Case Study II:
Multi-query Roadmap Planners:
Building C-Space Distance Oracles

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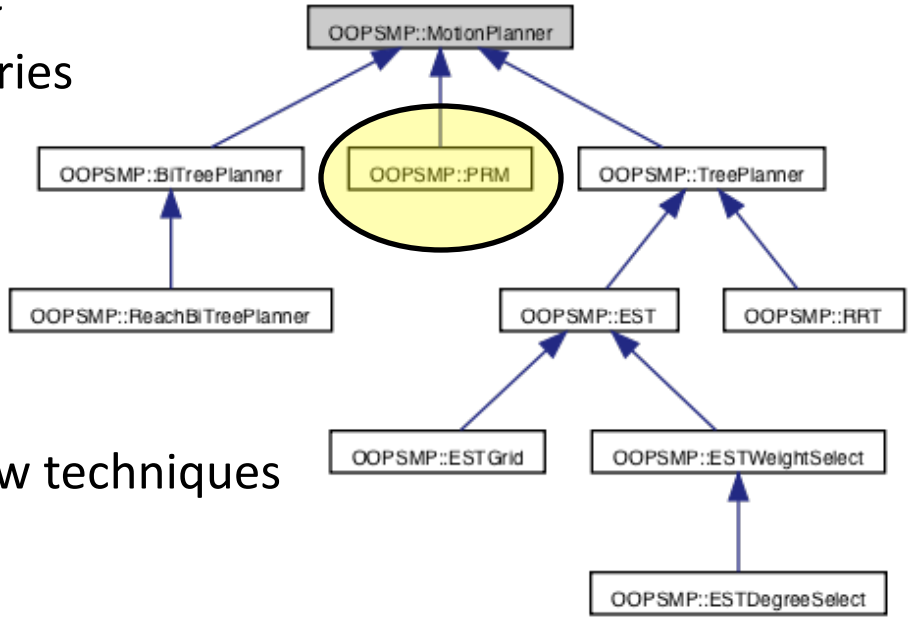
Overview

Roadmap motion planners

- Preprocess the configuration space
- Efficient in answering multiple queries



This presentation

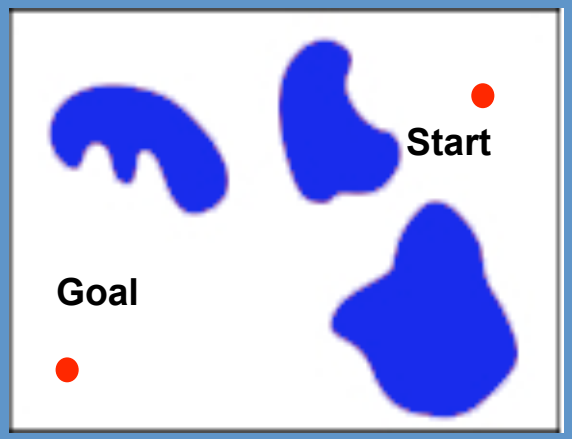
- OOPSMP's version of PRM
  - Study the implementation
- How to extend PRM and design new techniques
  - Visibility-PRM
  - Spanner Roadmaps

Motivation

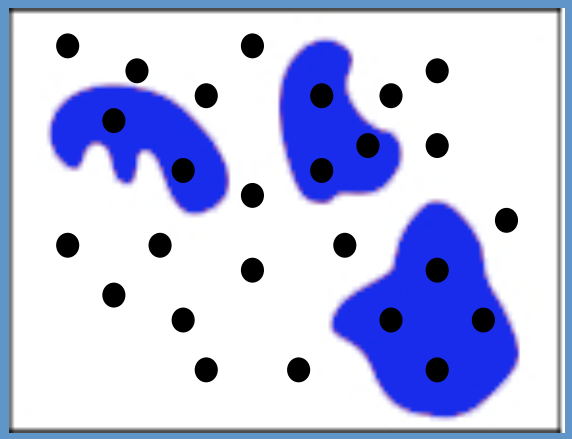
Roadmaps can be used as C-space preprocessing tools in problems beyond traditional motion planning

Probabilistic Roadmap Planner

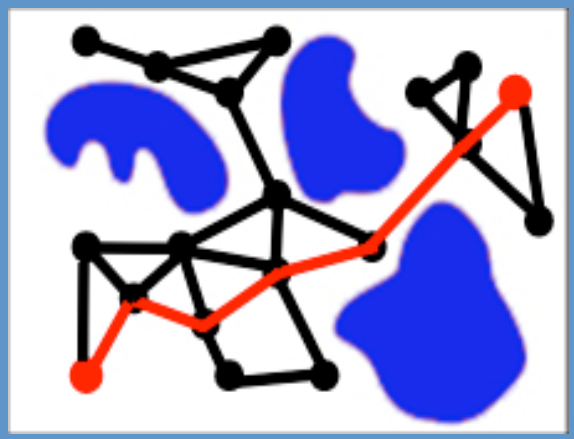
[Kavraki, Svestka, Overmars, Latombe '96]



C-space



Sampling



Roadmap

Probabilistic Roadmap Planner

- Important Elements-Data Structures in OOPSMP implementation:
  - Inner classes
    - EdgeData: Edge cost, Local path, etc.
    - VertexData: State, Node id, etc.
    - PathIterator
    - StateIterator
  - A roadmap: ***Graph_t m_roadmap***
  - A disjoint set: ***DisjointSet<int>* m_disjointSet***
  - Search graph: ***SearchGraph_t m_searchGraph***
  - Proximity Info: ***ProximityKeyPointer_t m_proximity***

