Real-time Adaptive Robot Motion Planning in Unknown and Unpredictable Environments

Jing Xiao
IMI Lab, Dept. of Computer Science
University of North Carolina – Charlotte

Outline

- Problem and Context
- Basic RAMP Framework
- Extension and Application of RAMP
  - Multiple Mobile Manipulators
  - Nonholonomic Robot Vehicle
  - Mobile Robots in Pursuit and Evasion
  - Continuum Manipulator

Basic Problem

- Plan the motion of a robot from a starting location to reach a goal in an environment with *unknown obstacles or unknown obstacle motions*.
- The robot can have *high degrees of freedom and redundancy* (e.g., a mobile manipulator).
- Robot motion *planning has to be on-line based on sensing*.

Motion planning for robot manipulators (DOF ≥ 6): existing work

- Off-line planning in known environments using sampling-based approaches, such as variants of PRM and RRT.
- On-line modifying pre-planned paths in largely known environments to avoid new obstacles or obstacle motion.
- Motion objectives or goals are often fixed.
- Relatively little work on real-time motion planning in unknown and unpredictable environments.

Real-time Adaptive Motion Planning (RAMP) Paradigm [Vannoy&Xiao 04-08]

- Interweave planning, sensing, and execution of motion:
  - plan path and trajectory simultaneously
  - plan and execute motion simultaneously
- Global planning is inspired by the general *anytime* and *parallel* idea of evolutionary computation
- Adapt or change motion objectives on the fly based on need

Information from Sensing

- Target objects, obstacles, and their poses at each sensing instant. Obstacles may not have to be segmented or identified.

Two types of approaches to handle obstacles of unknown motion:

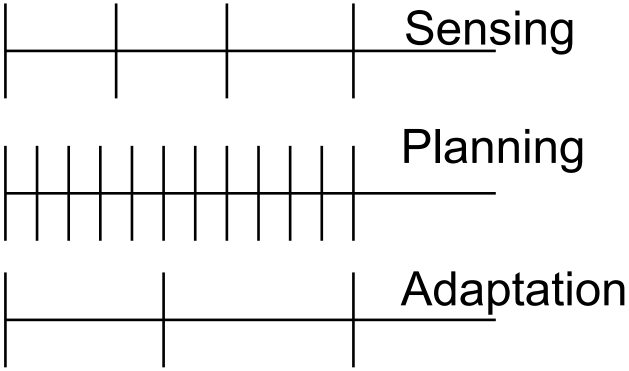
- Predict short-term obstacle trajectory based on time history of sensed obstacle poses – requiring obstacle identification
- Perceive if a robot at a pose at a future time will not collide with any obstacle no matter how obstacles move based on the concept of dynamic envelopes [Vatcha&Xiao08] – not requiring obstacle segmentation or identification

RAMP Algorithm

```
Initialize a set of trajectories P leading to the goal(s) and
    evaluate P based on initial sensed information
$\gamma \leftarrow$ best trajectory in P;

while goal is not reached do
    simultaneously move and plan:
    move along $\gamma$ unless forced to stop to avoid collision;

    plan:
    modify P
     if new sensing cycle then
         evaluate P;
     if new adaptation cycle then
         update starting configurations of P;
         evaluate P and update $\gamma$;
end while
```



The algorithm allows the robot to <u>smoothly</u> switch to a better trajectory at any time during execution

Trajectory Initialization

- Generate *m* trajectories in *P*:
  - either randomly or deliberately generate a path in terms of a sequence of knot configurations in the configuration space of the robot.
  - (optional) generate goal configuration(s)
  - generate trajectory under max. velocity and acceleration constraints
- Trajectory diversity in set *P* is important.

Evaluation

- Optimization criteria are different for completely feasible or partially feasible trajectories.

- Feasible (i.e., collision-free and singularity free): e.g.,
  - Minimize distance or time to goal
  - Minimize energy
  - Maximize manipulability
  - Maximize goodness of goal if there are alternative goals
- Partially feasible: e.g.,
  - Time or distance to first collision or singularity
  - Cost as if feasible + penalty

- Optimization criteria can be changed on the fly based on circumstances to steer planning in more effective directions.

