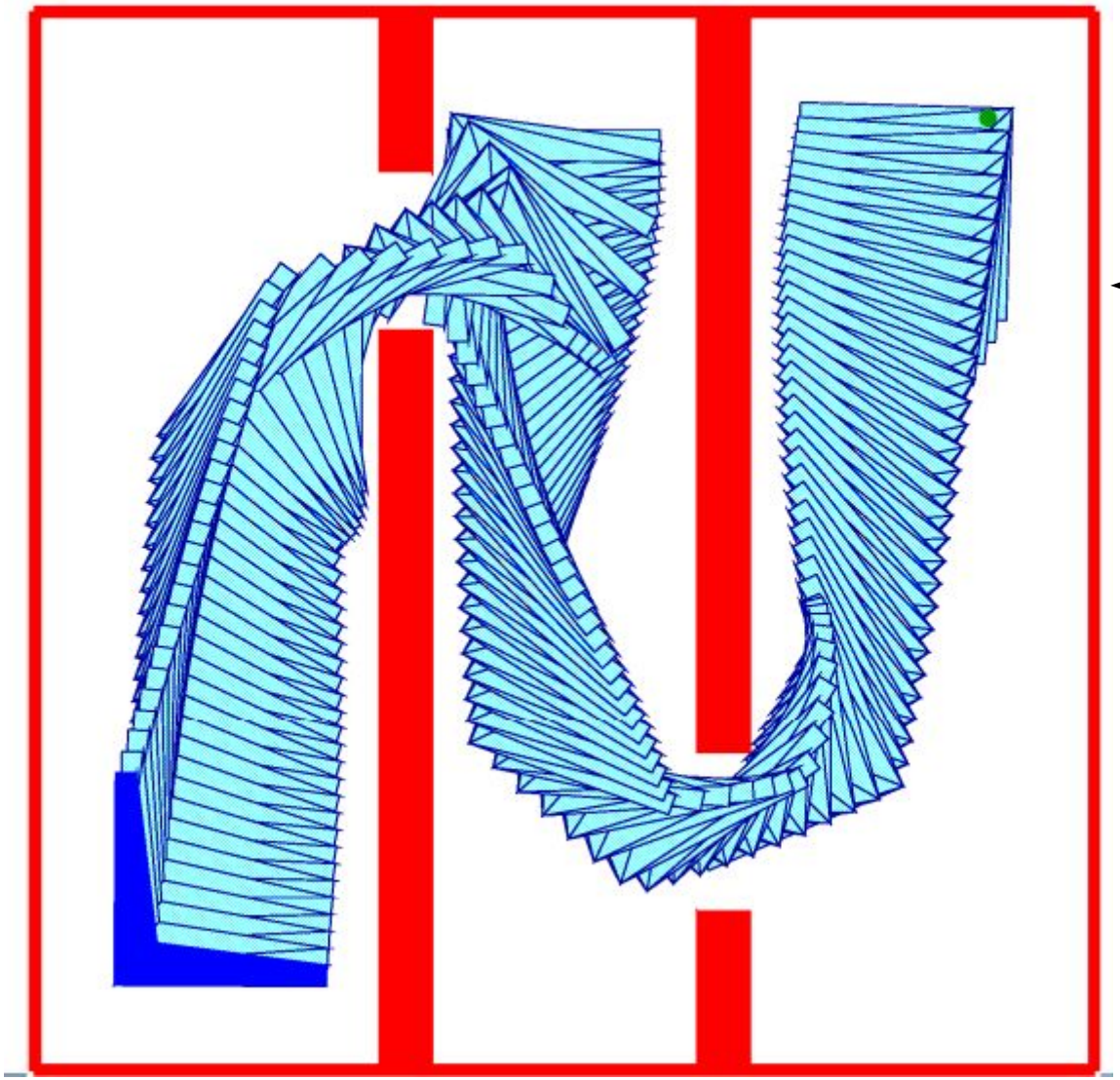


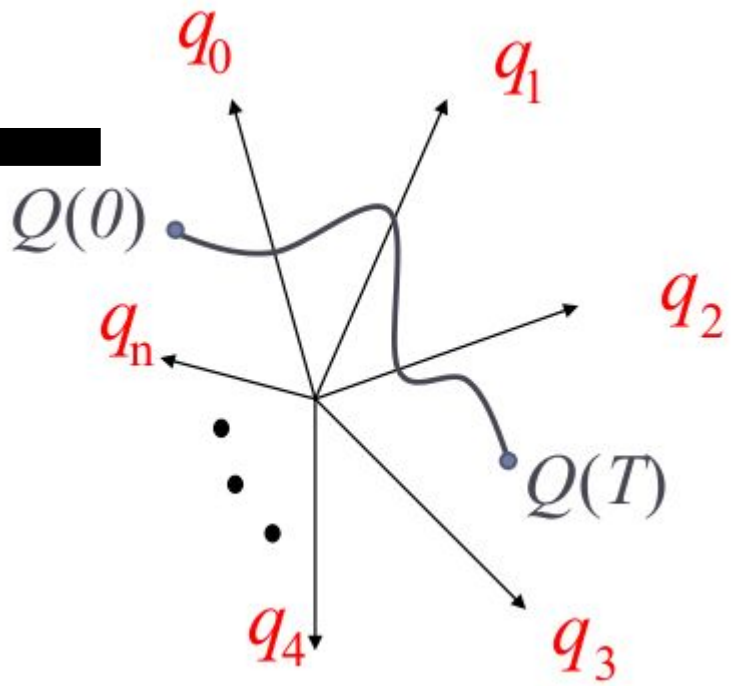
障害物

状態空間



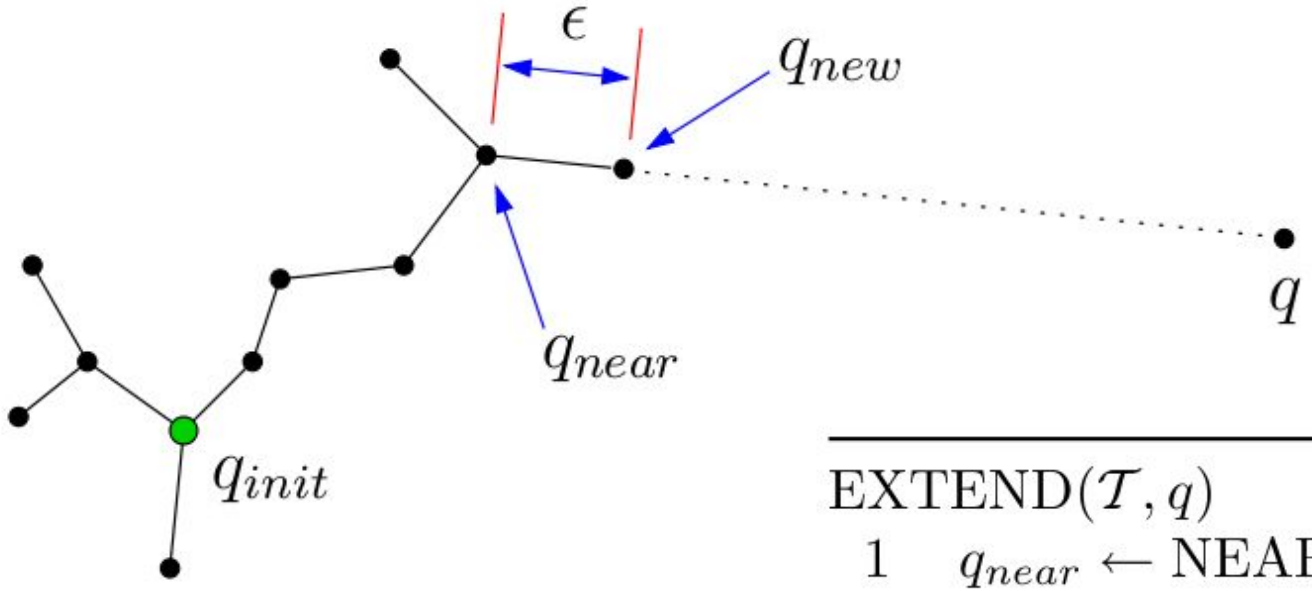
動作計画の目的：状態空間の経路





Rapidly-exploring Random Trees (RRTs)

James Kuffner, Steve Lavalle
カーネギーメロン大学

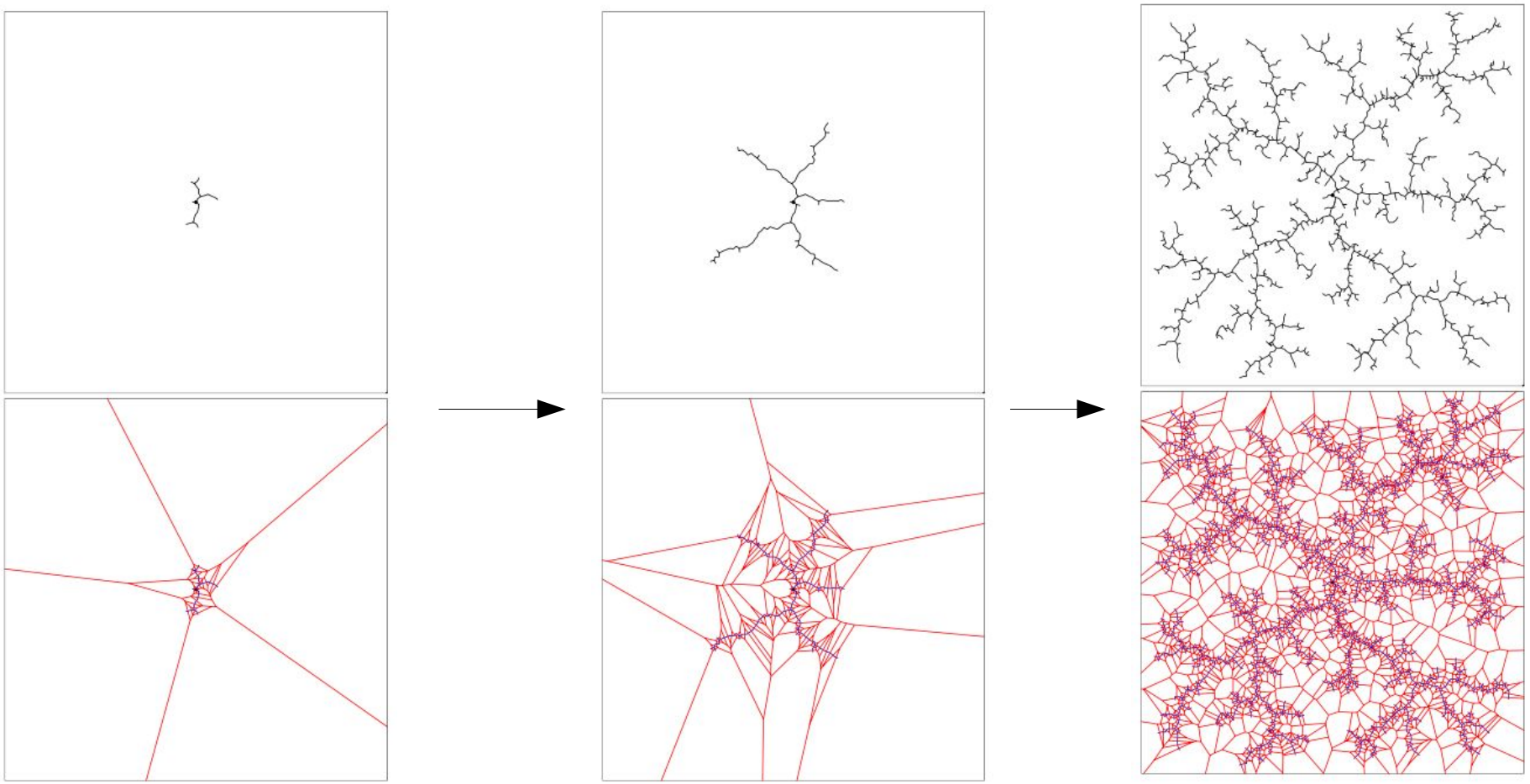



```
BUILD_RRT(q_init)
 1  T.init(q_init);
 2  for k = 1 to K do
 3      q_rand ← RANDOM_CONFIG();
 4      EXTEND(T, q_rand);
 5  Return T
```

```
EXTEND(T, q)
 1  q_near ← NEAREST_NEIGHBOR(q, T);
 2  if NEW_CONFIG(q, q_near, q_new) then
 3      T.add_vertex(q_new);
 4      T.add_edge(q_near, q_new);
 5      if q_new = q then
 6          Return Reached;
 7      else
 8          Return Advanced;
 9  Return Trapped;
```

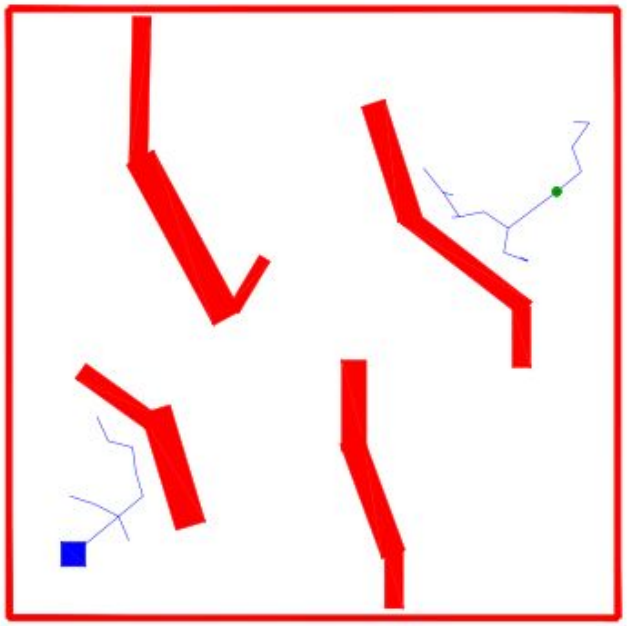
RRTsの探索傾向

- 不探索空間への生きがち



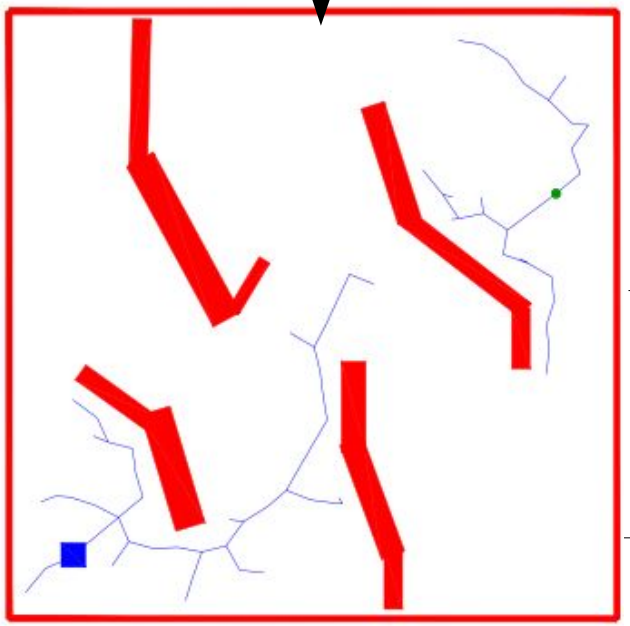
Voronoi Region

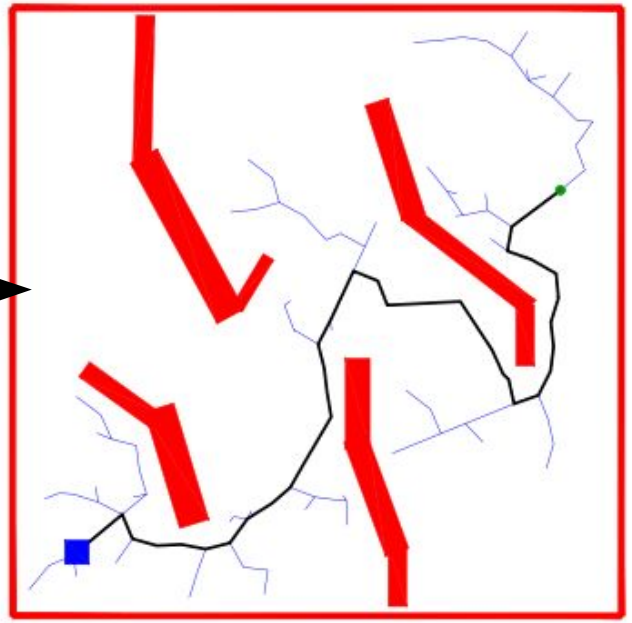
RiRRTs（両進探索）

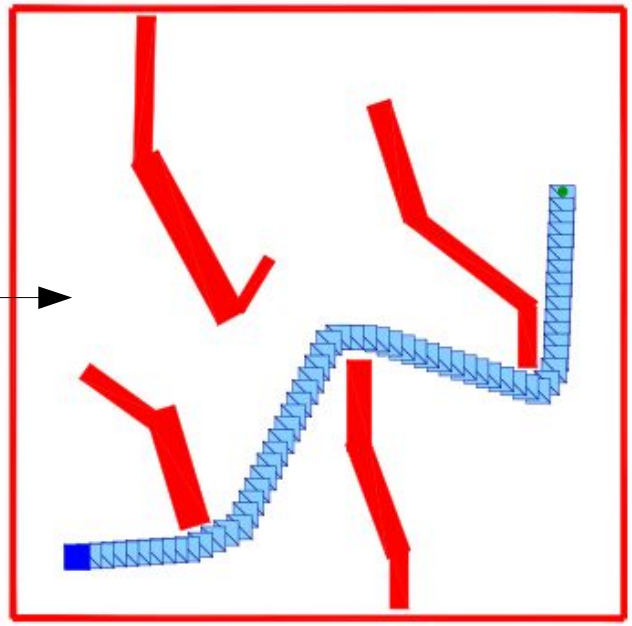


RRT_CONNECT_PLANNER(q_{init}, q_{goal})