ProximityQuery<OOPSMPpointer_t> m_proximityQuery

ProximityResults<OOPSMPpointer_t> m_proximityResults

Functionality

- clear()
- **preprocess(double ptime)**
- solve(double ptime)

```
void OOPSMP::PRM::preprocess(const double rtime)
{
    OOPSMPclock_t clk;
    double        t = 0.0;

    OOPSMPset_start_time(&clk);

    m_undirected = getCoreRobotData()->getPathGenerator()->isPathReversible();

    if(m_minNrSamples > 0 && m_roadmap->getNrVertices() < m_minNrSamples)
    {
        printf("time left = %f\n", rtime);
        printf("   current and min nr. samples = %5d %5d\n",
               m_roadmap->getNrVertices(), m_minNrSamples);
1.      generateManySamples(m_minNrSamples - m_roadmap->getNrVertices(), rtime);
        printf("   current and min nr. samples = %5d %5d\n",
               m_roadmap->getNrVertices(), m_minNrSamples);
    }

    if((t = OOPSMPelapsed_time(&clk)) < rtime && m_idConnectSample < m_roadmap->getNrVertices()
    {
        printf("time left = %f\n", rtime - t);
2.      connectSamples(rtime - t);
    }

    if((t = OOPSMPelapsed_time(&clk)) < rtime)
    {
        printf("time left = %f\n", rtime - t);
        printf("   begin generating additional samples and connections\n");
3.      generateAndConnectSamples(rtime - t);
        printf("   end   generating additional samples and connections %5d..%5d\n",
               m_idConnectSample, m_roadmap->getNrVertices());
    }
}
```

Functionality

preprocess(double ptime)

1. generateManySamples(int n, double rtime)

```
int OOPSMP::PRM::addSample(OOPSMP::State_t x)
{
    const int    id = m_roadmap->getNrVertices();
    VertexData_t v  = new VertexData(id, x);

    m_roadmap->addVertex(id, v);
    m_proximity->addKey(v);
    if(m_undirected)
        m_disjointSet->make(id);
    return id;
}
```

```
void OOPSMP::PRM::generateManySamples(
{
    CoreRobotData_t      crd = getCoreR
    ValidStateSampler_t  vss = crd->getV
    StateSpace_t         ss  = crd->getS
    State_t              x   = ss->alloc
    int                  i   = 0;
    double               t   = 0.0;
    OOPSMPclock_t        clk;

    OOPSMPset_start_time(&clk);
    while(i < n && (t = OOPSMPelapsed_time(&clk)) < rtime)
        if(vss->sample(x, rtime - t))
        {
            addSample(x);
            x = ss->allocState();
            i++;
        }
    ss->freeState(x);
}
```

Update the 3 data structures

```
void OOPSMP::PRM::addEdge(const int idFrom, const int idTo, OOPSMP::Path_t path)
{
    m_roadmap->addEdge(idFrom, idTo, new EdgeData(path));
    if(m_undirected)
    {
        assert(path->isReversible());
        m_roadmap->addEdge(idTo, idFrom, new EdgeData(path->reverse()));
        m_disjointSet->join(idFrom, idTo);
    }
}
```

```
void OOPSMP::PRM::connectSample(const int idFrom, const int k)
{
    if(m_proximity->isDataStructureConstructed() == false)
    {
        printf(" begin constructing proximity data structure: %d\n", m_roadmap->getNrVertices());
        m_proximity->setKeyDistFn(proximityKeyDistFn, getCoreRobotData()->getStateSpace());
        m_proximity->constructDataStructure();
        printf(" end   constructing proximity data structure\n");
    }

    LocalPlanner_t localPlanner = getCoreRobotData()->getLocalPlanner();
    VertexData_t   vFrom        = dynamic_cast<VertexData_t>(m_roadmap->getVertexData(idFrom));
    Path_t         path         = NULL;

    m_proximityQuery.setNrNeighbors(k);
    m_proximityQuery.setKey(vFrom);
    m_proximity->knearest(&m_proximityQuery, &m_proximityResults, NULL);

    const int nrResults = m_proximityResults.getNrValidResults(HUGE_VAL);
    for(int i = 0; i < nrResults; i++)
    {

        VertexData_t vTo = (VertexData_t) (m_proximityResults.getKey(i));
        if(shouldAddEdge(idFrom, vTo->m_id) &&
           (path = localPlanner->generateValidForwardConnectPath(vFrom->m_x, vTo->m_x)))
            addEdge(idFrom, vTo->m_id, path);
    }
}
```

Compute neighbors

If local path is free, then add edge

Functionality

preprocess(double ptime)

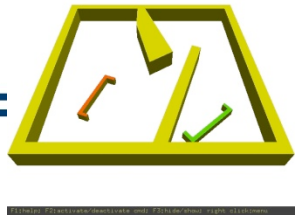
1. generateManySamples(int n, double rtime)
2. connectSamples(double time)
3. generateAndConnectSamples(double rtime)

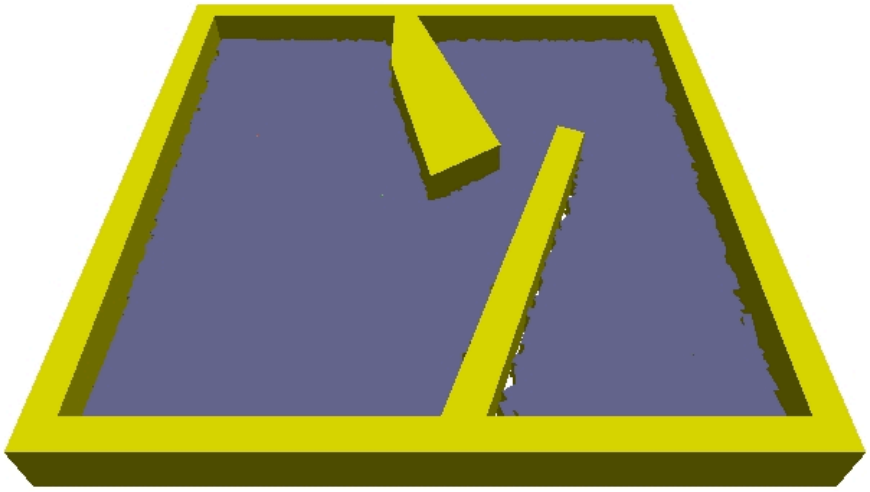
```
void OOPSMP::PRM::generateAndConnectSamples(const double rtime)
{
    OOPSMPclock_t clk;
    int           nrVertices  = m_roadmap->getNrVertices();

    OOPSMPset_start_time(&clk);
    for(double t = rtime; t > 0.0; t -= OOPSMPelapsed_time(&clk))
    {
        OOPSMPset_start_time(&clk);
        if(m_maxNrSamples < 0 || nrVertices < m_maxNrSamples)
        {
            generateSamples(t * m_fractionSamplingTime);
            nrVertices = m_roadmap->getNrVertices();
        }
        if(m_idConnectSample < nrVertices)
            connectSamples(t - OOPSMPelapsed_time(&clk));

        if(m_maxNrSamples >= 0 && nrVertices >= m_maxNrSamples && m_idConnectSample >= nrVertices)
            break;
    }
}
```