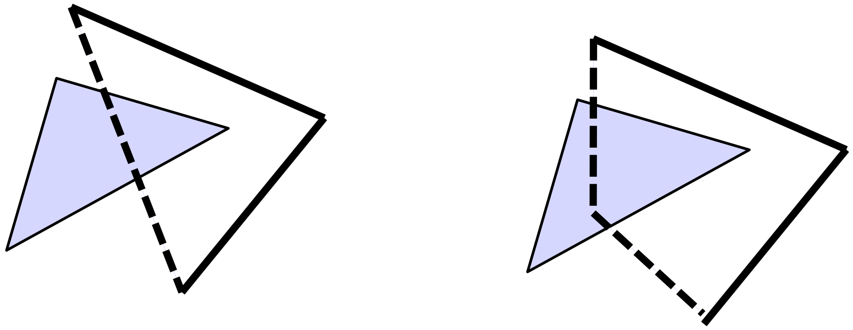
Modification

- Modify the shape of a path or create a new path by <u>generically random</u>

  insert, *delete*, *change*, *swap*, *crossover*

  and some <u>robot-specific random</u> operators

- Modified trajectory is evaluated and replaces randomly a non-best trajectory in *P* to promote the best while preserving diversity.



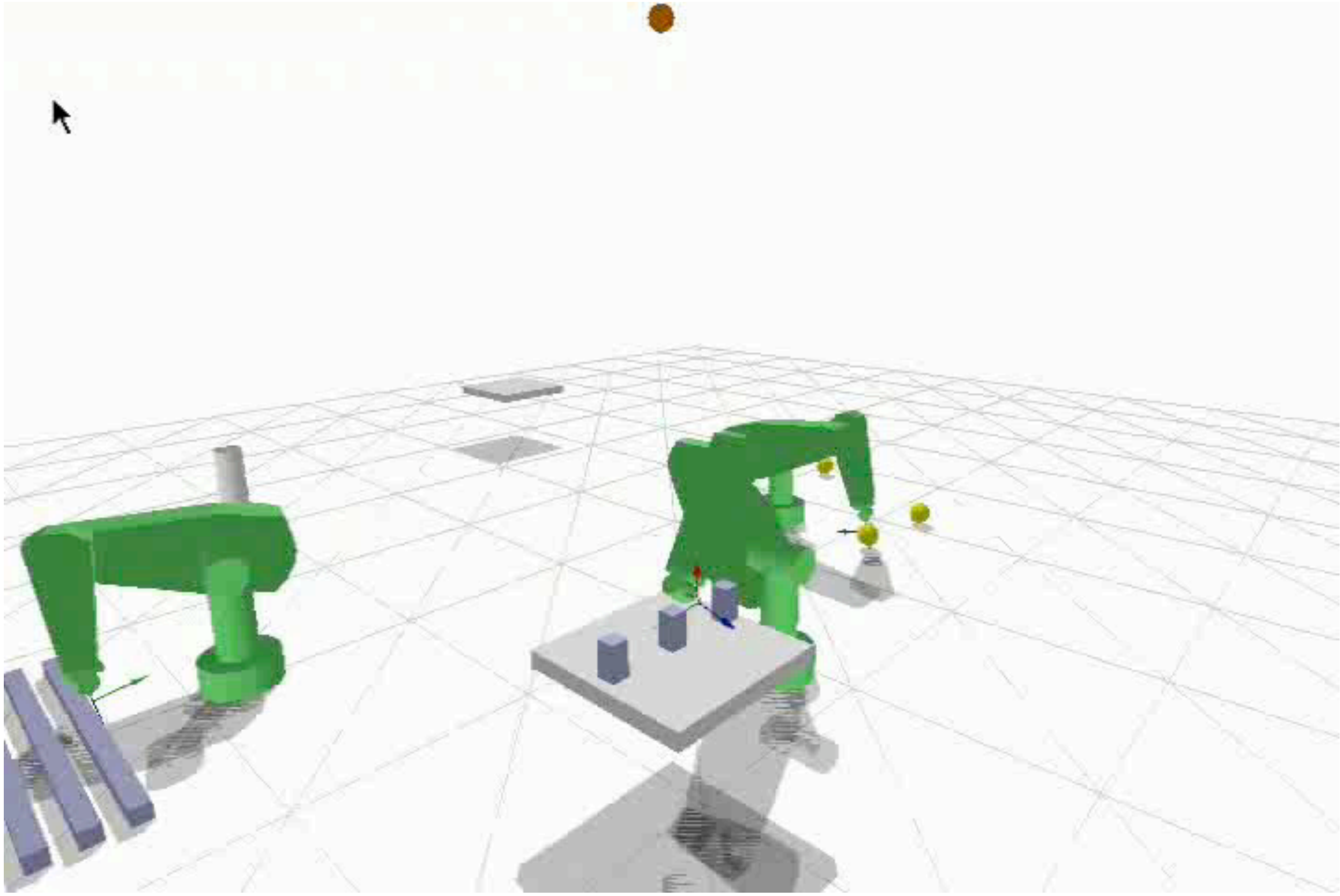
RAMP on Mobile Manipulators

- Trajectory: cubic-splined for arm and linear-with-parabolic-blends for base
- Special modification operator: random *stop* modifies the velocity profile to allow loose-coupling of the arm and the base for adaptive redundancy resolution

Loose Collaboration

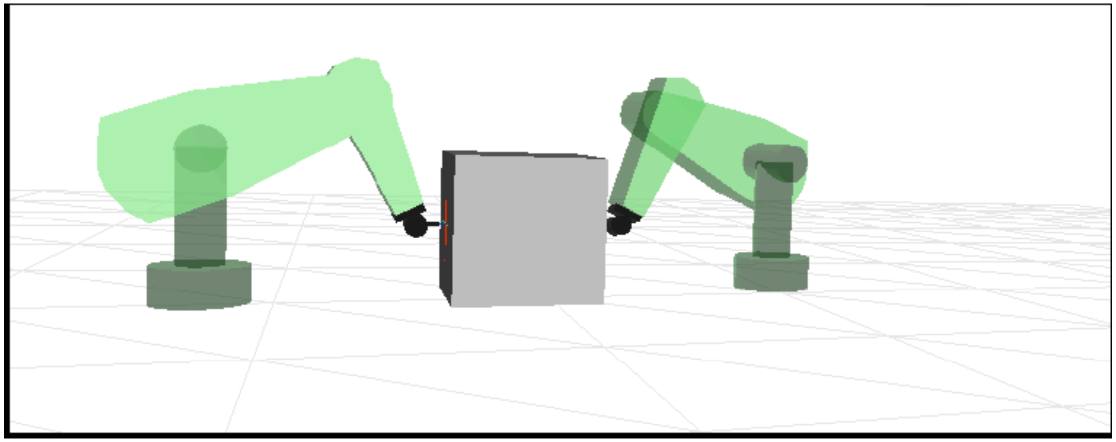
- Multiple Mobile manipulators pick up a large set of objects of unknown quantity and arrangement and move them to some destinations or re-arrange them.
- Every robot has its own RAMP planner and view other robots as obstacles with unknown motions. Real-time, distributed motion planning is achieved.
- Spontaneous division of work – each robot decides a target object for pick-up and a destination to put it down on the fly based on availability.

Examples



Tight Coordination

- Planning motion trajectories for two mobile manipulators moving and manipulating an object together through an environment with obstacles of unknown motion.
- Each mobile manipulator in the two-robot team is equipped with its own instance of the same real-time *leader-oriented planner*.



The Leader-oriented Planner

- Each mobile manipulator plans its motion as the leader with RAMP and then the other robot's motion as the helper's motion constrained by the leader's.
- The two robots run their planners in parallel at the same time as they move, but the actual motions that the robots execute are determined by a simple *coordinator* algorithm running on top of the two parallel planners.
- The coordinator constantly decides which robot's leader-helper motion plan is better and let the two-robot team to execute the better motion plan.
- At any time, the roles can be switched seamlessly as the robots always follow the better trajectories.

RAMP on Nonholonomic Robot Vehicle

- A robotic vehicle moves autonomously in an unknown environment guided by a GPS navigator and local sensing.
- The GPS system does not indicate the actual geometry of the road as well as small obstacles.
- The robot has to conduct on-line planning based on local sensing to produce collision-free nonholonomic trajectories for it to follow.