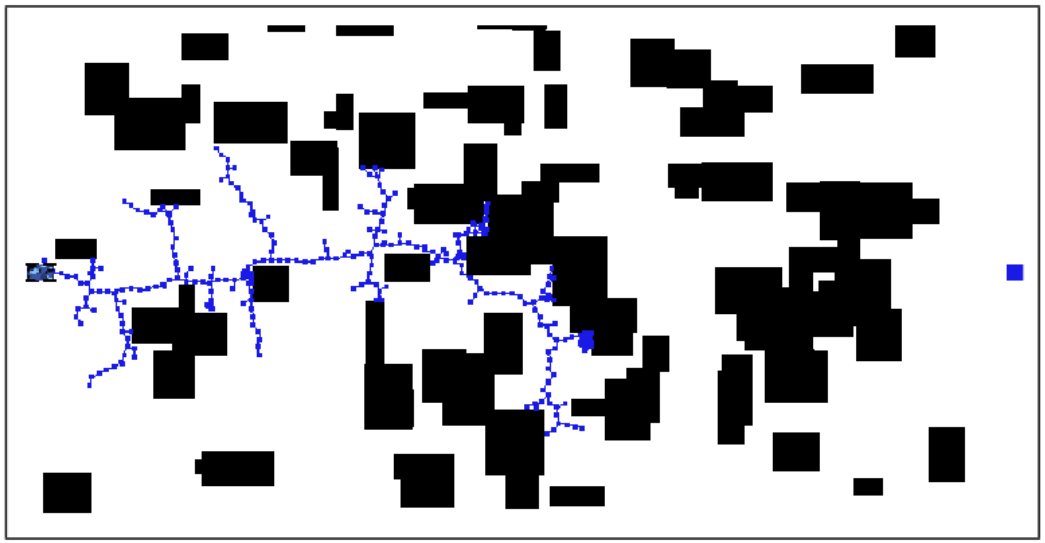
```
1  T_a.init(q_init); T_b.init(q_goal);
2  for k = 1 to K do
3      q_rand ← RANDOM_CONFIG();
4      if not (EXTEND(T_a, q_rand) = Trapped) then
5          if (CONNECT(T_b, q_new) = Reached) then
6              Return PATH(T_a, T_b);
7      SWAP(T_a, T_b);
8  Return Failure
```