Example





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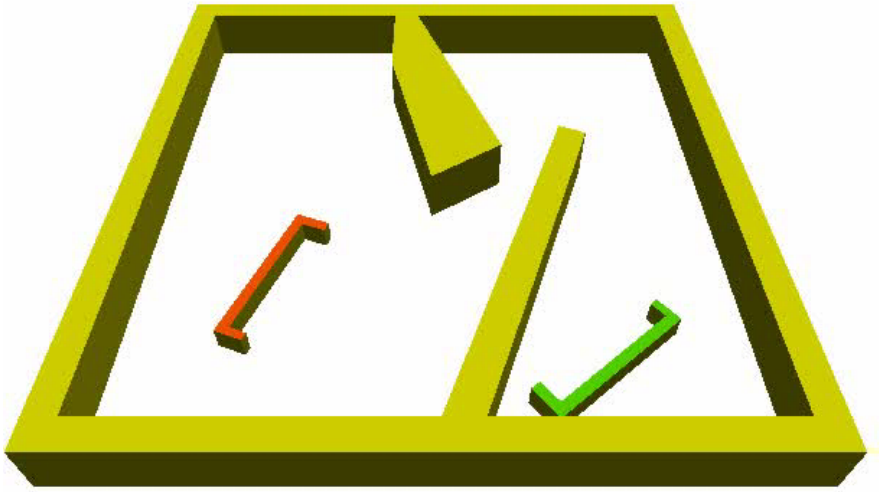

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Directions in Roadmap Planning

- Guarantee coverage and connectivity with a small number of nodes

[Simeon, Laumond, Nissoux '00] - [Geraerts, Overmars '04] - [Amato et al. '06] etc.

Example Case:

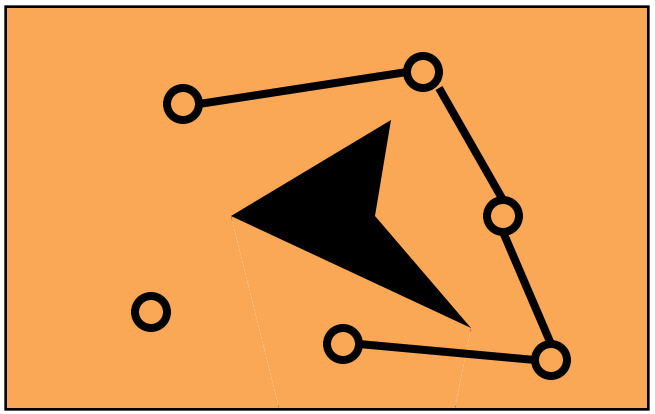
- Visibility-based PRM
  - Add samples only if they are:
    - Guards

(cannot by connected to roadmap nodes)

    - Connectors

(connect at least two disconnected components of the roadmap)

  - Stop when M attempts to add a node have failed
    - Natural probabilistic criterion (1-1/M prob. of covering the space)
  - Small roadmaps



First Steps in Extending a Planner

1. Create a new class that just extends the planner without any functionality

```
#ifndef OOPSMP_MOTION_PLANNERS_PRM_FOO_PRM__OOPSMP_FOO_PRM_H_
#define OOPSMP_MOTION_PLANNERS_PRM_FOO_PRM__OOPSMP_FOO_PRM_H_

#include "MotionPlanners/PRM/OOPSMPPRM.H"

namespace OOPSMP
{
    ForwardClassDeclaration(FooPRM);

    class FooPRM : public PRM
    {
    public:

        FooPRM(void) : PRM()
        {}
        virtual ~FooPRM(void)
        {}

    };

    DeclareInstanceFactory(FooPRM, PRMFactory);
}
```

2. If y
3. Cr
4. Ac re
   cc
5. Make sure compiles and runs – the old planner should be called and ex

```
#include "MotionPlanners/PRM/FooPRM/OOPSMPFooPRM.H"

BeginImplementInstanceFactory(FooPRM, PRMFactory);
EndImplementInstanceFactory(FooPRM);
```

First Steps in Extending a Planner

1.
```
#include "Graphics/GMotionPlanners/GPRM/GFooPRM/OOPSMPGFooPRM.H
BeginImplementInstanceFactory(GFooPRM, GPRMFactory);
EndImplementInstanceFactory(GFooPRM);
```
out any

2. If you want, create the equivalent graphical version

3.
```
#ifndef OOPSMP_GRAPHICS_GMOTION_PLANNERS_GPRM_GFOOPRM__OOPSMP_GFOOPRM_H
#define OOPSMP_GRAPHICS_GMOTION_PLANNERS_GPRM_GFOOPRM__OOPSMP_GFOOPRM_H
```

4.
```
#include "Graphics/GMotionPlanners/GPRM/OOPSMPGPRM.H"
#include "MotionPlanners/PRM/FooPRM/OOPSMPFooPRM.H"

namespace OOPSMP
{
    ForwardClassDeclaration(GFooPRM);

    class GFooPRM : public GPRM
    {
    public:

        GFooPRM(void) : GPRM()
        {}

        ~GFooPRM(void)
        {}

    };

    DeclareInstanceFactory(GFooPRM, GPRMFactory);
}
```