Approach

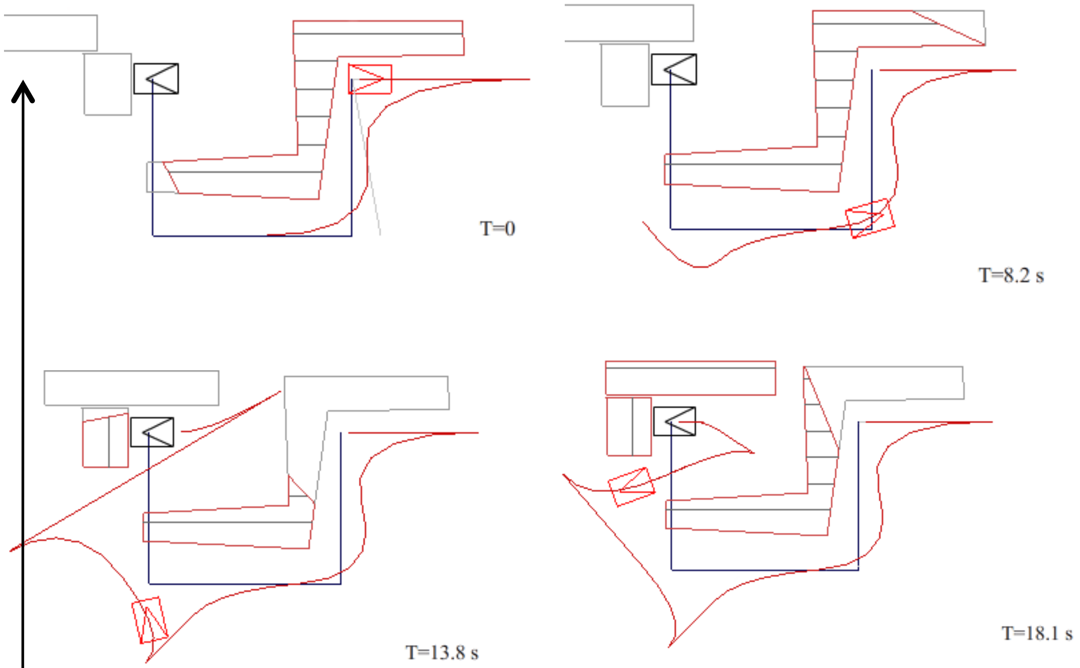
- Introduce a set of parameterized, basic maneuver patterns that our RAMP planner can use to build nonholonomic trajectories with arbitrary turns quickly in a piece-wise fashion.
- The maneuver patterns use Bezier curves, which allow both forward and backward driving of a vehicle with great flexibility,
  - can be modified analytically via control points – an advantage over clothoids, and
  - allow higher vehicle speeds than Reeds & Shepp curves.
- Special modification operators

Assumptions

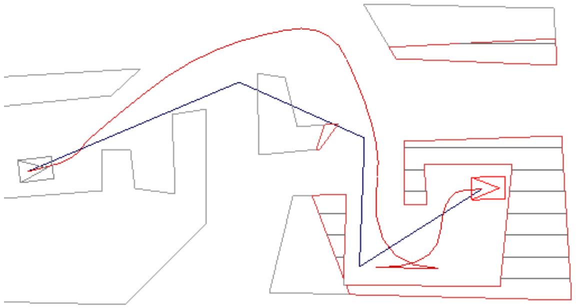
- A sequence of knot points are given (from GPS) that capture the topology of the path.
- Environment is unknown, but obstacles are visible if within sensing range.