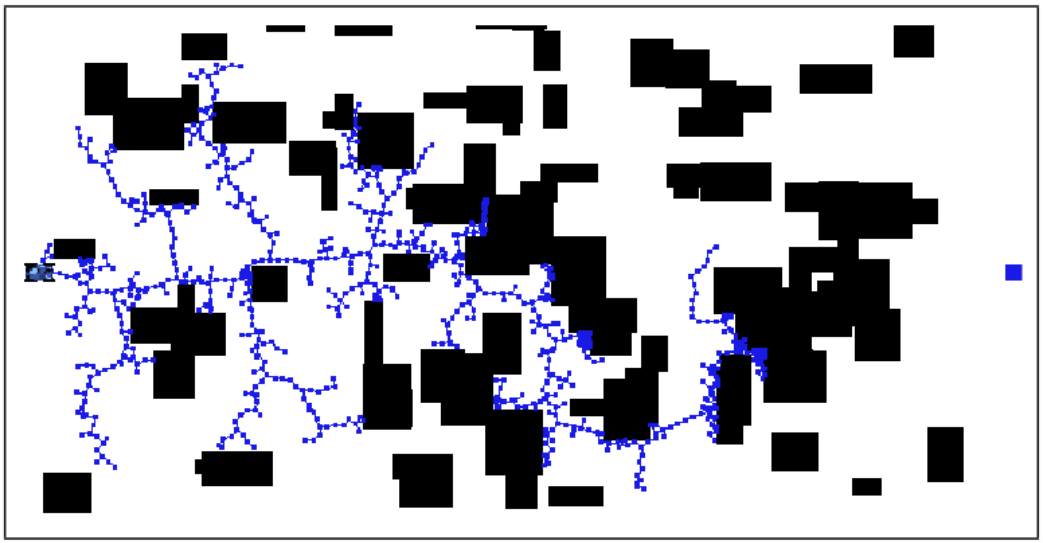


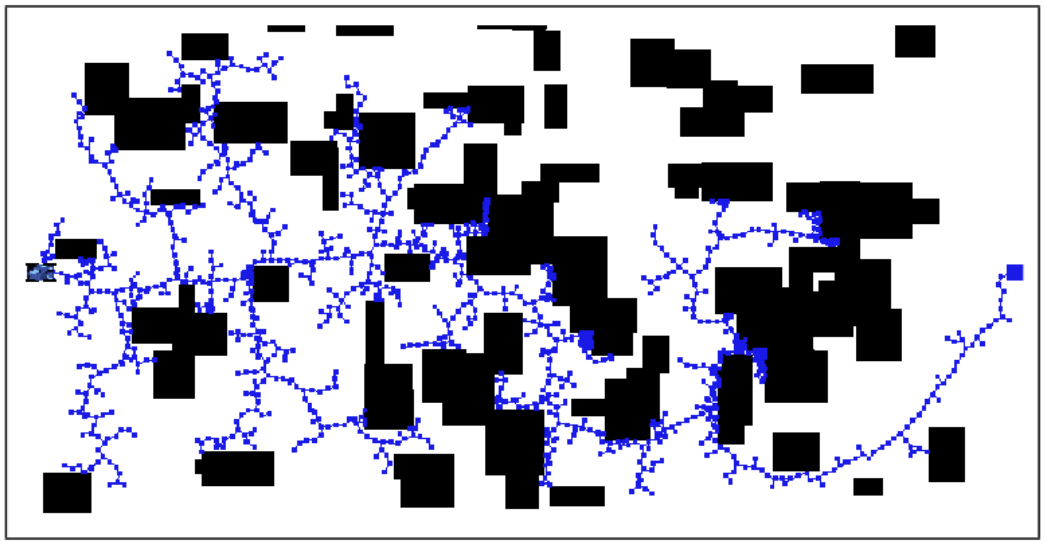


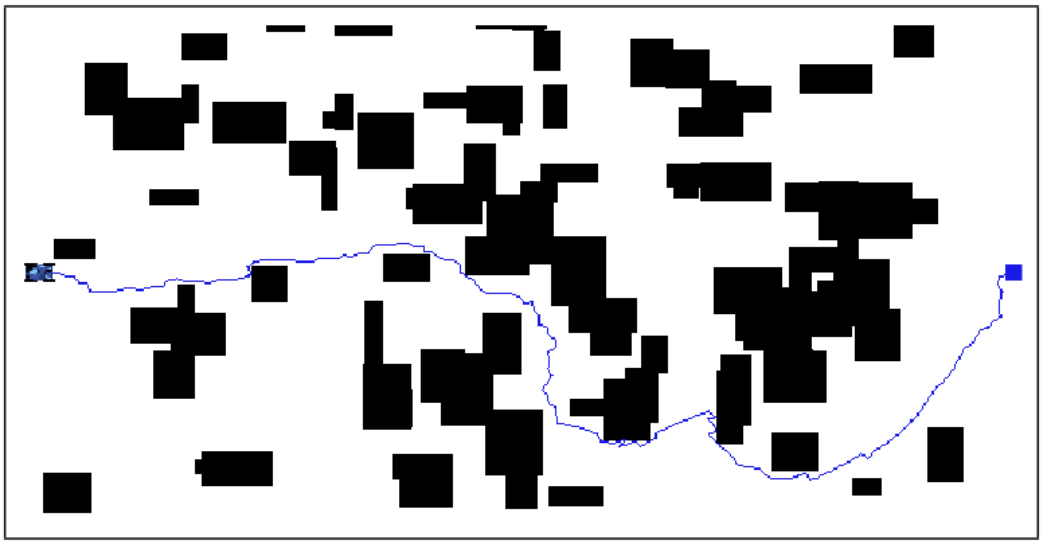


RRT探索例

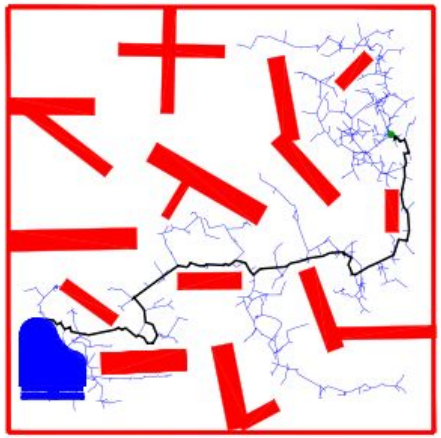








状態空間の柔軟性

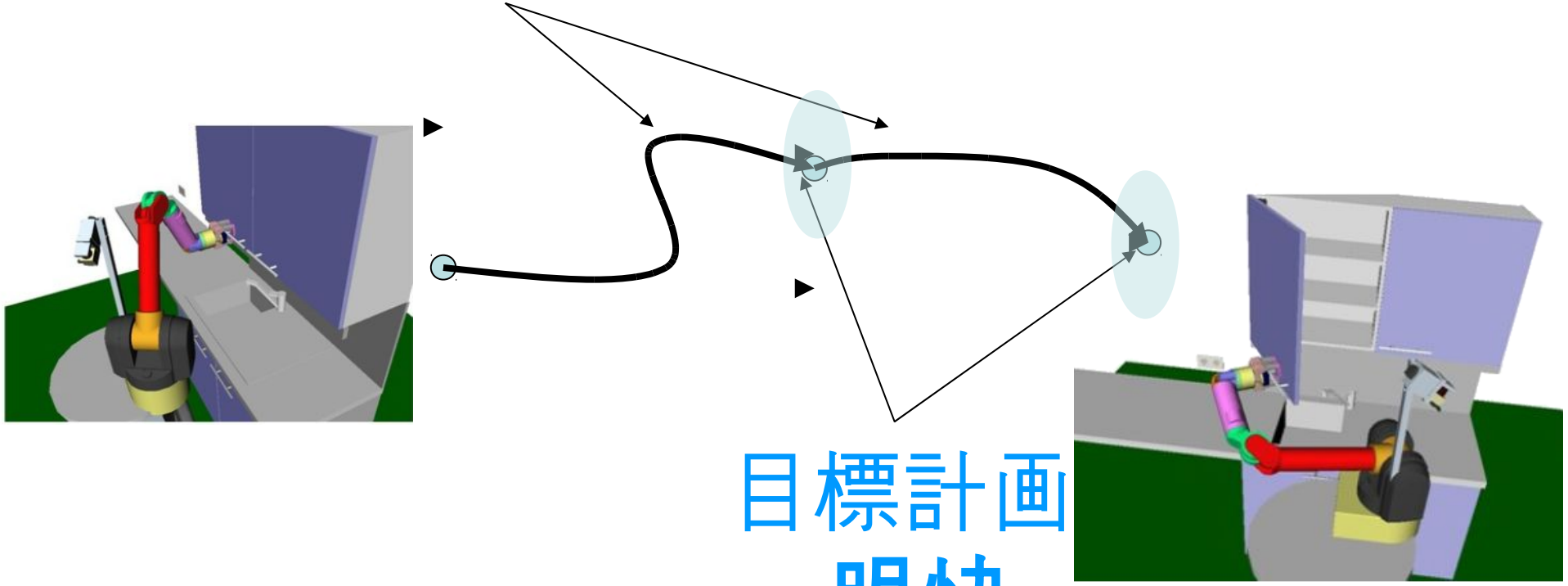


マニピュレーション
動作計画

OpenRAVE

計画の二段階

動作経路（BiRRT, Delayed D*, Anytime RRTs）

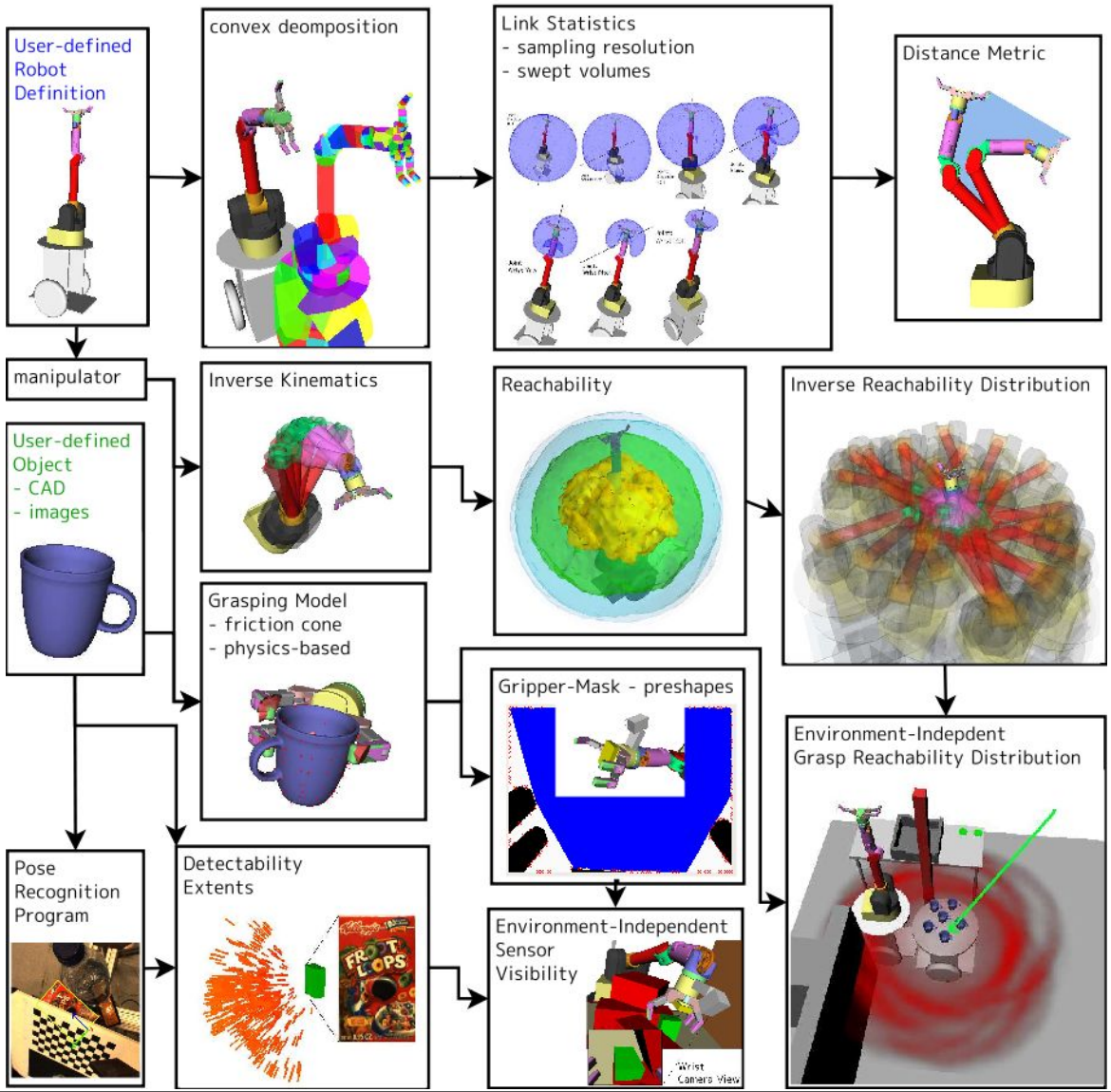


目標計画

- 明快
- 暗黙

動作と作業目標をつなぐ
知識ベース

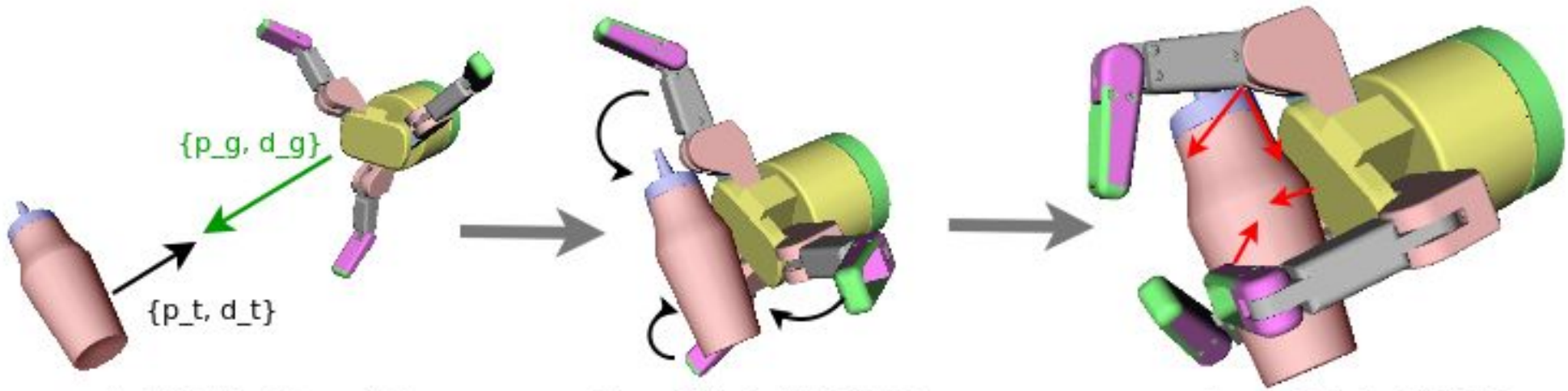
ユーザー



openrave.py --listdatabases

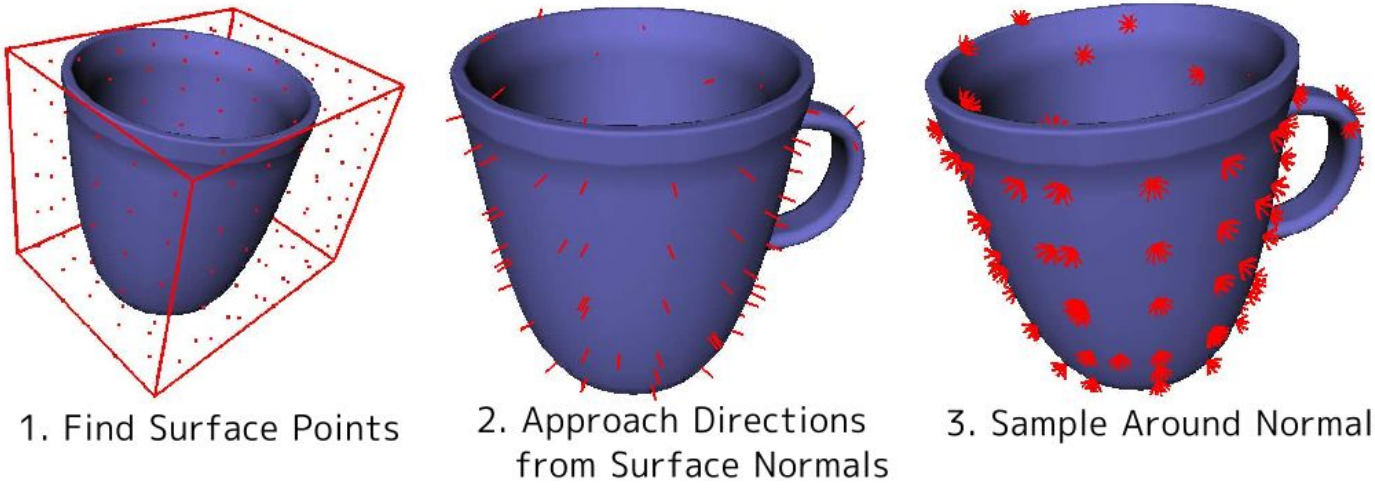
知識ベース：把持

- 戦略
- 把持空間のパラメーター化
- 把持安定性測定法
- OpenRAVE:
  - 把持セットの作成



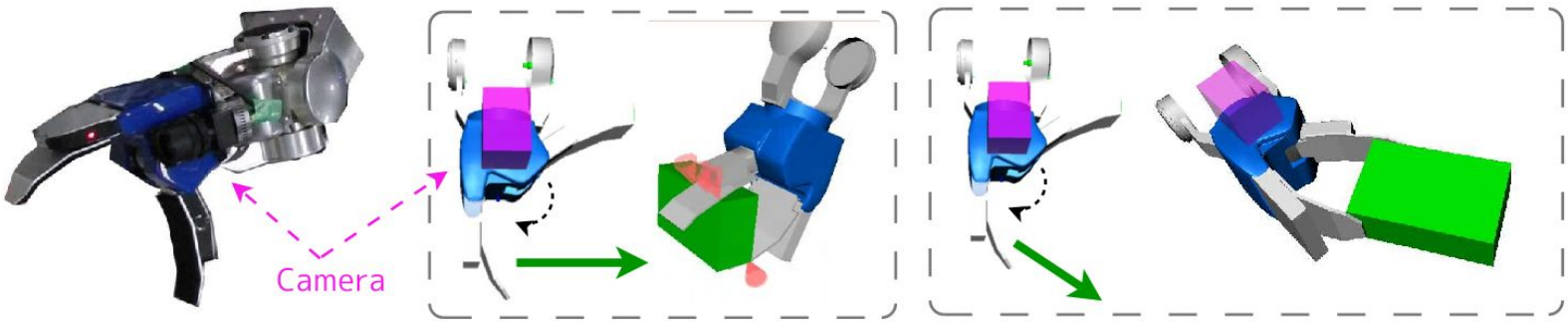
把持空間のパラメター化：８自由度

物体表面上
サンプリング
（4DOF）



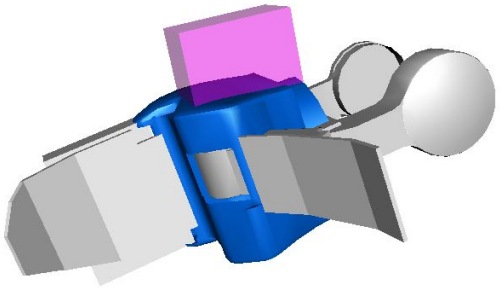
ロボット
表面上

（4DOF）



Stand-off（1DOF）

把持セット



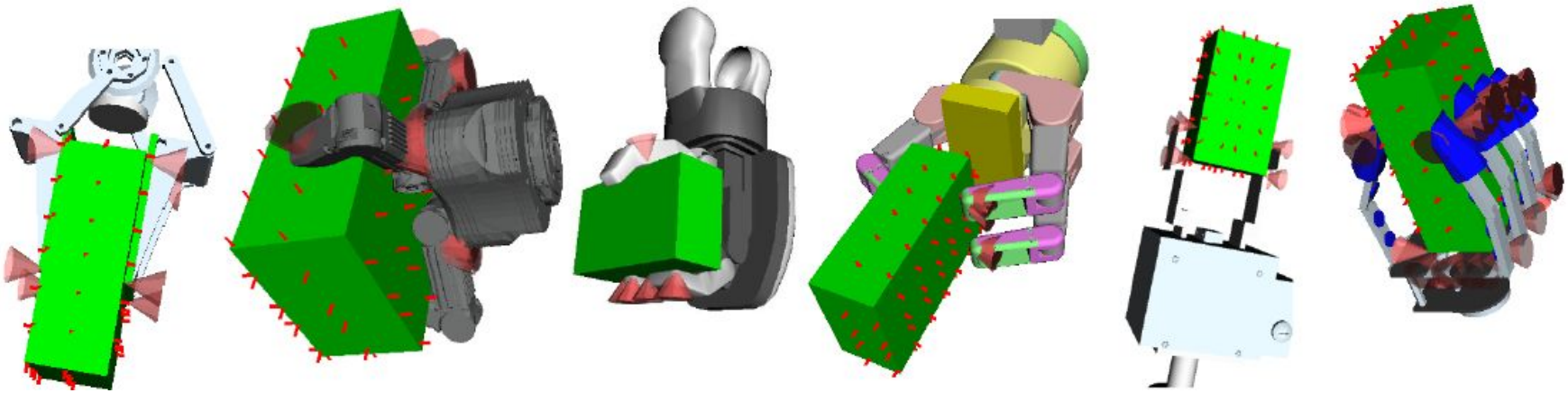
```
openrave.py --database grasping
```

把持セットの表示

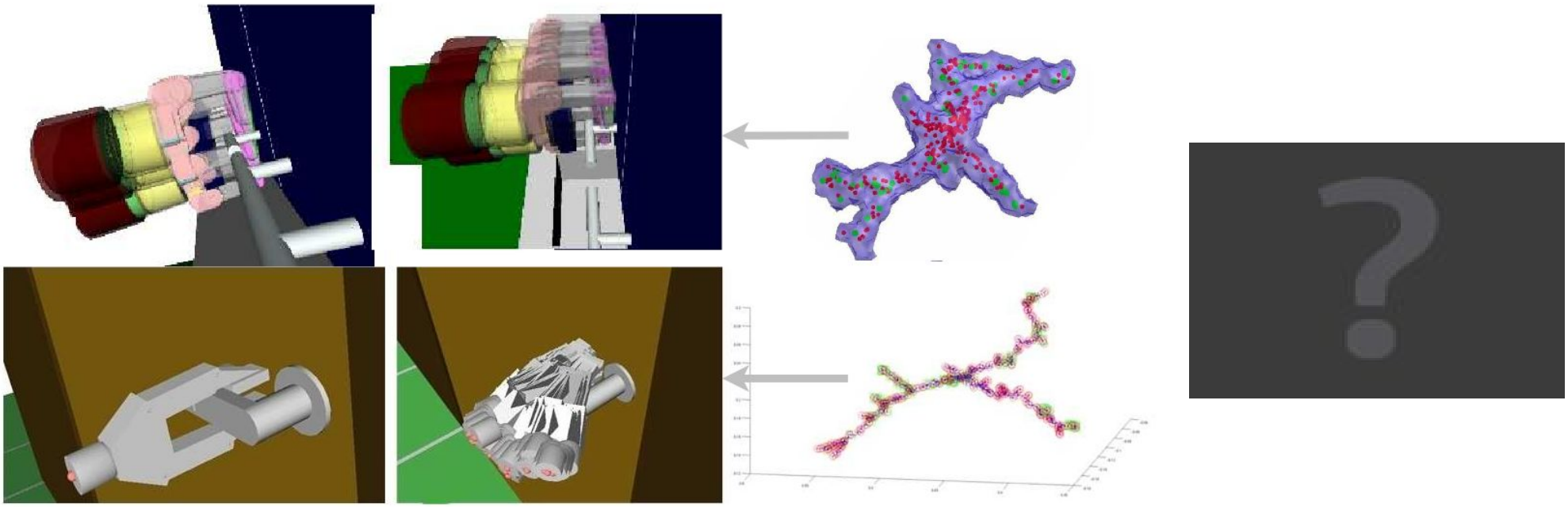
```
openrave.py --database grasping --show
```

ノイズを加える

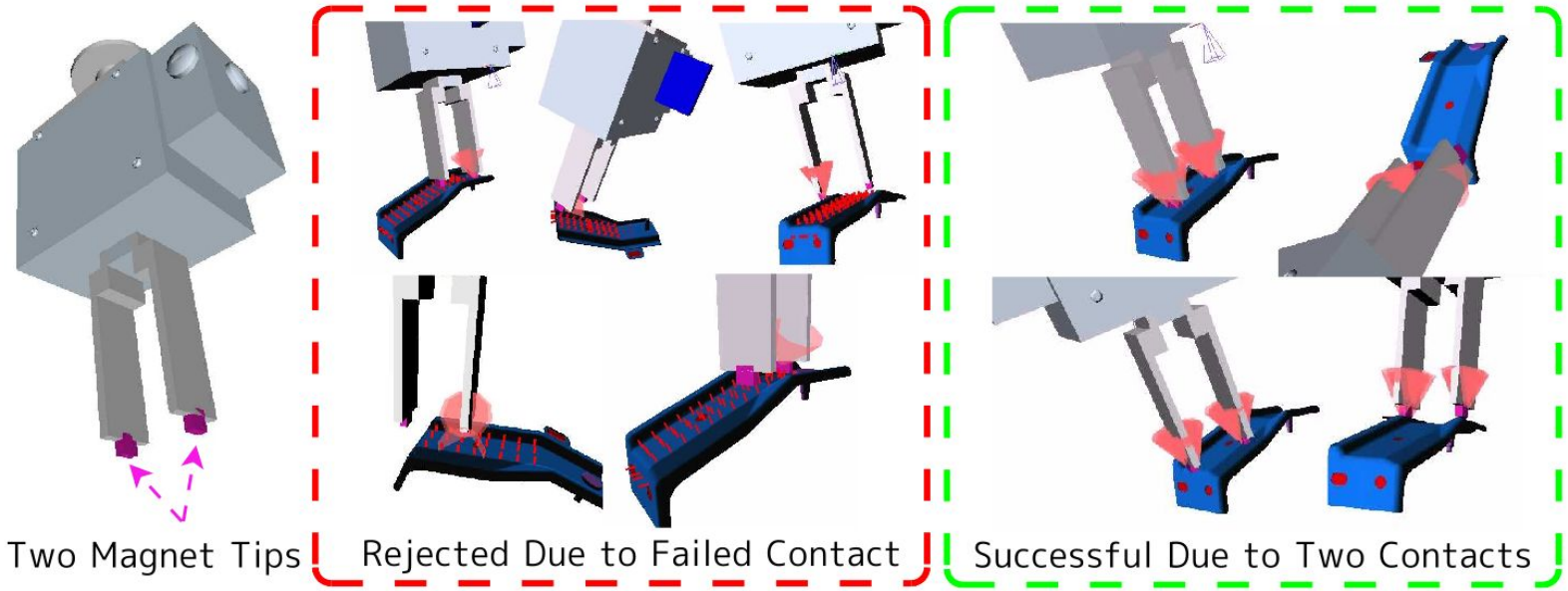
```
openrave.py --database grasping --graspingnoise=0.01
```

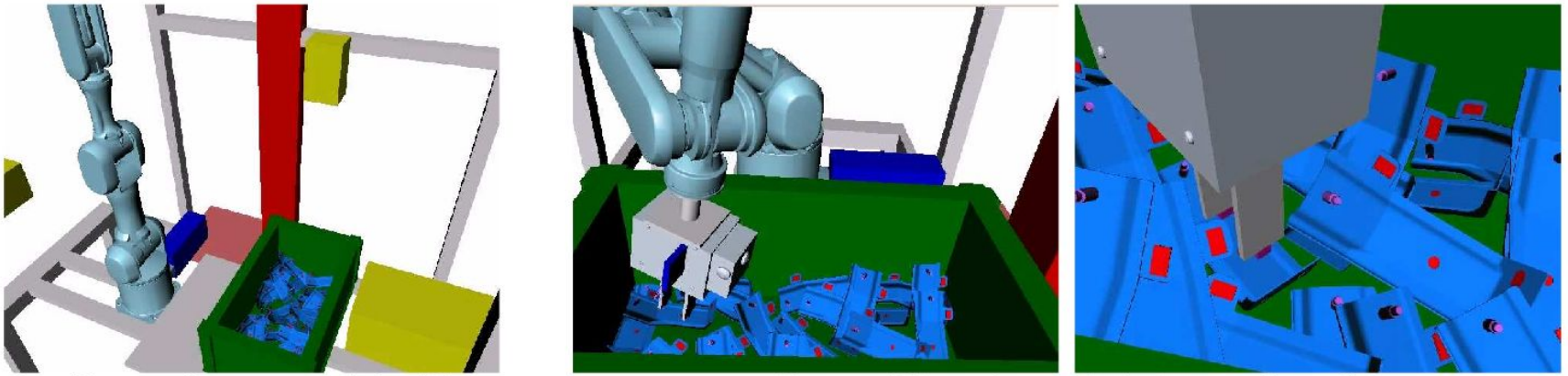


把持を空間で表現する



接触のみの把持


Two Magnet Tips
Rejected Due to Failed Contact
Successful Due to Two Contacts


Parts Scattered in Bin
Grasp Planning with Insertion Grasps

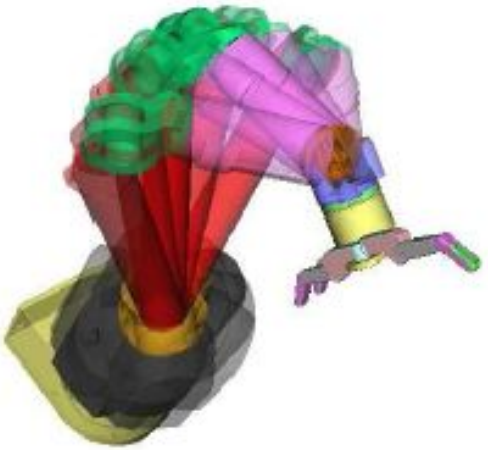
ikfastの計算速度

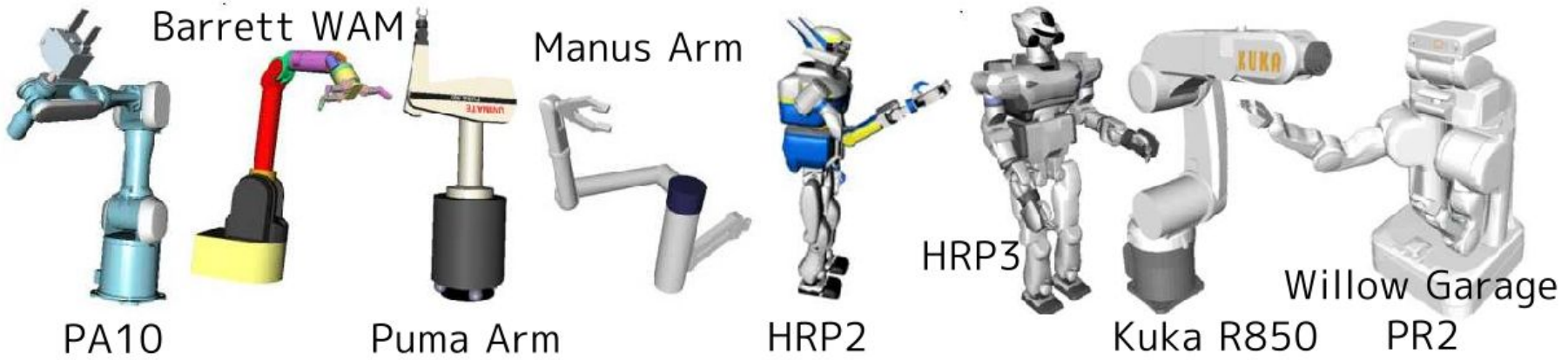
	Computation	Success	Discretization
Mitsubishi PA10	$7\mu s$	100%	0.1 radians
Barrett WAM	$6\mu s$	100%	0.1 radians
Puma Arm	$6\mu s$	100%	
Manus Arm	$6\mu s$	100%	
HRP2	$6\mu s$	99.5%	0.1 radians
Kuka R850	$5\mu s$	100%	
Willow Garage PR2	$6\mu s$	98.2%	0.1 radians
Willow Garage PR2	$6\mu s$	99.2%	0.02 radians
WAM Ray (Figure 4.7)	$4\mu s$	99.99%	