5. lled

```
   <call fn="setMotionPlanner"><arg type="pointer">
      <factory instance="FooPRM">

   <call fn="setProximity"><arg type="pointer">
      <factory instance="GNATProximityKeyPointer">
</factory>


   </arg></call>

   <call fn="setNrNeighborsSample"><arg type="int">15</arg></call>
   <call fn="setNrNeighborsQuery"> <arg type="int">50</arg></call>

   <call fn="allowCycles"><arg type="bool">false</arg></call>

   <call fn="setFractionSamplingTime">
      <arg type="double">0.2</arg>
   </call>

   <call fn="setMinMaxNrSamples">
      <arg type="int">2000</arg>
      <arg type="int">5000</arg>
   </call>

</factory>


   </arg></call>

   <call fn="setGMotionPlanner"><arg type="pointer">
      <factory instance="GFooGPRM">
</factory>
```

```
AUX_SOURCE_DIRECTORY(../MotionPlanners SRC_MOTION_PLANNERS)
AUX_SOURCE_DIRECTORY(../MotionPlanners/PRM SRC_PRM)
AUX_SOURCE_DIRECTORY(../MotionPlanners/PRM/FooPRM SRC_FooPRM)
AUX_SOURCE_DIRECTORY(../MotionPlanners/PRM/VisPRM SRC_VisPRM)
AUX_SOURCE_DIRECTORY(../MotionPlanners/PRM/VisPRM/SPR SRC_SPR)
AUX_SOURCE_DIRECTORY(../MotionPlanners/TreePlanner SRC_TREE_PLANNER)
AUX_SOURCE_DIRECTORY(../MotionPlanners/TreePlanner/RRT SRC_RRT)
AUX_SOURCE_DIRECTORY(../MotionPlanners/TreePlanner/EST SRC_EST)
AUX_SOURCE_DIRECTORY(../MotionPlanners/BiTreePlanner SRC_BI_TREE_PLANNE
SET(AUX_COMPLETE_SRC_MOTION_PLANNERS
        ${SRC_MOTION_PLANNERS}
        ${SRC_PRM}
        ${SRC_FooPRM}
        ${SRC_VisPRM}
        ${SRC_SPR}
        ${SRC_TREE_PLANNER}
        ${SRC_RRT}
        ${SRC_EST}
```

3. Create an input file that calls the new class

4. Add the new classes in the CMakeLists.txt so that they are compiled

5. Make sure compiles and runs – the old planner should be called and executed properly

First Steps in Extending a Planner

1. Create a new class that just extends the planner without any functionality

2. If you want, create the equivalent graphical version

3. Create an input file that calls the new class

4. Add the new classes in the CMakeLists.txt so that they are compiled

5. Make sure OOPSMP compiles and runs the new algorithms: the old planner should be called and executed properly

Visibility PRM Functionality

Algorithm

$ntry \leftarrow 0$
While $(ntry < M)$
  Select a random free configuration q
  $guard \leftarrow \emptyset; G_{vis} \leftarrow \emptyset$
  For all components G_i of $Guard$ **do**
    $found \leftarrow FALSE$
    For all nodes g of G_i **do**
      If(q belongs to $Vis(g)$) **then**
        $found \leftarrow TRUE$
        If $(\neg guard))$ **then** $guard \leftarrow g$; $G_{vis} \leftarrow G_i$
        Else /* *q is a connection node* */
          Add q to *Connection*
          Create edges (q, g) and $(q, guard)$
          Merge components G_{vis} and G_i;
    until $found = TRUE$
    If $(\neg guard)$ **then**/* *q is a guard node* /*
      Add $\{q\}$ to *Guard*; $ntry \leftarrow 0$
    Else $ntry \leftarrow ntry + 1$
End

[Simeon, Laumond, Nissoux '00]

Data Structures – Necessary Info

```
class GuardVisibility
{
    friend class VisPRM;
    friend class SPR;

protected:
    int nr_connections;    // the number of roadmap nodes from different connected components
                           // that the current sample is visible from
    int* connections;      // the indices of the nodes from different connected components that can
                           // view the state
    Path_t* paths;         // the paths that connect the state to roadmap nodes which can "see" the state

    int allocated;         // number of allocated connections and paths

public:
    GuardVisibility()
    {}

    ~GuardVisibility()
    {}

    void clearGuardVisibility()
    {}

    void addConnection( int index, Path_t path )
    {}

    // is the current state a guard
    bool isGuard() { return (nr_connections == 0); }

    // is the current state a connector
    bool isConnector() { return (nr_connections >= 2); }

};
typedef GuardVisibility* GuardVisibility_t;
```

```
// is the sampled state already visible from a roadmap on the same
// component as the the node: "node_index"?
bool OOPSMP::VisPRM::isNodeVisibleFromComponent( int node_index )
{
    // is the state already visible by a node in the same component as the i-th node?
    bool not_visible_from_component = true;

    for( int i=0; not_visible_from_component == true && i<g_vis->nr_connections; i++ )
        if( m_disjointSet->same( g_vis->connections[i], node_index ) == true )
            not_visible_from_component = false;

    return not_visible_from_component;
}
    int nrVertices  = m_roadmap->getNrVertices();

    // a temporary variable to remember paths
    Path_t path = NULL;

    // iterate over all nodes
    for( int i=0; i<nrVertices; i++ )
    {
        State_t vTo = (State_t) ((VertexData_t) m_roadmap->getVertexData(i))->m_x;

        // is the state already visible by a node in the same component as the i-th node?
        bool notVisibleFromComponent = isNodeVisibleFromComponent( i );

        // consider the i-th roadmap node only if the state is not already
        // visible by a node in the same component like the i-th node
        if( notVisibleFromComponent == true )
        {
            //  check whether the i-th node is able to "view" the state
            if( (path = lp->generateValidForwardConnectPath( state, vTo )) )
                g_vis->addConnection( i, path );
        }
    }
}
```

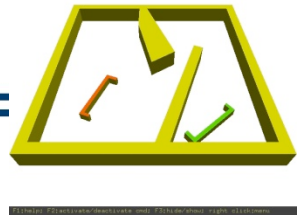
```
CoreRobotData_t     crd     = getCoreRobotData();
ss      = crd->getStateSpace();                  // State Space
vss     = crd->getValidStateSampler();           // Valid State Sampler
lp      = getCoreRobotData()->getLocalPlanner(); // Local Planner
```