Implementation Results

Example 1



Example 2



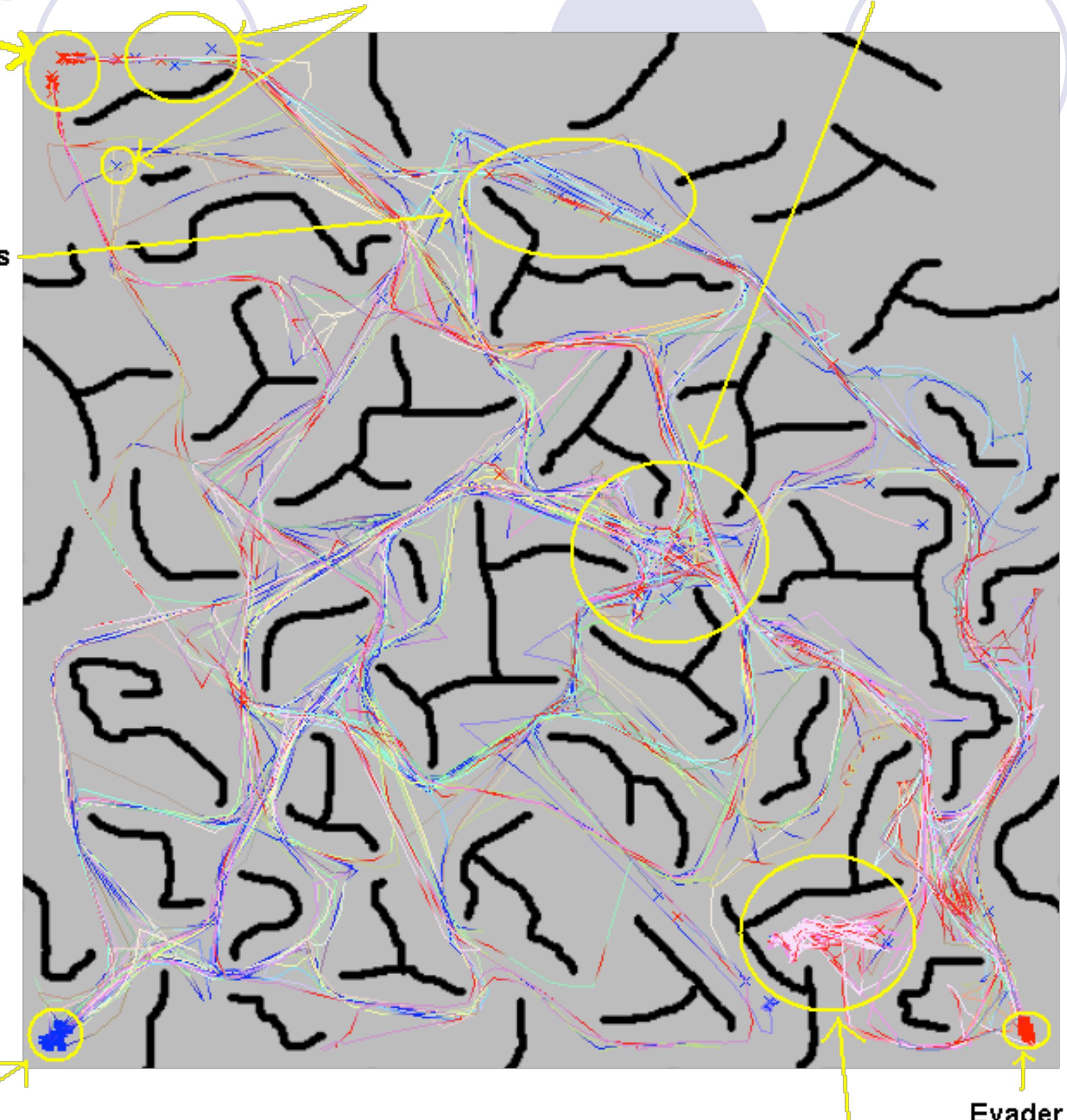
Note the quasi-static moving obstacle above

RAMP on Pursuit and Evasion

- Two mobile robots: one pursuer and one evader. Each moves in an initially unknown environment and relies on line-of-sight sensing to discover the environment and the other agent.
- The pursuer aims to catch the evader without knowing its motion and destination.
- The evader aims to reach its destination as quickly as possible while avoiding being caught by the purser.

Approach

- Each agent has a RAMP-based motion planner. Each agent is unaware of the other’s motion strategies.
- Optimization objectives are dynamically changed based on an agent's need:
  - escaping, goal-seeking, or hiding for the evader, and
  - chasing based on recent sighting or exploring possible evader locations for the pursuer.