運動学の解析的な解

[Low,Dubey (1987)], [Raghavan, Roth (1990)], [Manocha,Zhu (1994)]

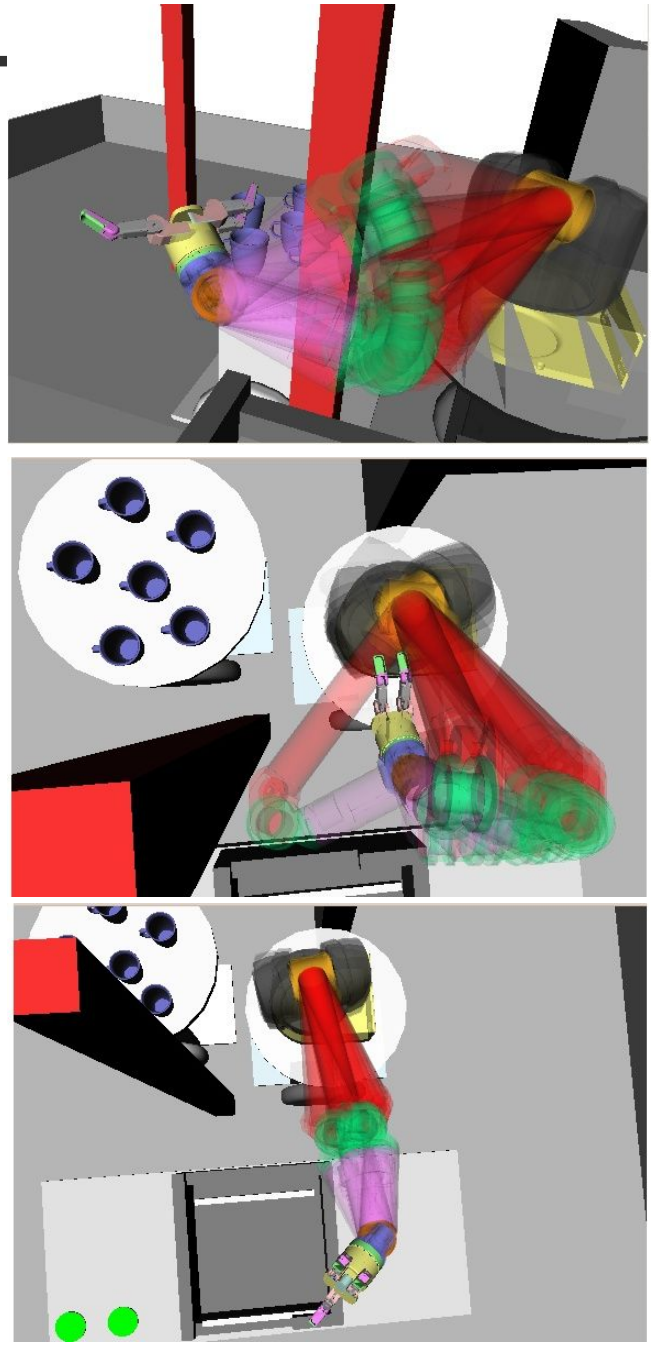
- **ikfast** – 最適化かつ安定化されたC＋＋生成
- ゼロ除算の検出
- degenerateケースの検出
  - 軸の整列
- 全解の返し **~6マイクロ秒**
- 6D，3D移動，3D回転，4D光線，2D方向、3D





冗長なマニピュレ-

- 6関節を選択
- 逆運動学関数の入力
  - ６D姿勢
  - 残りの関節度
- 含まれるチェック
  - 環境障害物衝突
  - 自己衝突
  - 関節のリミット
  - カスタム・フィルター



IKの生成方法

```
openrave.py --database inversekinematics
```

成功率の試験

```
openrave.py --database inversekinematics --usecached --iktests=100
```

新しいロボットを指定する

```
openrave.py --database inversekinematics --robot=robots/pa10.robot.xml
```

新しいロボットの特定のマニピュレーターを指定する

```
openrave.py --database inversekinematics --robot=robots/pr2-beta-
static.robot.xml  manipname=leftarm
```

フリー関節の選択：

```
openrave.py --database inversekinematics --robot=robots/pa10.robot.xml --
freejoint=S3
```

関節の出力：

```
openrave.py -p 'print env.GetBodies()[0].GetJoints()' robots/pa10.robot.xml
```

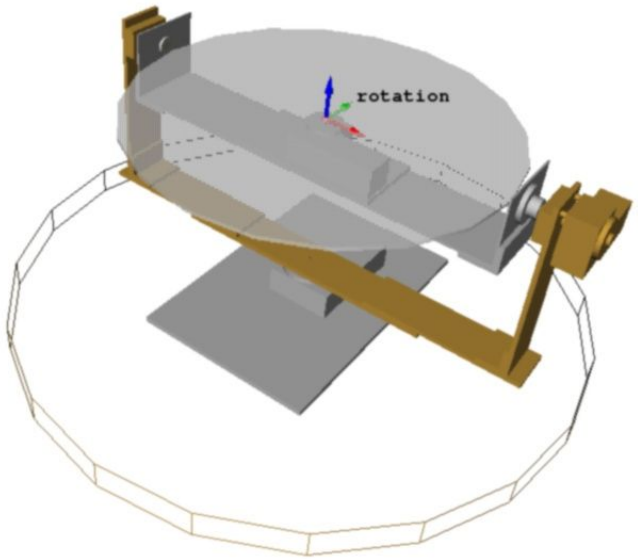
ファイル名：

```
openrave.py --database inversekinematics --getfilename
```

3D回転

- ロボットリンクの３D回転を世界座標系の３D回転に合わせる

```
openrave.py --database inversekinematics --robot=robots/rotation_stage.robot.xml
--iktype=rotation3d --iktests=100 --usecached
```



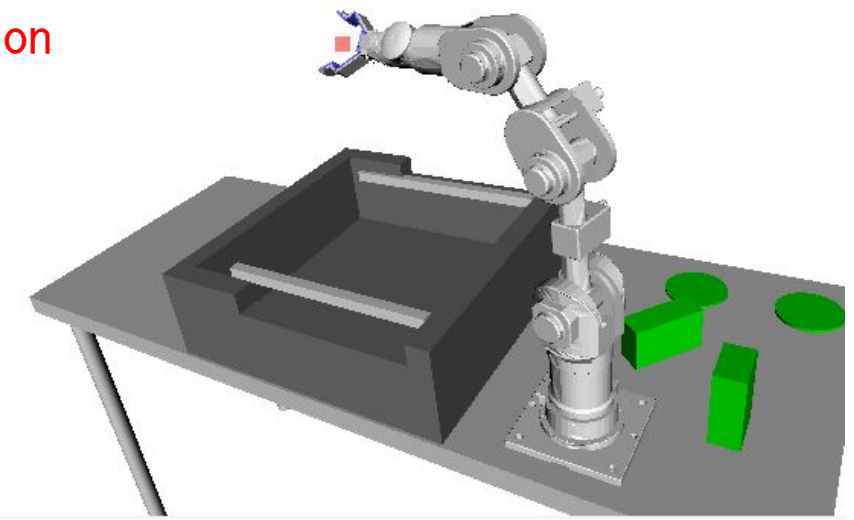
３D移動

- ロボット上の３D位置を世界座標系の３D位置に合わせる

```
openrave.py --database inversekinematics --robot=robots/katana.robot.xml
--iktype=translation3d --freejoint=j4 --freejoint=j5 --iktests=100
--usecached
```

サンプリングの例

```
openrave.py --example tutorial_iktranslation
```



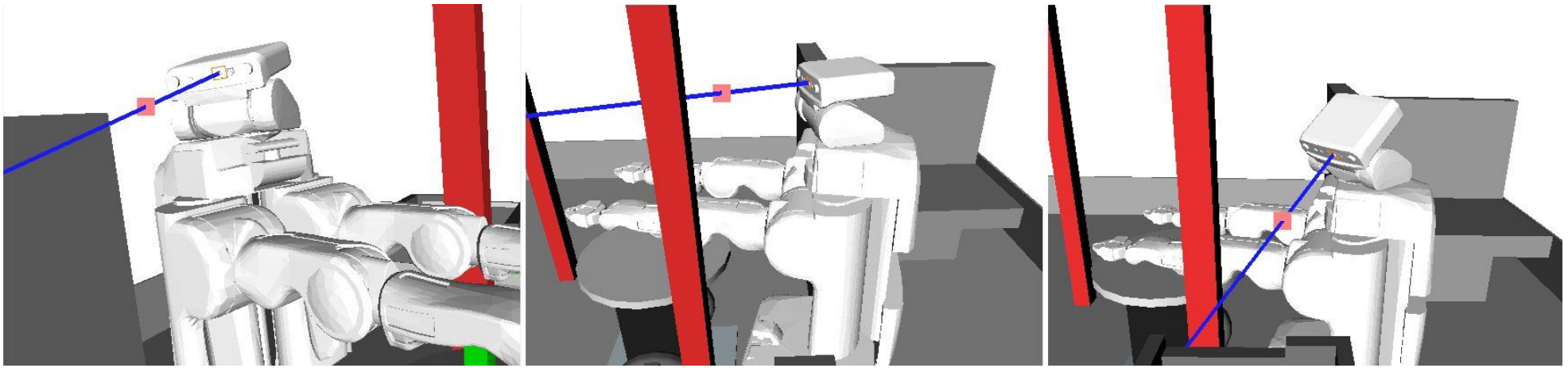
３D対象

- 対象の位置に光線ベクトルを合わせる

```
openrave.py --database inversekinematics --robot=robots/pr2-beta-
static.robot.xml --manipname=head --iktype=lookat3d --usecached --iktests=100
```

サンプリングの例

```
openrave.py --example tutorial_iklookat
```

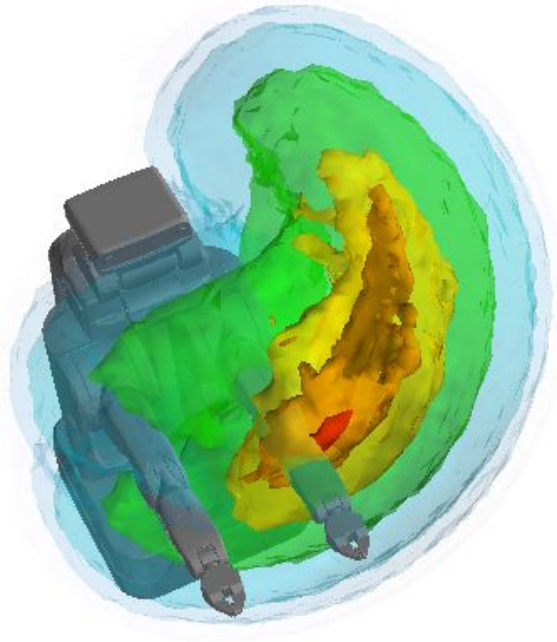


到達範囲の応用

- 把持選択
- 物体の視認性の優先
- 関節状態のサンプリング
- 胴体の位置サンプリング

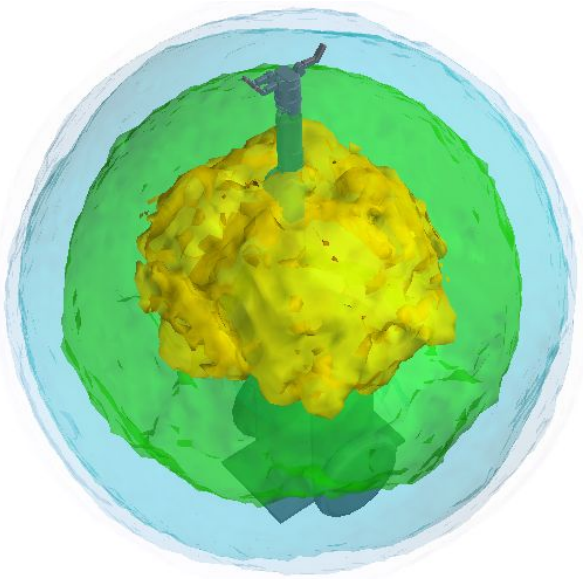
運動学の到達範囲

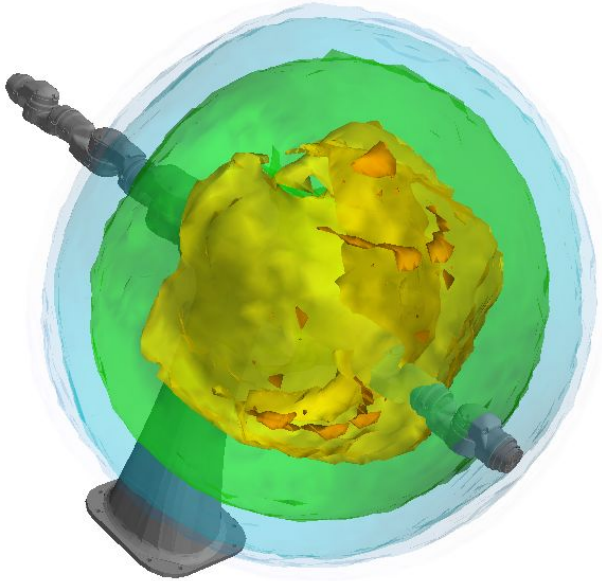
[(Zacharias (2007-2010)]

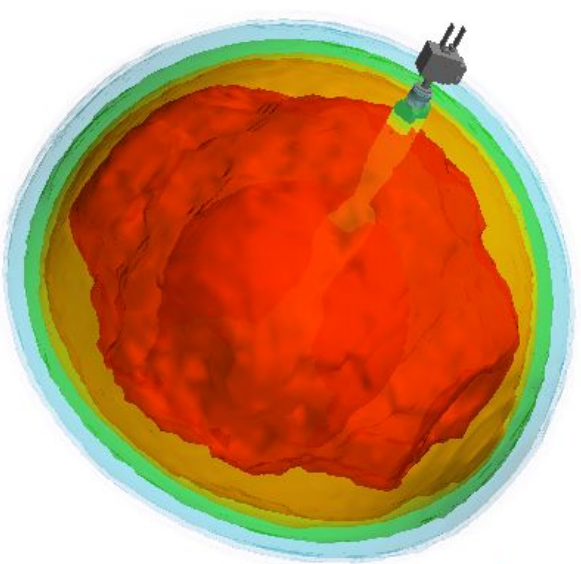


- ハンドの6D位置姿勢のマップ

```
openrave.py --database kinematicreachability --robot=robots/pa10.robot.xml
```