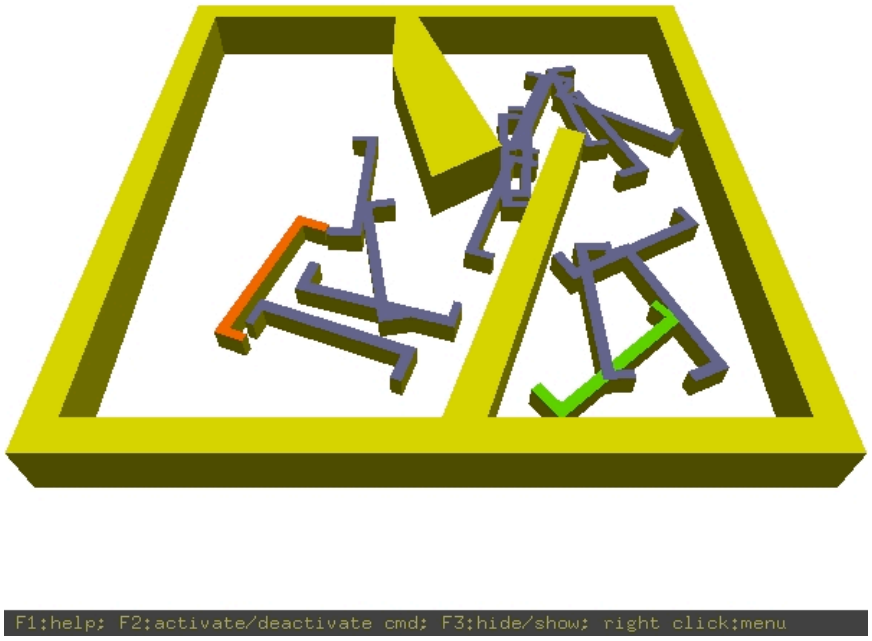
```
// initial number of efforts to add a guard/roadmap node is 0
int nr_tries = 0;

g_vis = new GuardVisibility( );

// keep trying while we have not exceeded the
// maximum number of failed attempts to add a guard
while( nr_tries < max_tries )
{
    // sample a random valid state
1.  sampleState( );

    // compute the nodes from different connected components that can view the sample
2.  computeGuardVisibility( );

    if( g_vis->isGuard() || g_vis->isConnector() ) // this is a guard or a "connection" node
    {
        nr_tries = 0;
3a.     addGuard();
    }
    else
    {
3b.     ss->freeState( state );
        nr_tries++;                 // another failed attempt to add a new node
    }

    g_vis->clearGuardVisibility();
}

delete( g_vis );
```

```
void OOPSMP::VisPRM::sampleState( )
{
    state    = ss->allocState();
    vss->sample( state );
}
```

```
// add the sampled state as a guard
void OOPSMP::VisPRM::addGuard()
{
    int node_index = m_roadmap->getNrVertices();
    addSample( state );
    for( int i=0; i<g_vis->nr_connections; i++ )
        addEdge( node_index, g_vis->connections[i], g_vis->paths[i] );
}
```

Example

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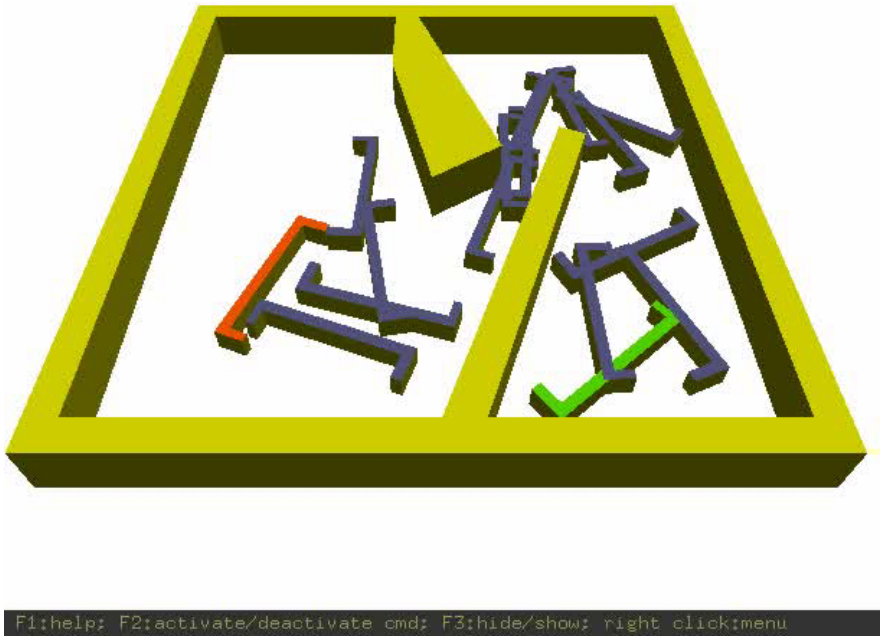
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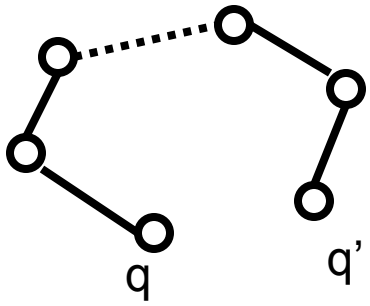
Developing New Planners

- Quality of paths returned by previous techniques is low
  - Can we improve path quality returned directly by the planner
    - Before smoothing
  - Retain connectivity and coverage properties of VisPRM

[Jaillet, Simeon '06] – [Geraerts, Overmars '05-'07] etc.

Useful Edge Criterion [Nieuwenhuisen, Overmars '04]



Is edge (q,q') useful?

Yes, if: $K \cdot d(q,q') < G(q,q')$
d(q,q'): C-space distance
G(q,q'): graph distance (∞ if no path)

Graph Theory: Spanner Graph

- A sub-graph G' is a spanner of a graph G if:

$$\pi_{G'}(p,q) \leq s^* \pi_G(p,q)$$

for constant s and for all pairs of nodes p and q in G, where $\pi_G(p,q)$ denotes the shortest path distance between p and q in the graph G.