Evader Success

Close Calls

Initial Confrontation

Pursuer Success

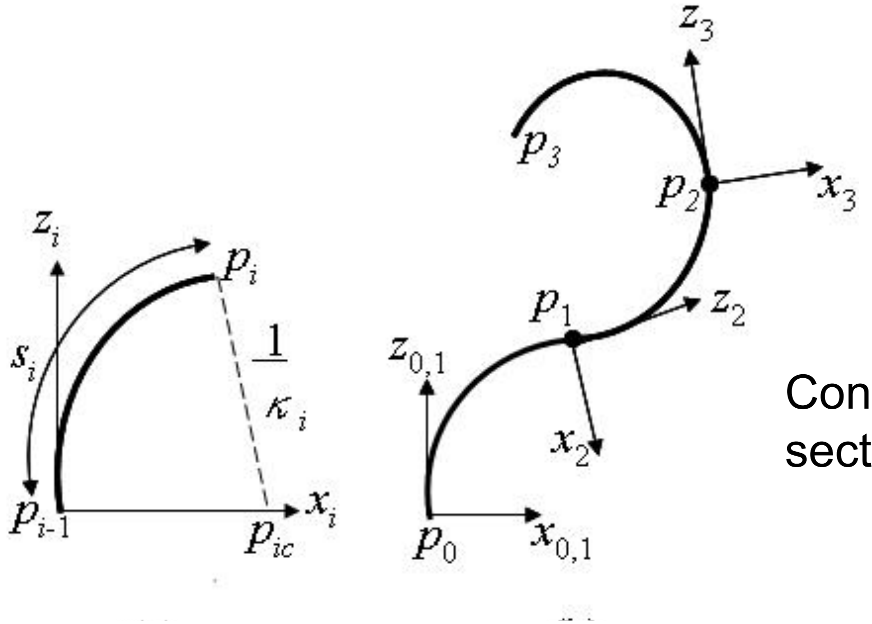
Pursuer Start

Evader Trap

Evader Start

RAMP on Continuum Manipulators

A continuum manipulator is inherently smooth and compliant and can deform almost everywhere.

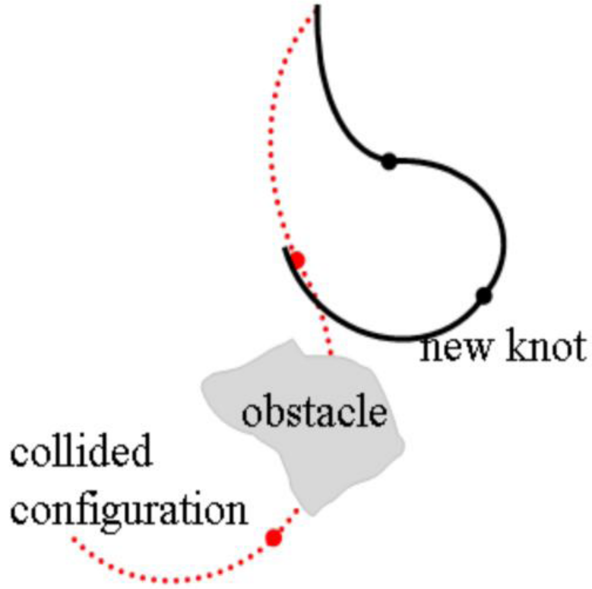


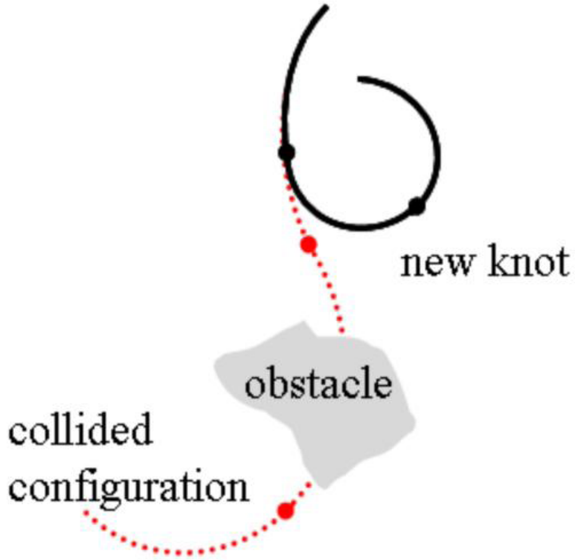
A three-section OctArm designed by Walker *et al.* at Clemson University