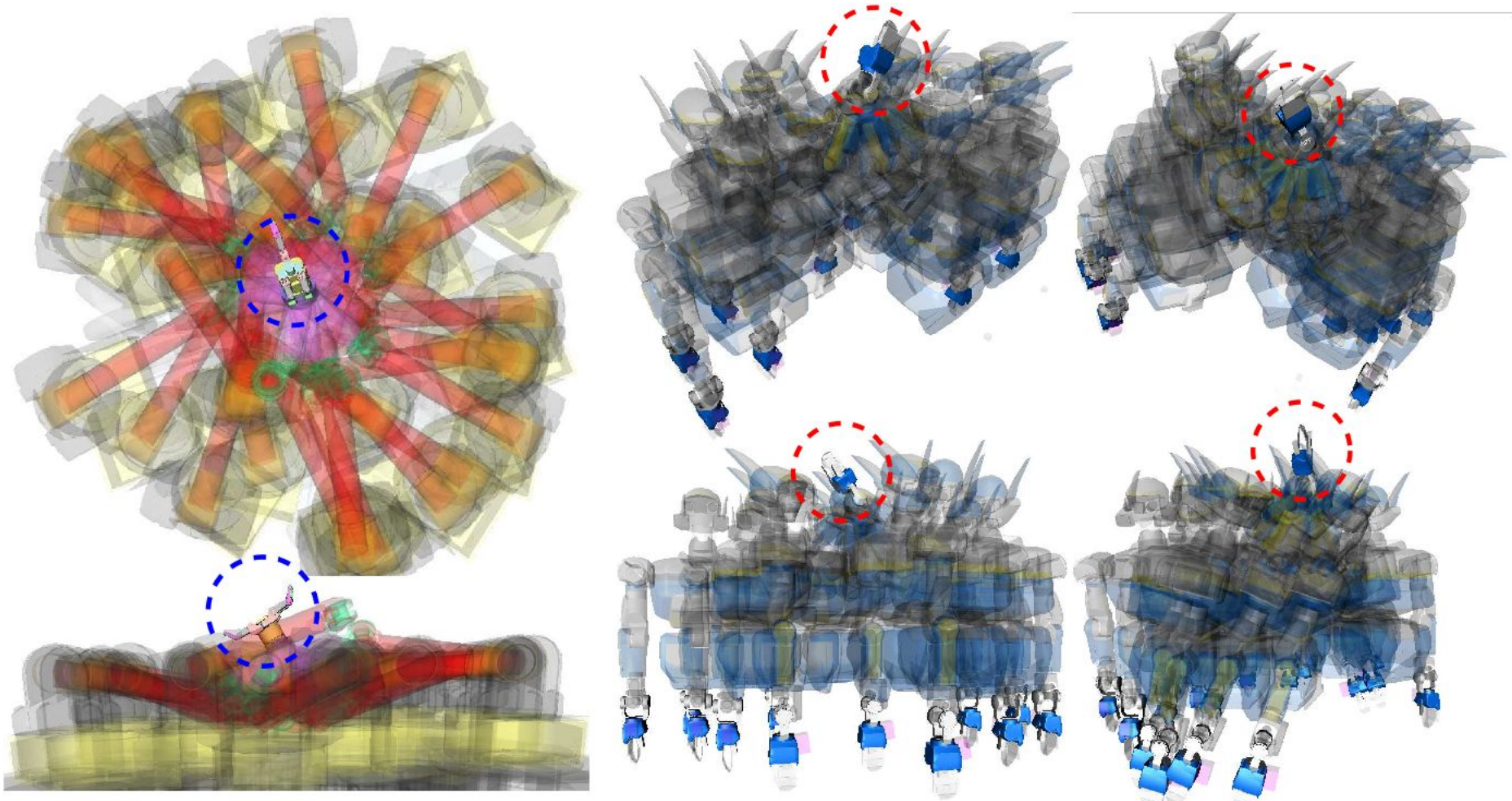




投影された逆運動学分布

[Stulp, Beetz (2009)], [Asfour et al (2010)]

```
openrave.py --database inversereachability --robot=robots/pa10.robot.xml
```

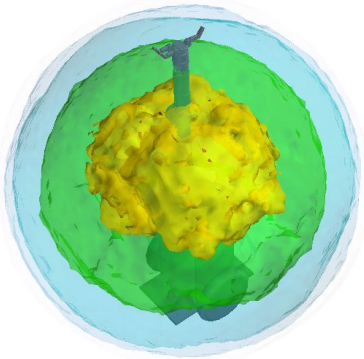


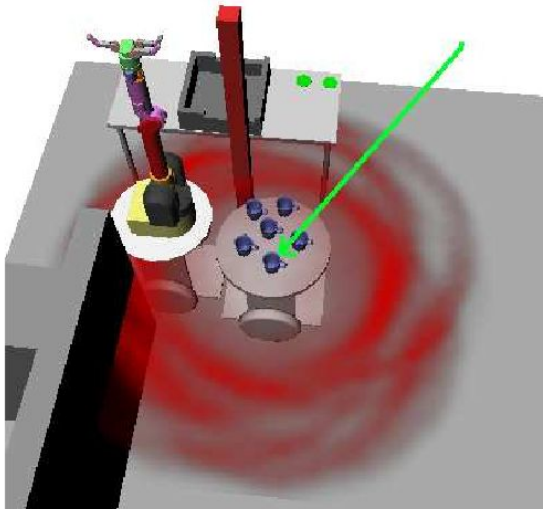
7 DOF Arm　　7 DOF Arm　　8 DOF Arm+Chest

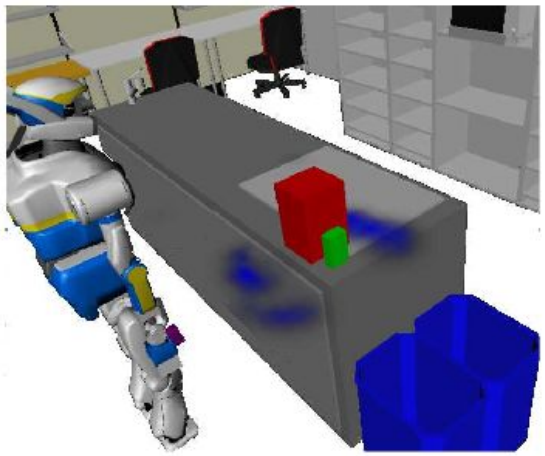
東京大学
THE UNIVERSITY OF TOKYO

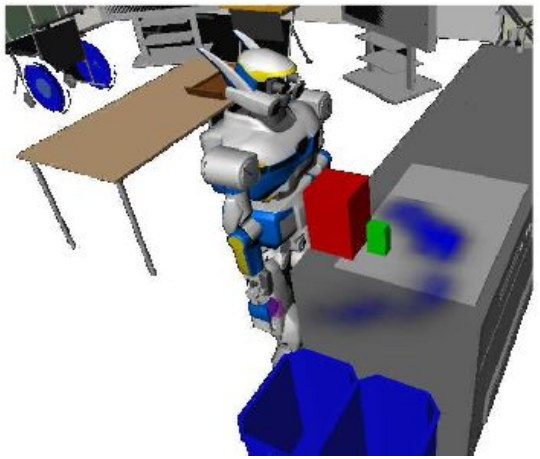
把持可能位置姿勢空間

```
openrave.py --example tutorial_inversereachability
```

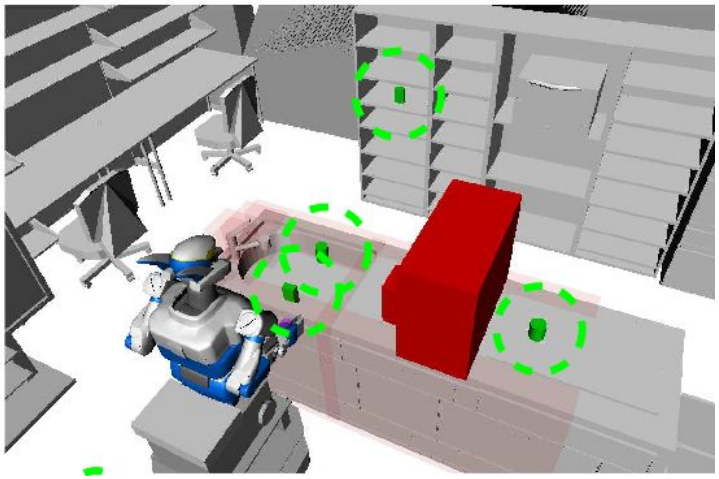








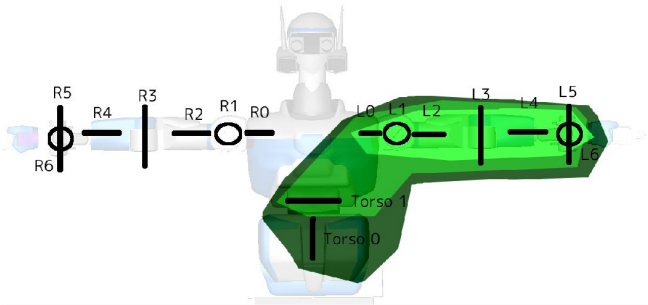
把持可能位置姿勢空間



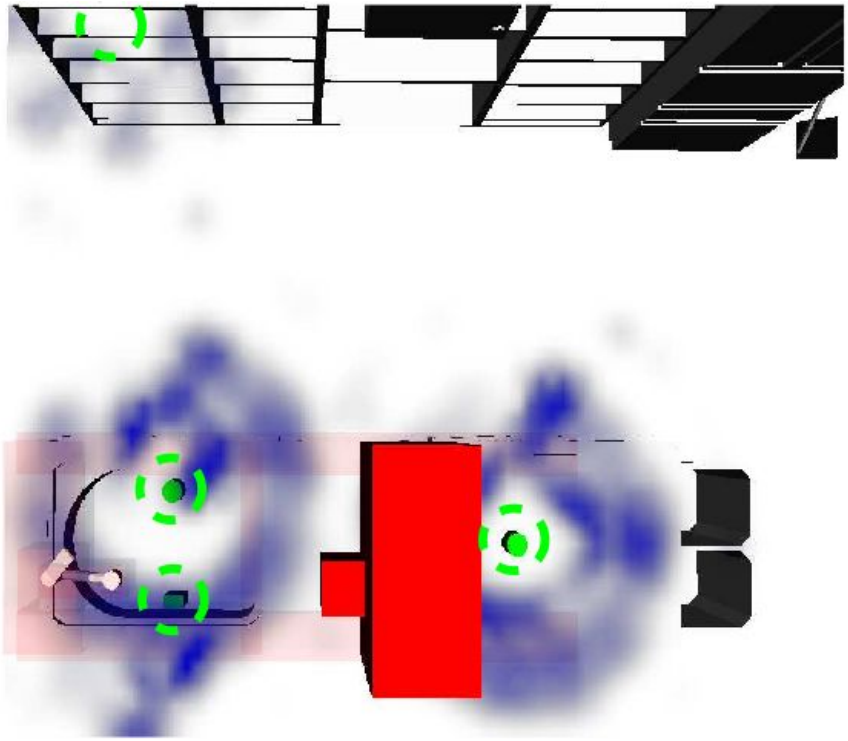
4物体

＋

6アーム

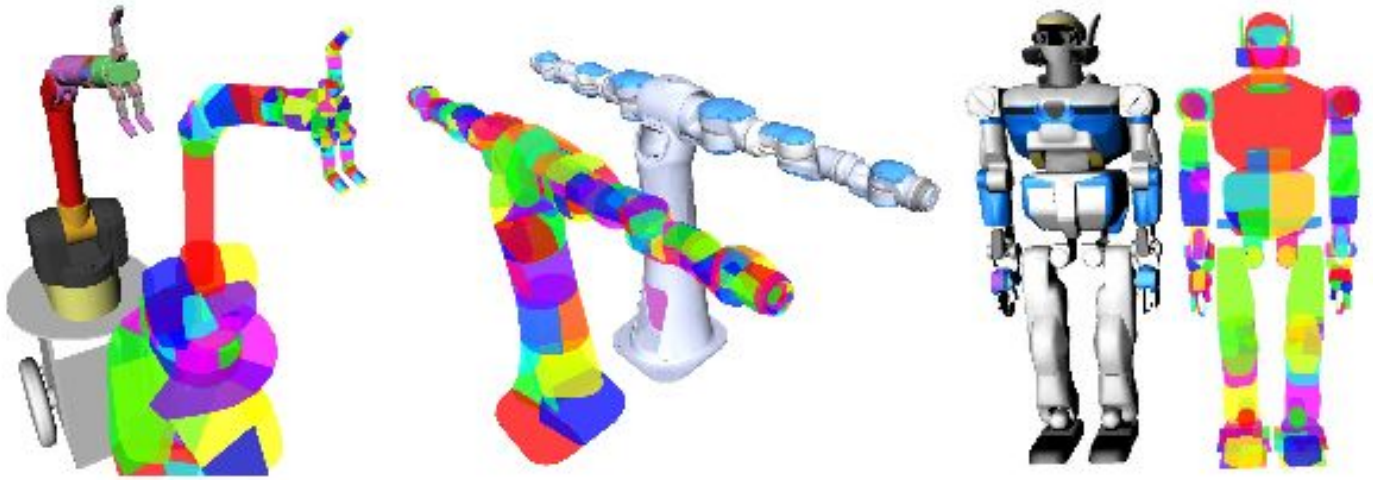


＝



XY+回転の胴体分布

凸形状分解



Running the Generator

```
openrave.py --database convexdecomposition --robot=robots/barrettsegway.robot.xml
```

Showing the Decomposition

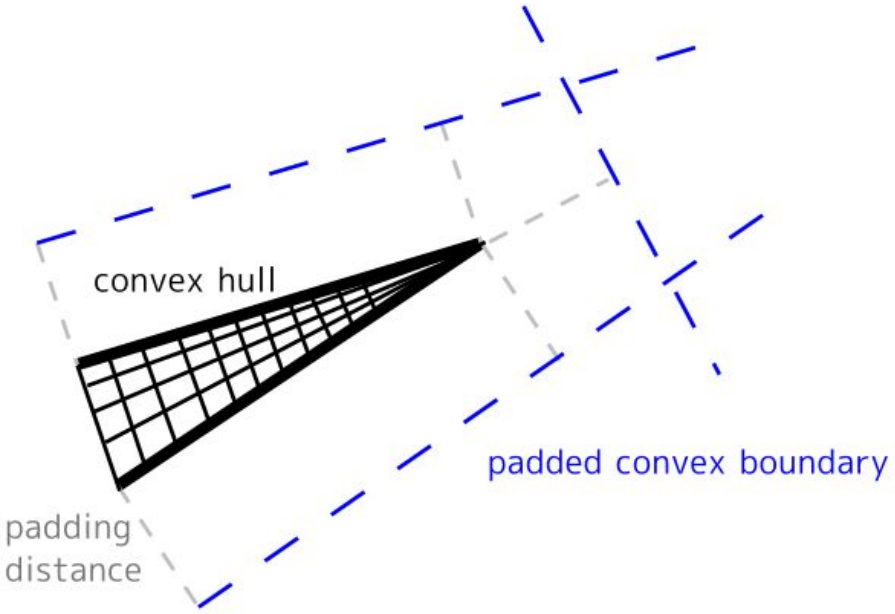
```
openrave.py --database convexdecomposition --robot=robots/barrettsegway.robot.xml --show
```

Usage

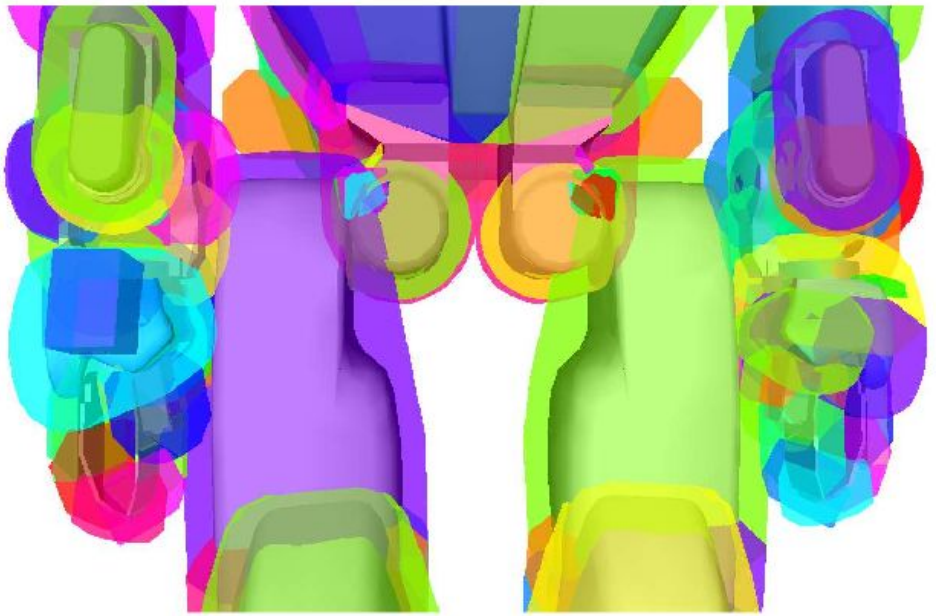
Dynamically load the convex hulls for a robot:

```
cdmodel = openravepy.databases.convexdecomposition.ConvexDecompositionModel(robot)
if not cdmodel.load():
    cdmodel.autogenerate()
```