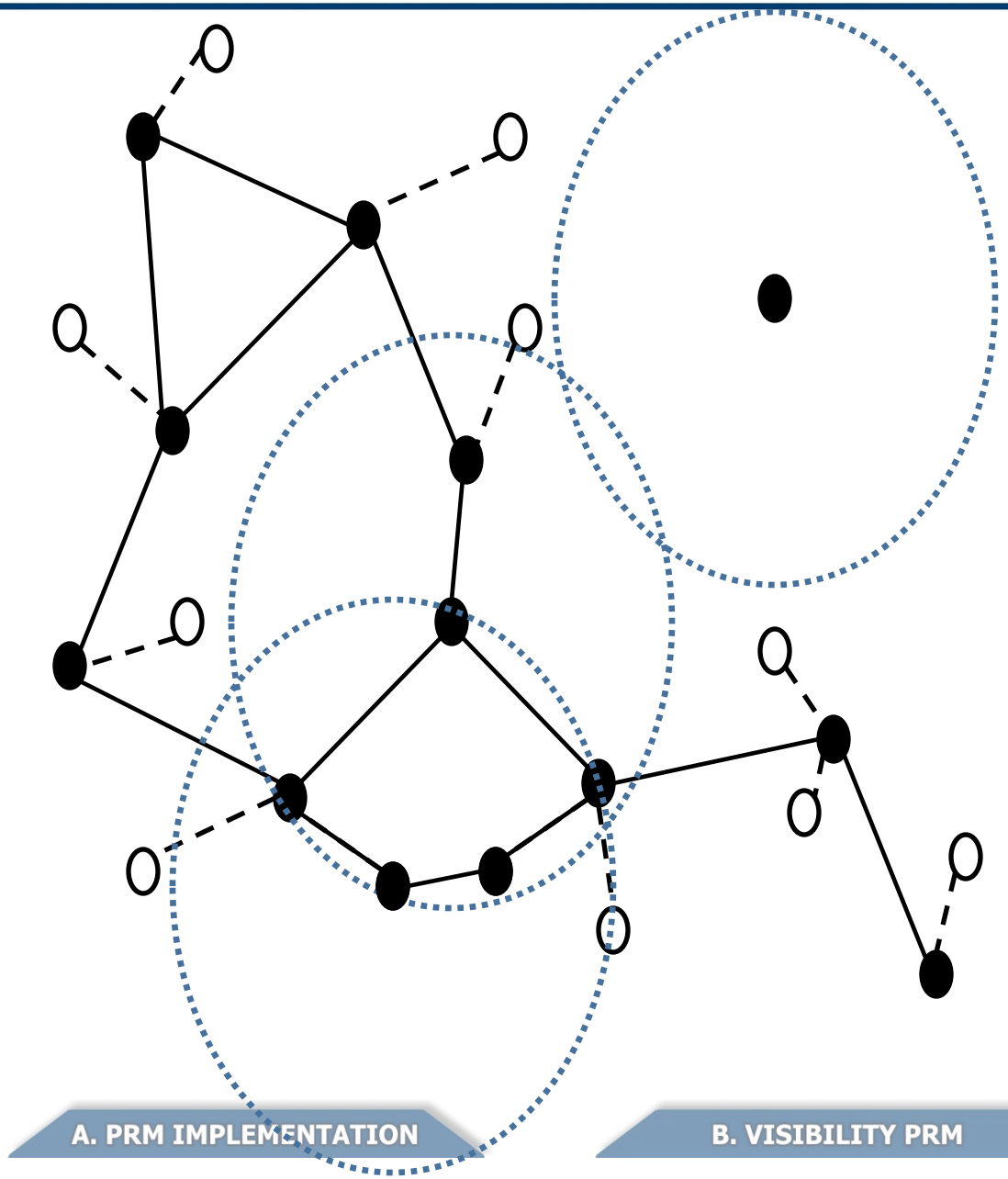
Direction:

Implicitly and incrementally build a spanner of the full graph defined by the sampled configurations

(Based on incremental spanner graph construction by [Baswana, Sen '08])
(Read more about incremental spanners: [Gao, Guibas, Nguyen '04])

Spanner Roadmaps

Objective: Small roadmaps with guarantees about path quality (bounded by K*optimal)



A. PRM IMPLEMENTATION

B. VISIBILITY PRM

- We store the failed samples
  - Defines a bipartite graph
  - The roadmap is a skeleton (spanner graph) of the complete graph
- Nodes have visibility limits
- Nodes are still added as guards and connectors
- Cycles are allowed and added between roadmap nodes
- Secondary nodes can later be inserted into the roadmap by defining a useful cycle

```
// the class to store the information of samples that are not added
// directly to the roadmap
// these states may be added later on to the roadmap
class SecondaryNode
{
    friend class SPR;

protected:
    State_t state;
    int guardIndex;
    double distance;
    bool isAdded;

public:
    SecondaryNode( State_t st = NULL, int gIn = -1, double dis = 0 )
    { setInfo( st, gIn, dis ); }
    virtual ~SecondaryNode()
    {}

    State_t getState() { return state; }
    int getGuard() { return guardIndex; }
    double getDistance() { return distance; }
    bool hasBeenAdded() {return isAdded; }

    void setInfo( State_t st, int gIn, double dis )
    {   state = st;   guardIndex = gIn;   distance = dis;  isAdded = false; }
    void setNewGuard( int gIn, double dis )
    {  guardIndex = gIn;    distance = dis; }

    void addAsGuard()
    { isAdded = true; }
};
typedef SecondaryNode* SecondaryNode_t;
```

```
// initial number of efforts to add a guard/roadmap node is 0
int nr_tries = 0;

allocateProximityStructures();

g_vis = new GuardVisibility( );
// keep trying while we have not exceeded the
// maximum number of failed attempts to add a guard
while( nr_tries < max_tries )
{
    // sample a random valid state
    sampleState( );
    // compute the nodes from different connected components that can view the sample
    computeGuardVisibility( );

    bool added = true;
    if( g_vis->isGuard() || g_vis->isConnector() ) // this is a guard or a "connection" node
        addGuard();
    else
        added = false;
    if( added )
    {
        int latest_sample_index = m_roadmap->getNrVertices() - 1;

        // connect to other roadmap nodes to create useful cycles
        addUsefulCycles( latest_sample_index );

        // change the guard info of the closest secondary nodes
        updateGuards( stateNode, latest_sample_index );
    }
    // check neighboring upgrade nodes for upgrades
    added = checkForUpgrades( stateNode, added );

    if( !added )
    {
        addSecondaryNode( stateNode );
        nr_tries++;      // another failed attempt to add a new node
    }
    else
    {
        nr_tries = 0;
        delete( stateNode );
    }
```

1.
2.
3.
4.
5.
6.
7a.
7b.

4. Adding Useful Cycles

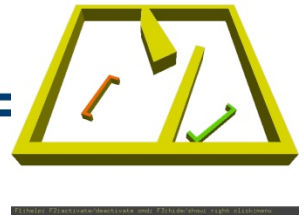
```
void OOPSMP::SPR::addUsefulCycles( int nodeIndex )
{
    Path_t path;

    // the state at the nodeIndex
    VertexData_t vFrom = dynamic_cast<VertexData_t>(m_roadmap->getVertexData(nodeIndex));
    State_t sFrom      = (State_t) vFrom->m_x;

    // find the 20 closest neighbors to nodeIndex
    m_proximityQuery.setNrNeighbors( 10 );
    m_proximityQuery.setKey( vFrom );
    m_proximity->knearest( &m_proximityQuery, &m_proximityResults, NULL );
    const int nrResults = m_proximityResults.getNrValidResults(HUGE_VAL);

    // iterate over the neighbors as long as their distance is less than distVis
    // attempt to add an edge if we have a useful cycle:  K * state_dis < graph_dis
    double stateDis = 0, graphDis;
    for( int i = 0; i < nrResults && stateDis < distVis; i++ )
    {
        VertexData_t vTo = (VertexData_t) (m_proximityResults.getKey(i));
        State_t sTo      = (State_t) vTo->getState();
        int toIndex      = vTo->getId();

        graphDis = graphDistance( nodeIndex, toIndex );
        stateDis = ss->distanceStates( sFrom, sTo );

        if( K * stateDis < graphDis )
            if( (path = lp->generateValidForwardConnectPath( sFrom, sTo ) ) )
                addEdge( nodeIndex, toIndex, path );
    }
}
```

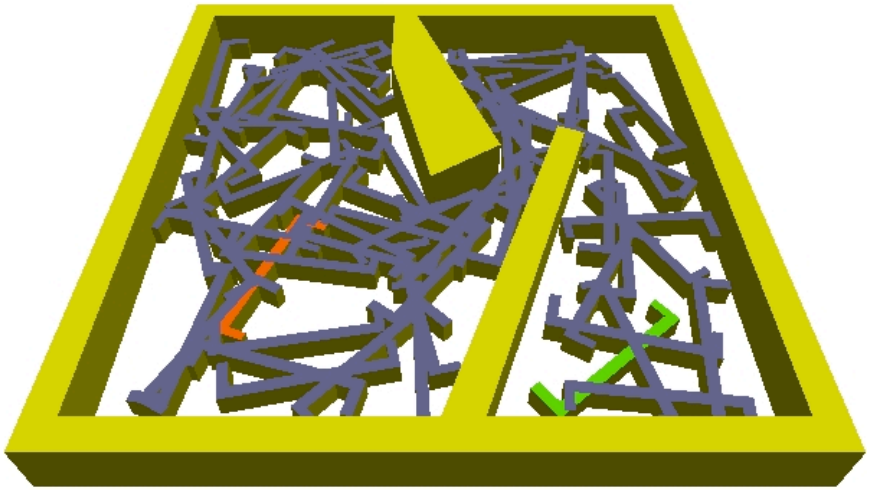
5/6: Dealing with Secondary Nodes

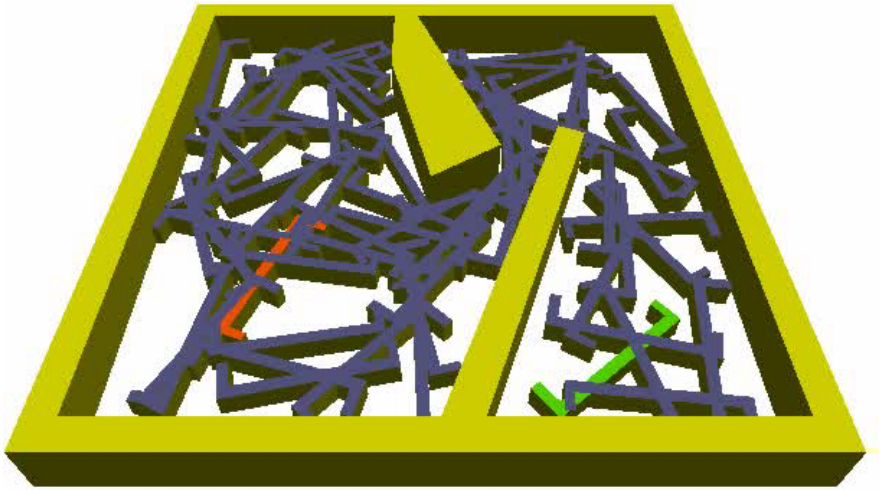
```
void OOPSMP::SPR::allocateProximityStructures()
{
    if( m_proximity->isDataStructureConstructed() == false )
    {
        m_proximity->setKeyDistFn( proximityKeyDistFn, getCoreRobotData()->getStateSpace() );
        m_proximity->constructDataStructure();
    }

    if( sec_proximity->isDataStructureConstructed() == false )
    {
        sec_proximity->setKeyDistFn( secProximityKeyDistFn, getCoreRobotData()->getStateSpace() );
        sec_proximity->constructDataStructure();
    }
}
```

```
void OOPSMP::SPR::updateGuards( SecondaryNode_t stateNode, int nodeIndex )
{
    Path_t path;
    State_t staState = (State_t) stateNode->getState();

    // find the 100 secondary nodes closest to nodeIndex
    sec_proximityQuery.setNrNeighbors( 50 );
    sec_proximityQuery.setKey( stateNode );
    sec_proximity->knearest( &sec_proximityQuery, &sec_proximityResults, NULL );
    const int nrResults = sec_proximityResults.getNrValidResults(HUGE_VAL);

    // iterate over the neighbors as long as their distance is less than distVis
    double stateDis = 0;
    for( int i=0; i<nrResults && stateDis < distVis; i++ )
    {
        SecondaryNode_t secNode = (SecondaryNode_t) (sec_proximityResults.getKey(i));

        State_t secState = (State_t) secNode->getState();
        stateDis = ss->distanceStates( staState, secState );

        if( secNode->hasBeenAdded() == false )
            if( stateDis < secNode->getDistance() )
                if( (path = lp->generateValidForwardConnectPath( staState, secState ) ) )
                    secNode->setNewGuard( nodeIndex, stateDis );
    }
}
```