凸形状分解：パッディング

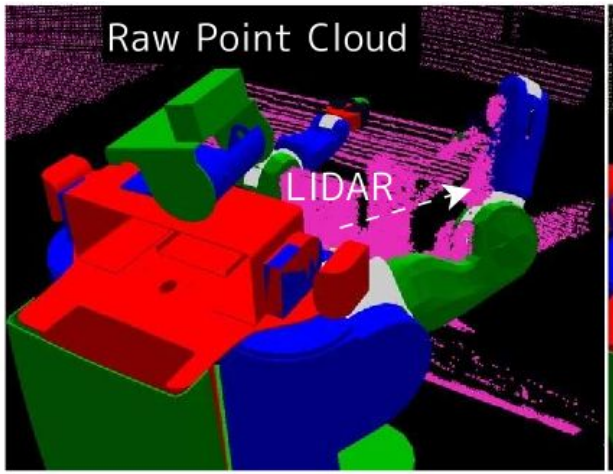


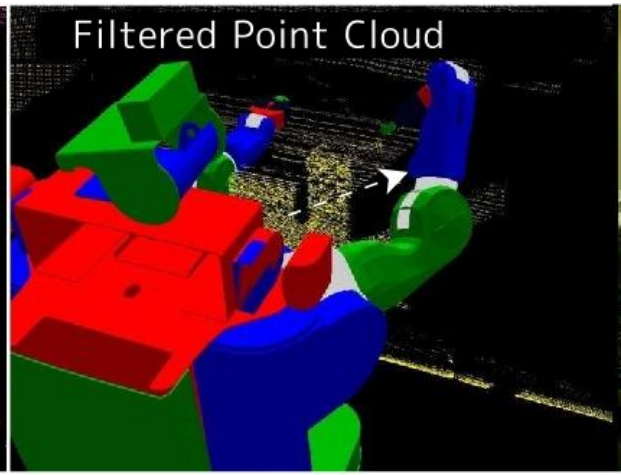
Padding Geometry at Vertices

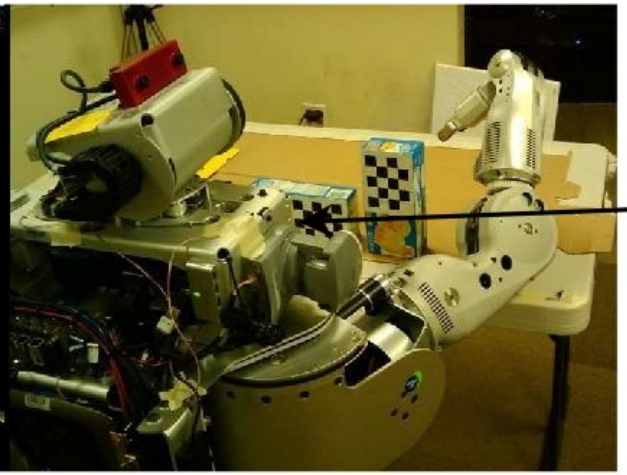


0.02m Padded Convex Decomposition

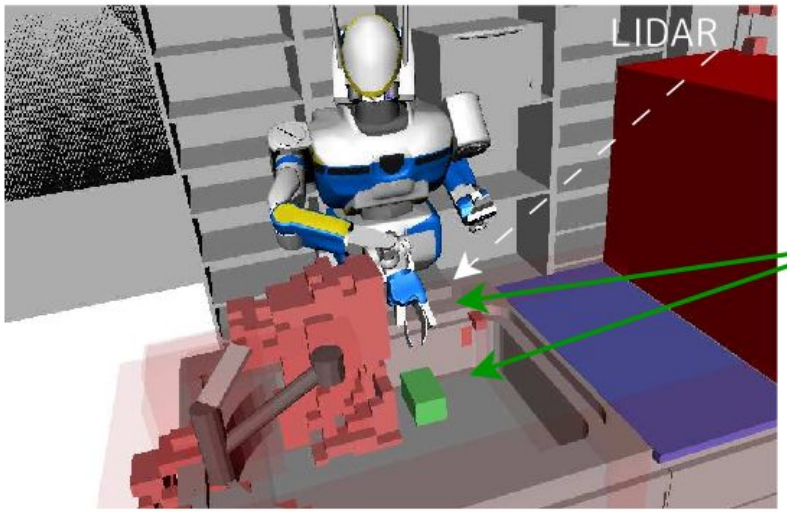
凸形状分解：体積







on-board spinning laser



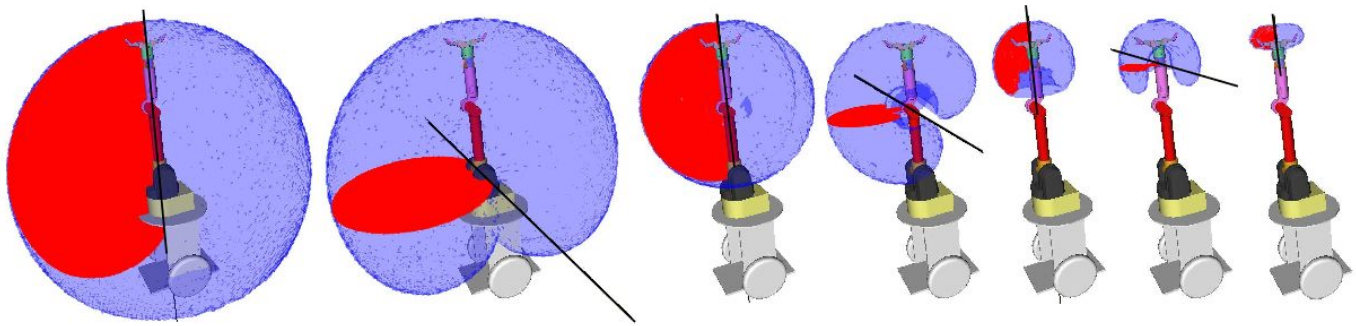
Subtracted Known Geometry

fixed flash lidar

凸形状分解：Distance Metric

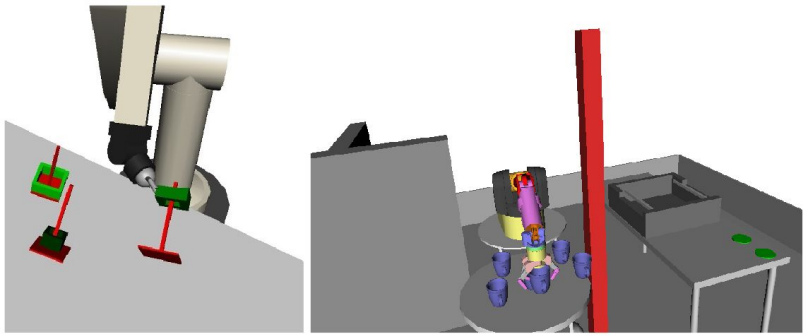
掃引体積

$$\omega_i = \left(\textsc{CrossSection}(SV_i) * \sum_{j \in DependentLinks_i} LV_j \right)^{\frac{1}{3}}$$



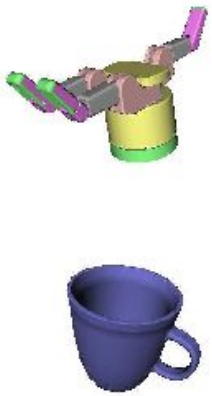
動作計画の処理時間

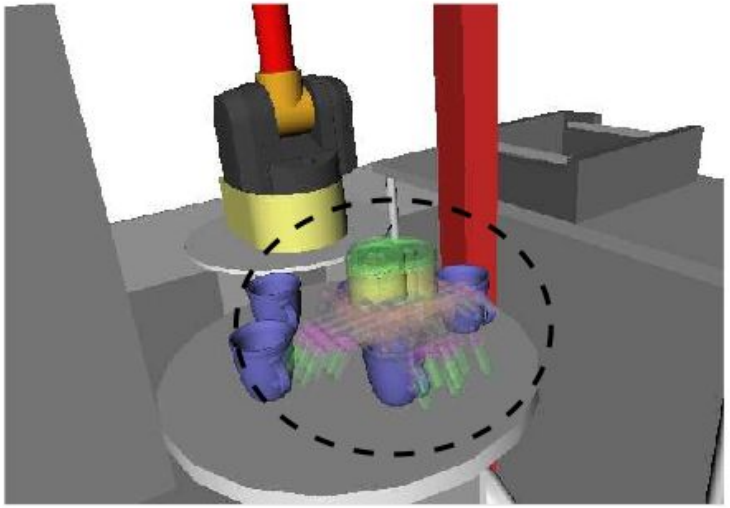
	Uniform Weights	Swept Volume Weights (ω_i)
WAM scene	2.89s	1.24
Puma Scene	0.71s	0.57s



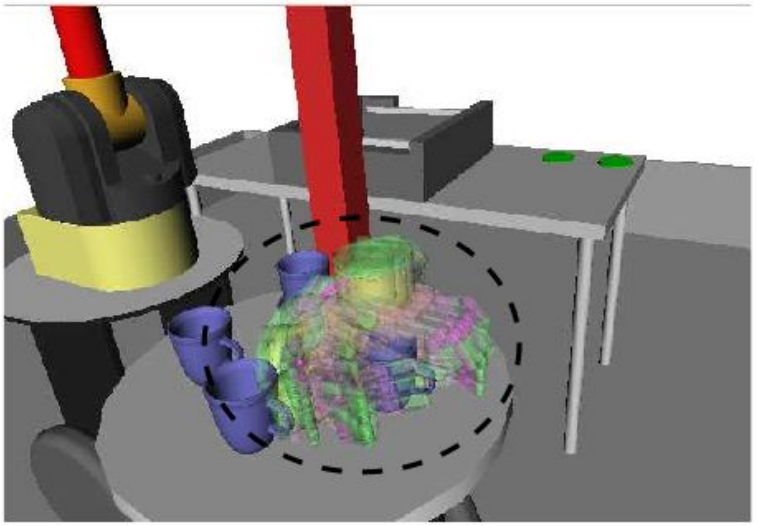
把持の選択

[Berenson, Diankov (2007)]

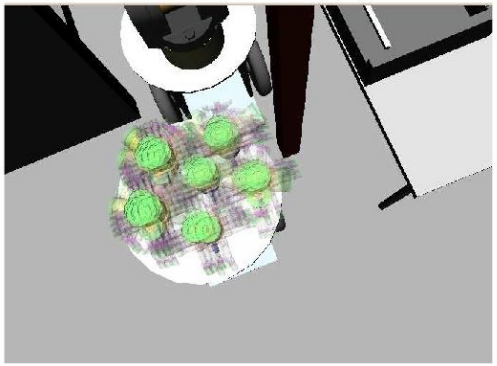


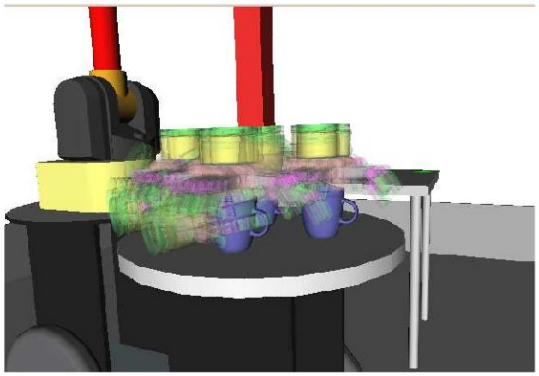


Reachable (has IK)

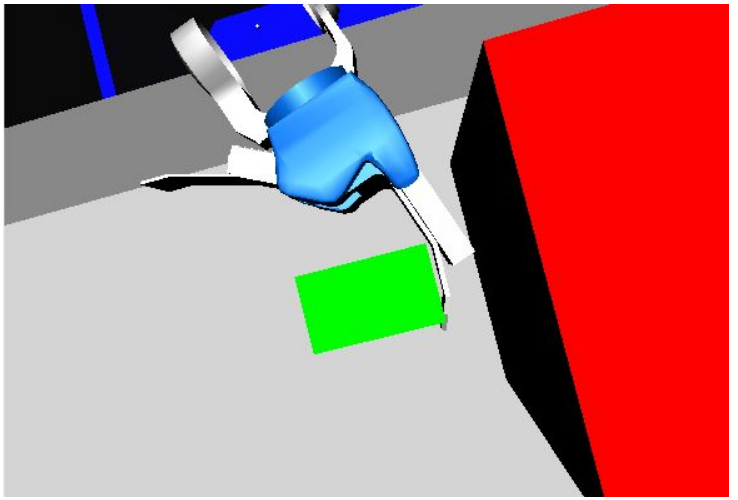


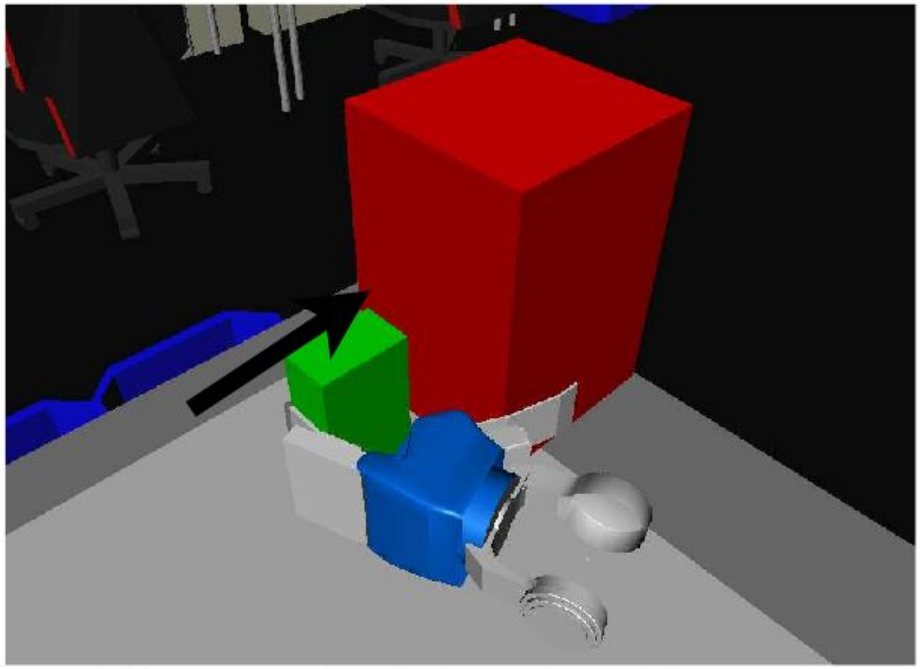
Unreachable



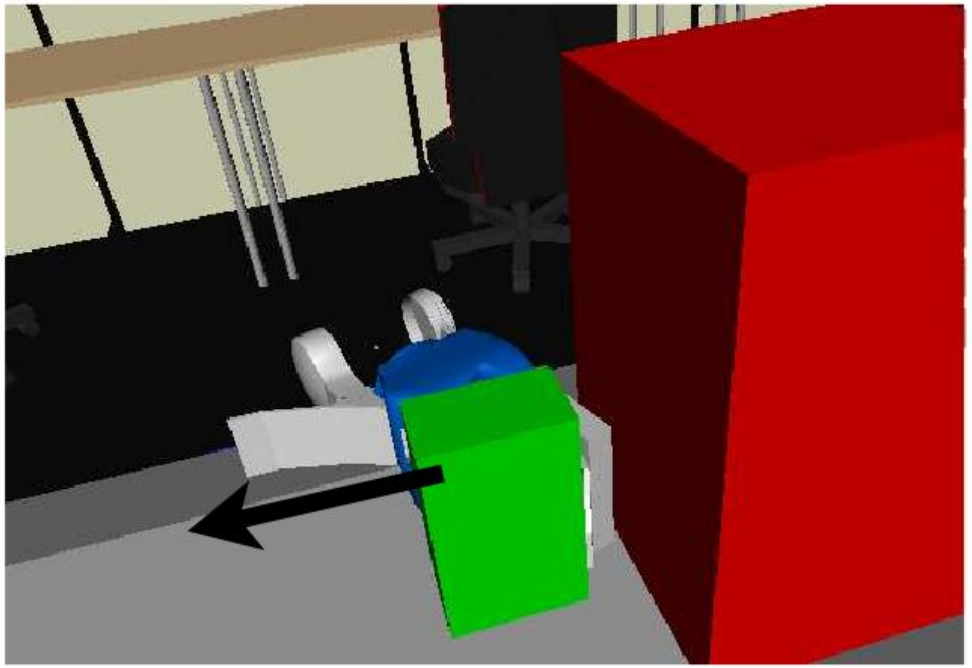


把持の検証



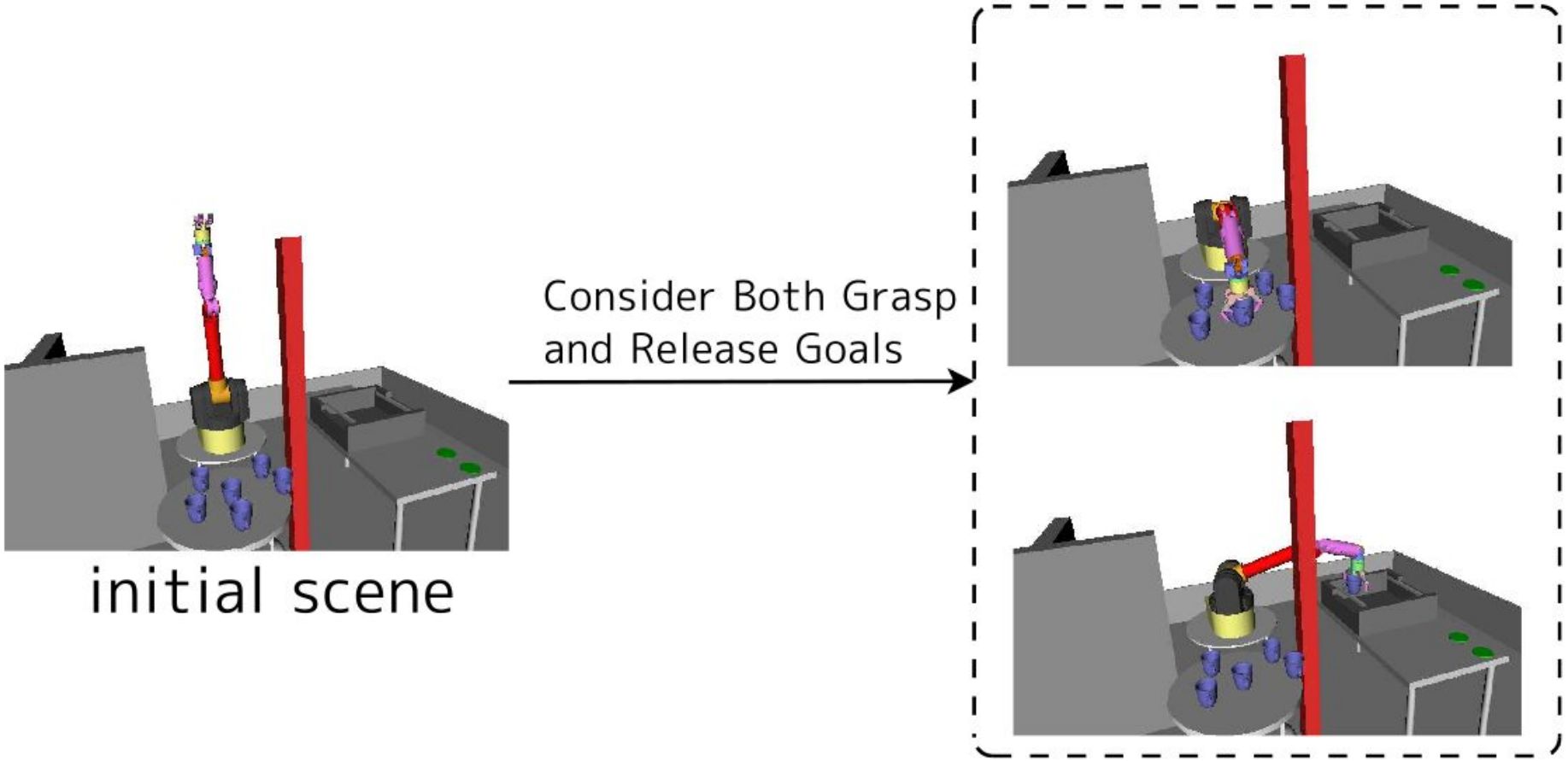


Obstacle Blocks Finger

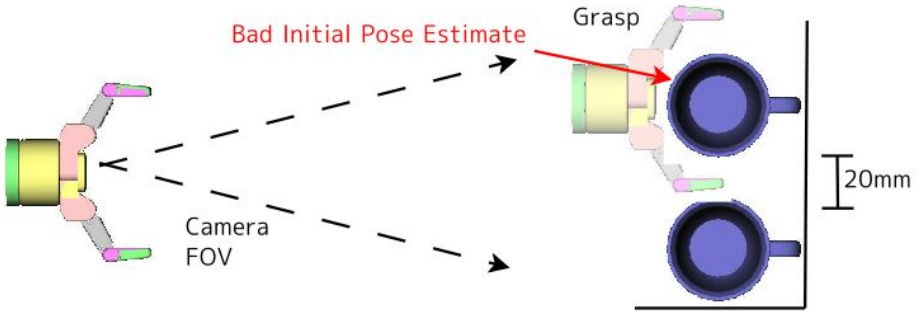


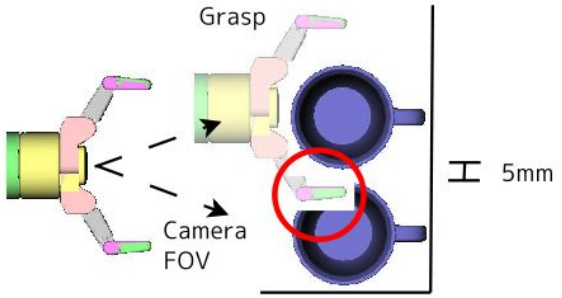
Tight Place

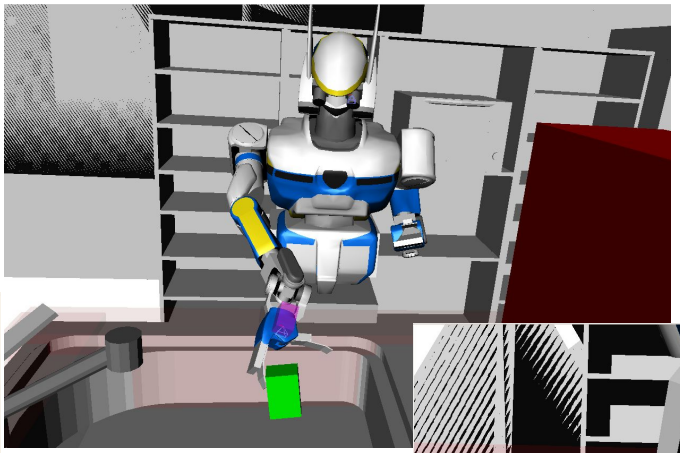
把持選択時に目的地も考慮する



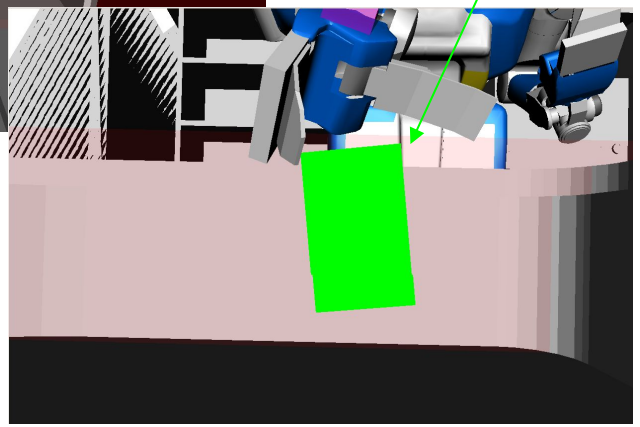
位置姿勢の誤差







Head Camera Results

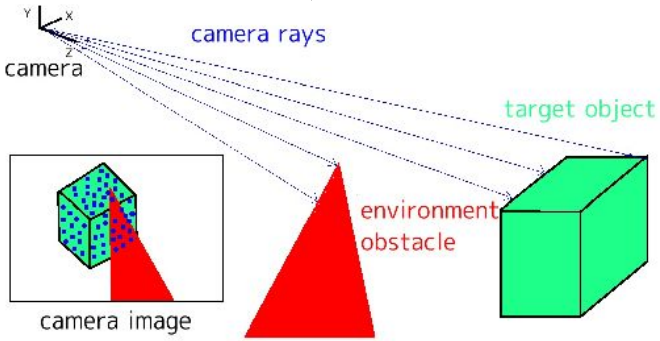


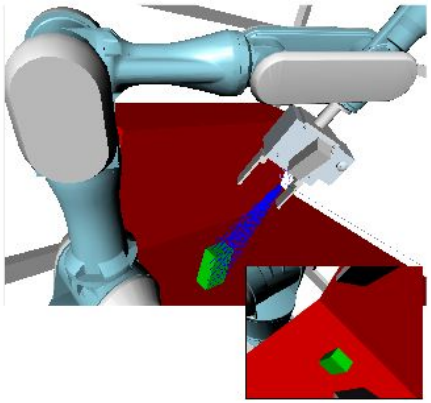
4cm

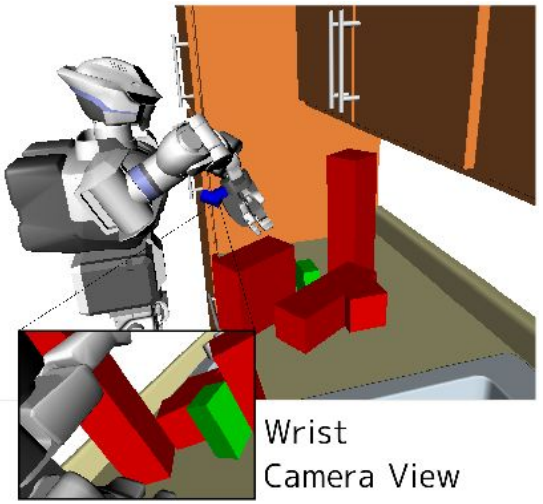
物体の視認性を目標にする

[Diankov, Kanade, Kuffner (2009)]

- 三つの要因
  - 視認性範囲
  - 運動学
  - 障害物

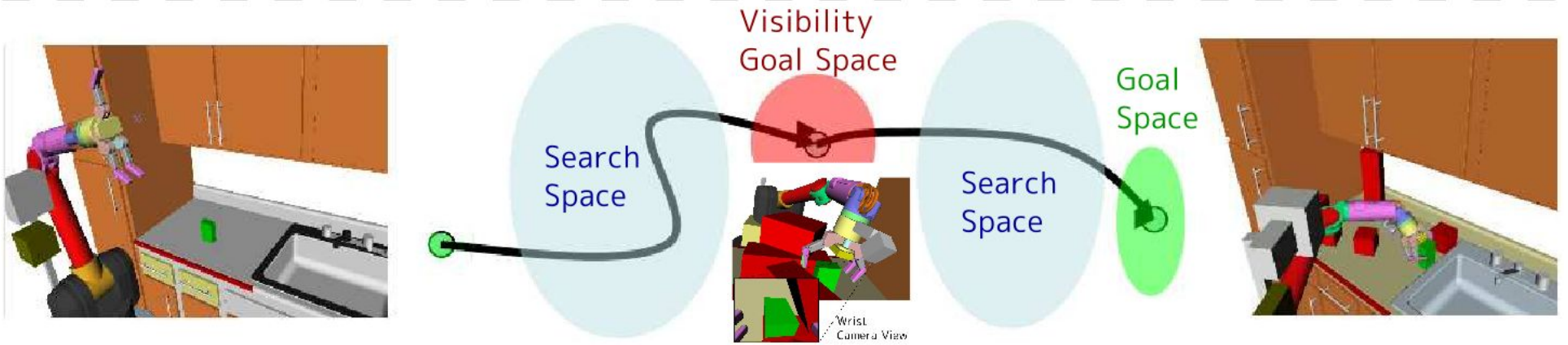






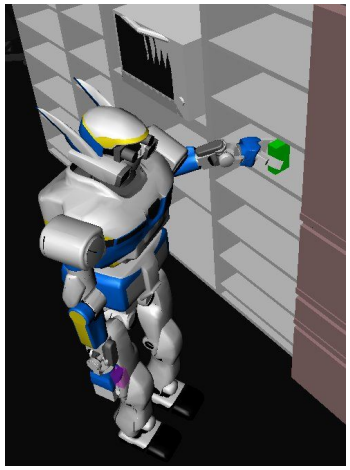
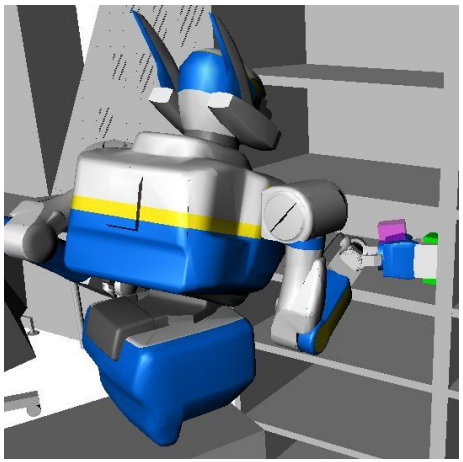
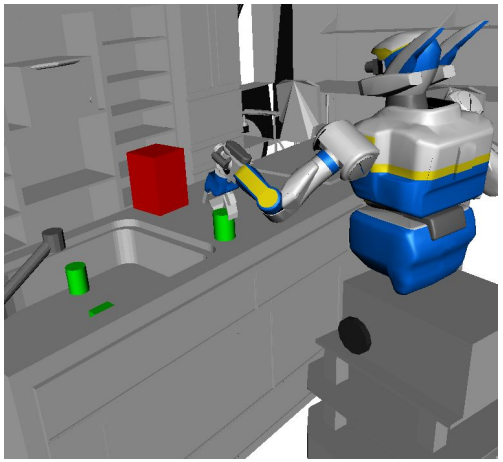
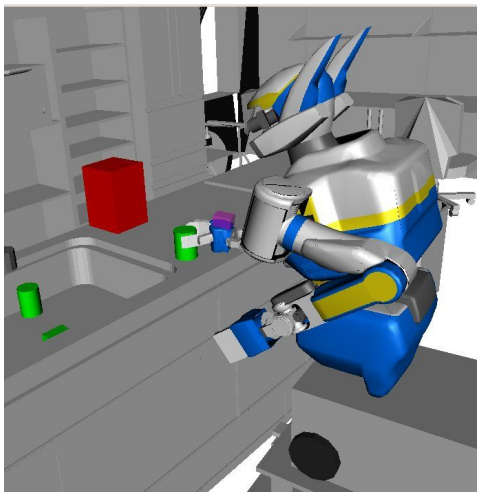
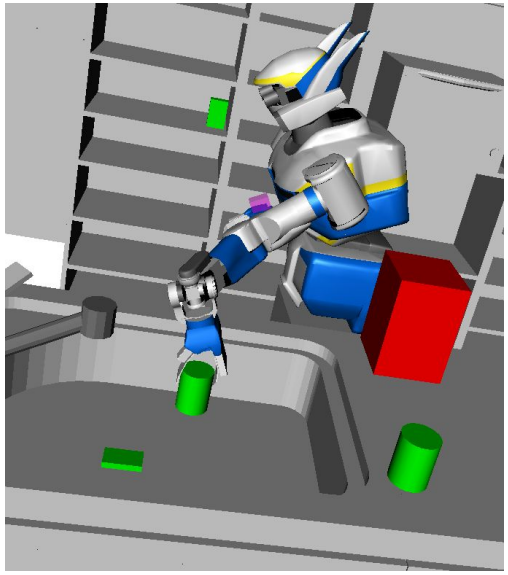
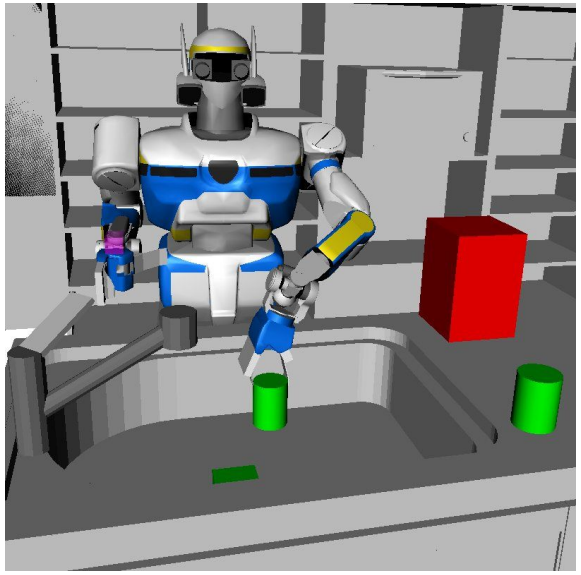
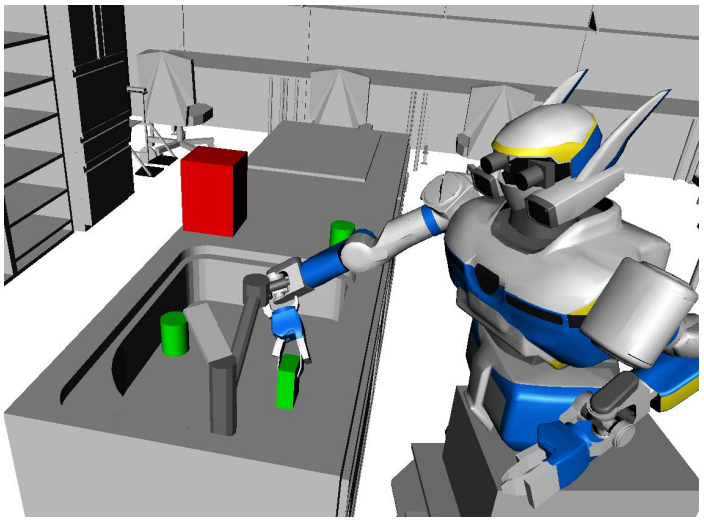
2段階の効率