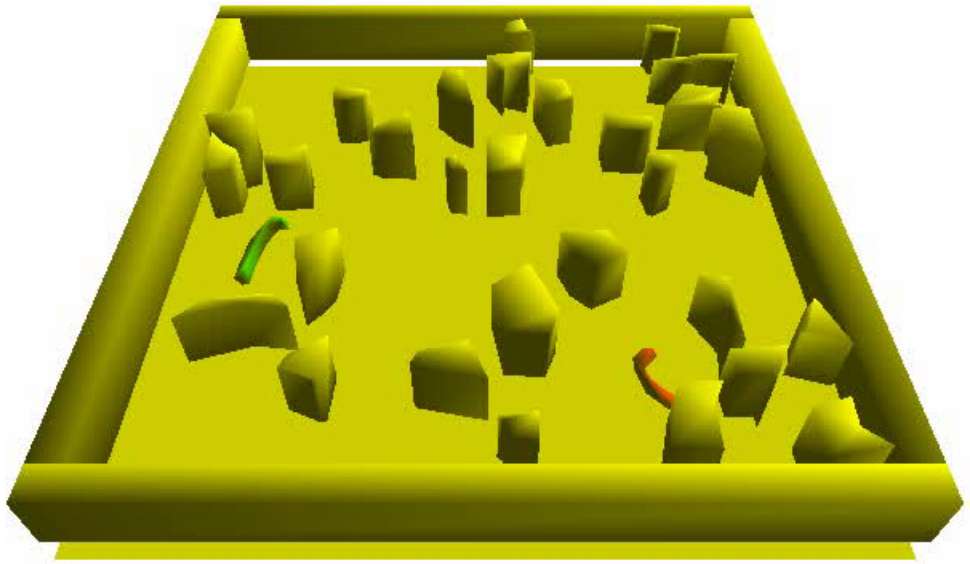
Example


F1:help; F2:activate/deactivate cmd; F3:hide/show; right click:menu

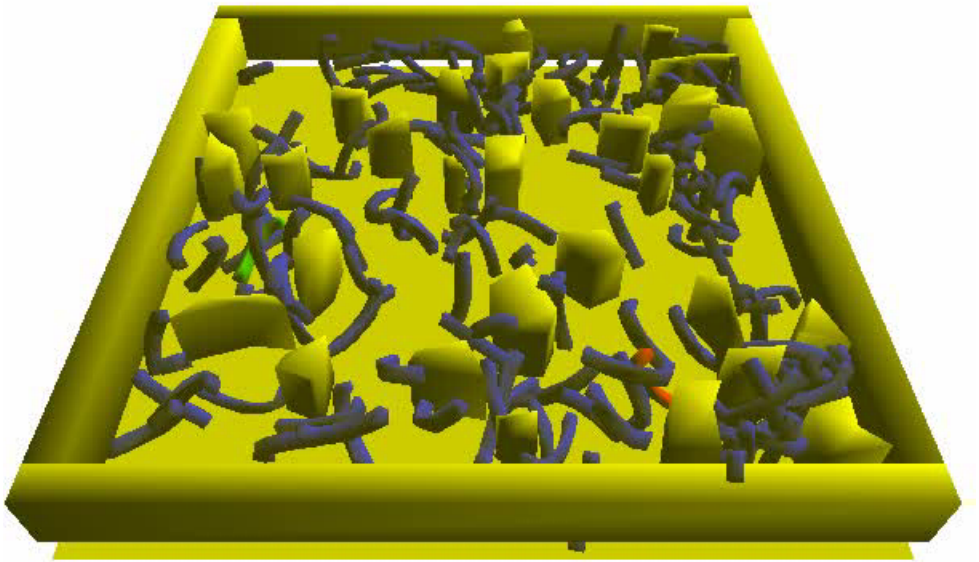

F1:help; F2:activate/deactivate cmd; F3:hide/show; right click:menu


F1:help; F2:activate/deactivate cmd; F3:hide/show; right click:menu

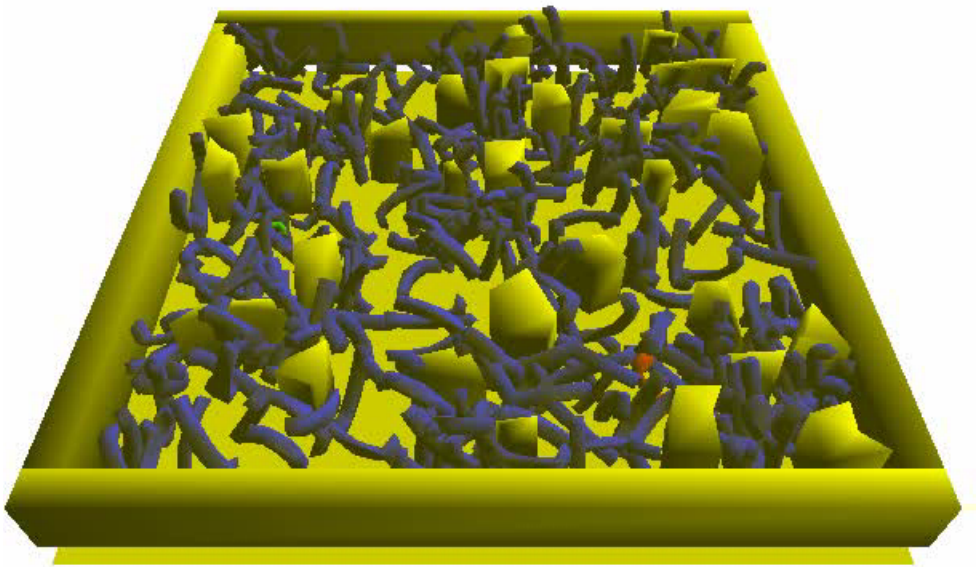
Example



Example


F1:help; F2:activate/deactivate cmd; F3:hide/show; right click:menu

Example


F1:help; F2:activate/deactivate cmd; F3:hide/show; right click:menu

Summary

- Using OOPSMP we showed that
  - Easy to create new roadmap planners
  - We can create more complicated but powerful algorithms given the basic planning modules in OOPSMP

- OOPSMP + ScetchUp allow
  - Common benchmarks and an easy way to construct new ones
  - An easy way to compare between alternative techniques using common tools (e.g., collision detection, state representation, local planner)
  - Simplify the process of designing new algorithms
  - And streamline the experimental process