One-Stage Grasp Planning



Two-Stage Visibility + Grasp Planning

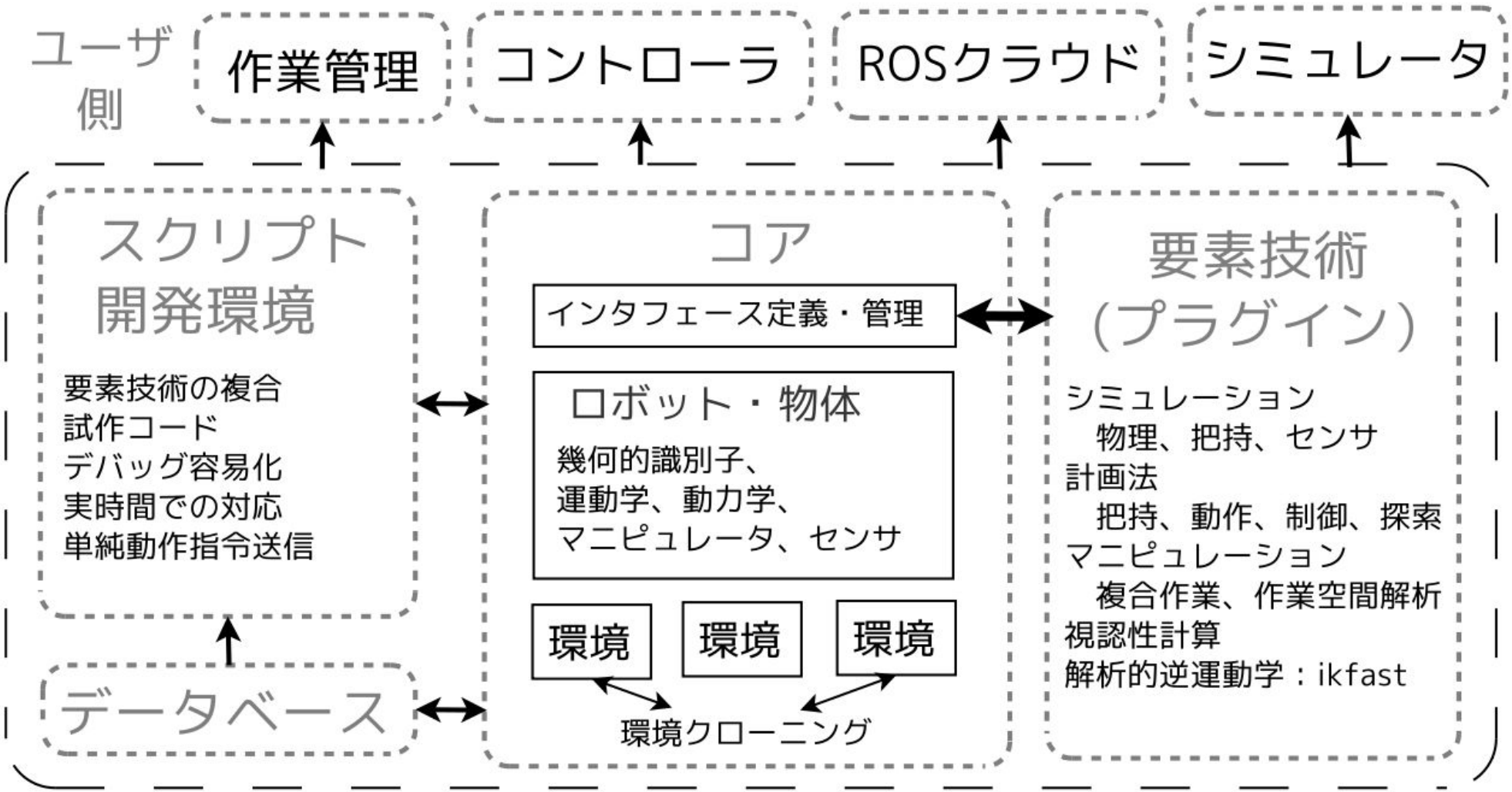
胴体＋アーム＋把持のサンプリング

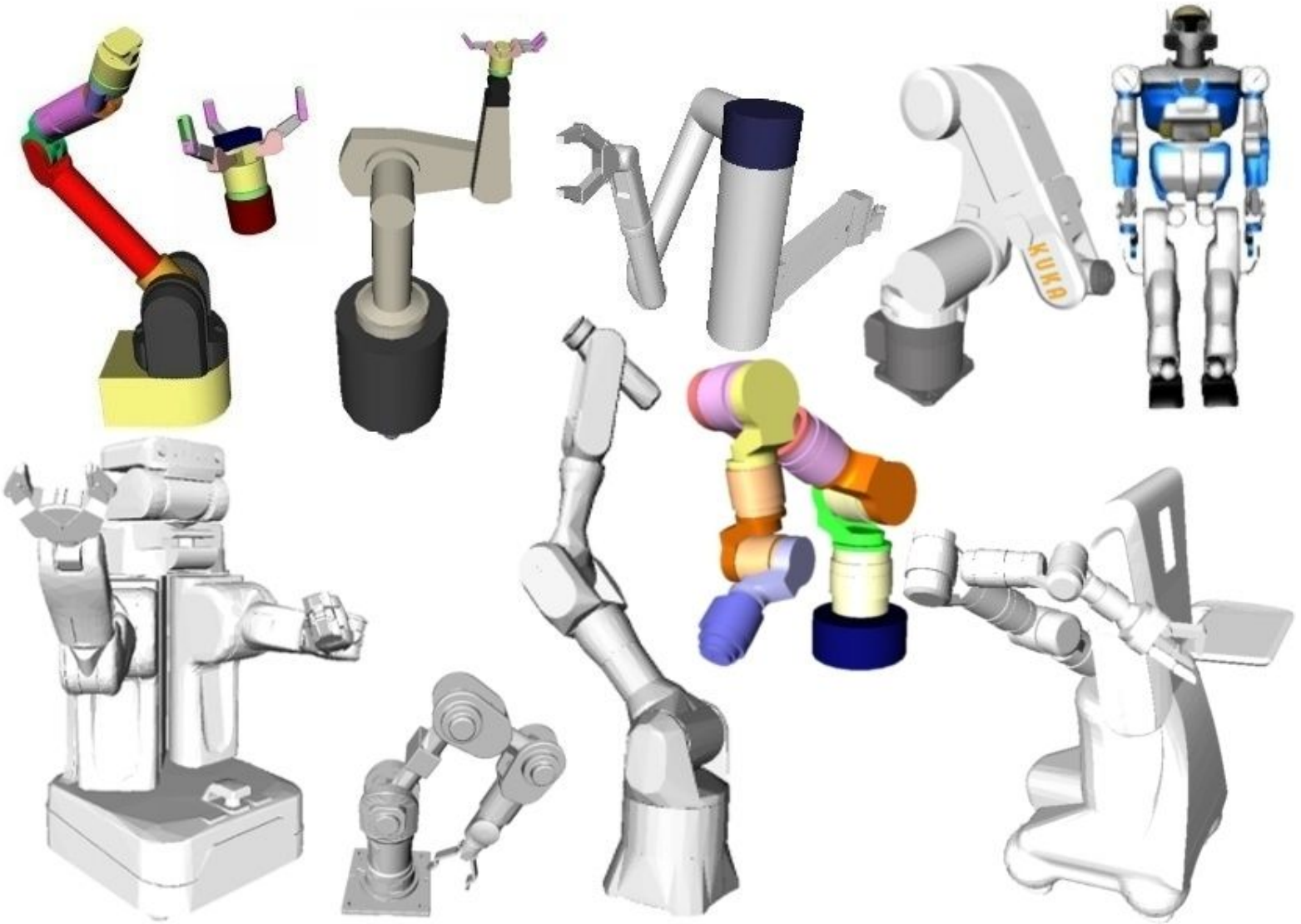
移動マニピュレーション動作計画

不明な物体の把持動作

OpenRAVEアーキテクチャー



使えるロボットの一覧



Environment

- 役割
  - 物体・ロボットの生成、ロード、破壊
  - 衝突関数
  - 物理ライブラリとの動機
  - 表示ライブラリとの動機
  - クローン
  - メッシュの抽出

Environmentロック

- 環境更新管理
  - ロックを持ったら環境が変わらない
- マルチスレッド対応
- ユーザ向けのRecursiveロック
  - スコープを気にせずにロック可能

Environmentクローン

- 新しいコピー
  - 速い
  - コピー対象物の調整
  - 静的なデータは参照される
- 実際のロボットデモ
  - 一つの環境：実世界との動機
  - 動作計画用のクローン
    - 他のユーザに干渉せずに長くロック可能

Hashes for Body Structure

- Unique MD5 Hash for a Body's *Structure*
  - Removes online state and names
- Structure includes:
  - Geometry
  - Kinematics
  - Manipulators
  - Sensors
- OpenRAVE Knowledge-base indexes with respect to information it depends on
  - IK generation only uses the kinematics of a sub-chain
  - Kinematic reachability uses geometry and kinematics of manipulator
  - Grasping uses geometry of the target body and the kinematics and geometry of gripper

Kinematics Bodyインタフェース

- リンクと関節のリスト
  - **階層ではない！**
  - 関節の値はリンクの一姿勢から計算されている
  - 一部の構造で動作計画可能
  - 構造への探索
- 運動学・動力学
- ヤコビアンの計算
- 自己干渉
- **物体との接続**
  - マニピュレーションへ必要不可欠

Robotインタフェース

- マニピュレーター
  - Base and End Links forms arm sub-chain - **IK**
  - List of gripper joints - **grasping**
  - check collision or query links
    - gripper only
    - Independent links of the manipulator
- アクティブ関節
- 物体との剛体接地
- センサー設置

逆運動学のインターフェース

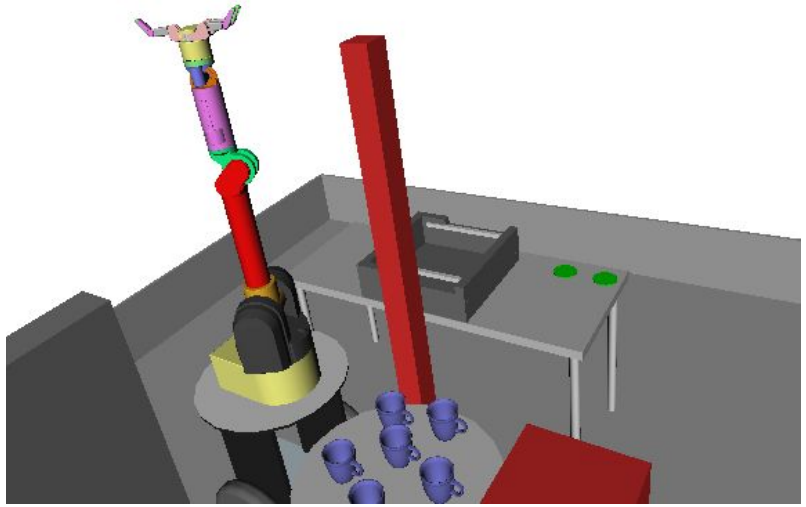
- 10個のIK種類
- 追加機能
  - 環境障害物
  - 自己干渉
  - 関節リミット
  - プランナー用

OpenRAVE Python Scripting

http://openrave.org/en/main/getting_started.html#getting-started

環境のロード

```
from openravepy import *
env = Environment() # create openrave environment
env.SetViewer('qtcoin') # attach viewer (optional)
env.Load('data/lab1.env.xml') # load a simple scene
robot = env.GetRobots()[0] # get the first robot
print "Robot ",robot.GetName()," has ",robot.GetDOF()," joints with values:\n",robot.GetJointValues()
robot.SetJointValues([0.5],[0]) # set joint 0 to value 0.5
T = robot.GetLinks()[1].GetTransform() # get the transform of link 1
print "The transformation of link 1 is:\n",T
env.Destroy() # explicitly destroy the environment once done with it
```



BiRRTの利用

```
from openravepy import *
env = Environment() # create the environment
env.Load('data/lab1.env.xml') # load a scene
env.SetViewer('qtcoin') # start the viewer
robot = env.GetRobots()[0] # get the first robot
manipprob = interfaces.BaseManipulation(robot) # create the interface for basic manipulation programs
res = manipprob.MoveManipulator(goal=[-0.75,1.24,-0.064,2.33,-1.16,-1.548,1.19]) # call motion planner
robot.WaitForController(0) # wait
env.Destroy()
```

環境ロックの掛け方

- withスコープ

```
env = Environment()
# initialization code
with env:
    # environment is now locked
    env.CheckCollision(...)
```

- ロボットの状態保存とロック

```
with robot:
    robot.SetTransform(newtrans)
    robot.SetActiveDOFs(...)
    # do work

# robot now has its previous state restored
```

openrave.py program

- Jump into ipython after loading environment:

```
openrave.py -i data/lab1.env.xml
```

- Set default collision checkers/phisics

```
openrave.py --collision=pqp --viewer=qtcoin --physics=ode data/lab1.env.xml
```

- サンプルの実行

```
openrave.py --example graspplanning
```

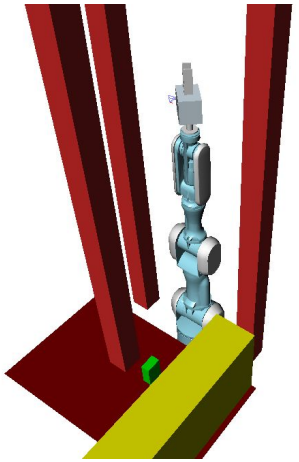
- Execute database generator: solve analytic IK, create C++ file

```
openrave.py --database inversekinematics --robot=robots/pa10.robot.xml
```

openravepy特徴

- C++関数のone-to-one対応
- C++のエラーが起こればpythonに戻される
  - 再起動せずにエラー復帰
- 新しいプラグインのロード

PA10で把持計画



```
openrave.py --example visibilityplanning

openrave.py data/pa10grasp2.env.xml

openrave.py --database grasping --robot=robots/pa10schunk.robot.xml
--target=data/box_frootloops.kinbody.xml --show


openrave.py --database visibilitymodel --robot=robots/pa10schunk.robot.xml
--target=data/box_frootloops.kinbody.xml --show
```

PA10で把持計画

- 環境のロードと準備

```
# OpenRAVEをロード
from openravepy import *
env=Environment()
env.SetViewer('qtcoin')
env.Load('data/pa10grasp2.env.xml')

# モデルの作成
robot=env.GetRobots()[0]
manip=robot.GetActiveManipulator()
target=env.GetKinBody('frootloops')
gmodel=databases.grasping.GraspingModel(robot,target)
if not gmodel.load():
    gmodel.autogenerate()

ikmodel=databases.inversekinematics.InverseKinematicsModel(robot,iktype=IkParameterization.Type.Transform6D)
if not ikmodel.load():
    ikmodel.autogenerate()

basemanip = interfaces.BaseManipulation(robot)
taskmanip = interfaces.TaskManipulation(robot)
```

```
# 把持計画
taskmanip.ReleaseFingers()
validgrasps = gmodel.computeValidGrasps()[0]
gmodel.showgrasp(validgrasps[0])
for g in validgrasps: gmodel.showgrasp(g)

with env:
    for i,g in enumerate(validgrasps):
        with robot:
            Tgrasp = gmodel.getGlobalGraspTransform(g,collisionfree=True)
            sol = manip.FindIKSolution(Tgrasp,IkFilterOptions.CheckEnvCollisions)
            robot.SetDOFValues(sol,manip.GetArmIndices())
            if env.CheckCollision(robot):
                print i
            env.UpdatePublishedBodies()
            raw_input('pause')

# プランニング
basemanip.MoveToHandPosition(matrices=[gmodel.getGlobalGraspTransform(validgrasps[0],collisionfree=True)])
```

```
# 視認性
vmodel=databases.visibilitymodel.VisibilityModel(robot,target)
if not vmodel.load():
    vmodel.autogenerate()

validjoints = vmodel.computeValidTransform()
with robot:
    sol,index = validjoints[0]
    robot.SetJointValues(sol,manip.GetArmIndices())
    env.UpdatePublishedBodies()
    raw_input('pause')
```

第4宿題

- 箱の６平面をハンドで接触する経路
  - 左と右ハンドで経路を作る
- 環境
  - 障害物
  - 箱の位置姿勢
- 宿題演習セッション
  - 土曜日？