Configuration variables for each section: κ, s, ϕ

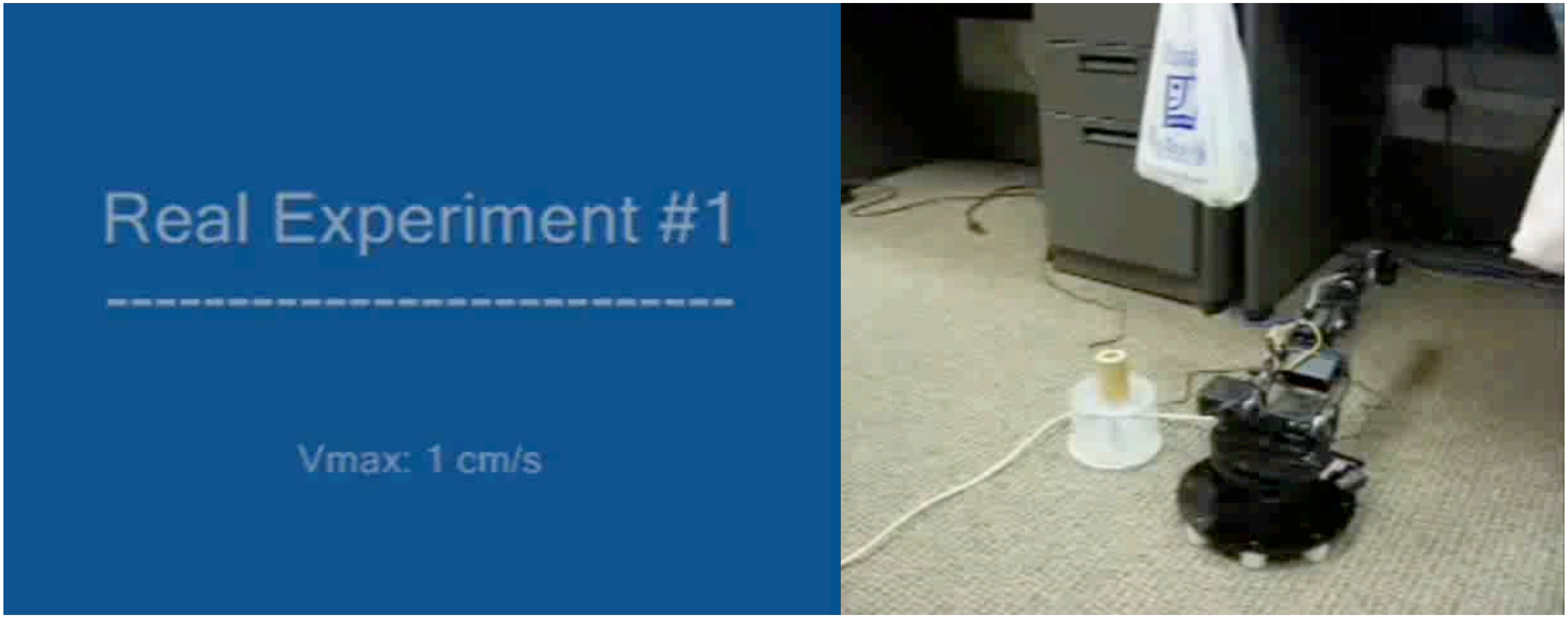
Special Features

- Goals must be generated and adapted along with the motion to reach a goal by the planner.
- Path/trajectory evaluation includes a unique distance metric and a goodness measure for goals.
- Special modification operators: repair and curl-up.





Some real experiments



7-DOF manipulator in unknown environment with stereo vision sensing. Obstacles are not segmented/identified.

Conclusions

- Introduced a general RAMP paradigm for on-line motion planning of high-DOF robots or teams of robots in unknown and unpredictable environments.
- Further work is on effective sensing and real-world testing of RAMP.
- Extend RAMP to incorporate compliant motion, especially for continuum robot manipulation.

Acknowledgement

- Dick Volz for guiding me into robotics research
- The work presented here is done mostly by my (former and current) students:
    - John Vannoy
    - Yanbo Li
    - Rayomand Vatcha
    - Jonathan Annas
- Work on continuum robots is a collaboration with Ian Walker's group
- The work has been supported by NSF grants.

References

- J. Vannoy and J. Xiao, "Real-time Adaptive Motion Planning (RAMP) of Mobile Manipulators in Dynamic Environments with Unforeseen Changes," *IEEE Transactions on Robotics , 24(5):1199-1212, Oct. 2008.*
- J. Vannoy and J. Xiao, "Real-time motion planning of multiple mobile manipulators with a common task objective in shared work environments," *IEEE International Conference on Robotics and Automation*, April 2007.
- J. Vannoy and J. Xiao, "Real-time Tight Coordination of Mobile Manipulators in Unknown Dynamic Environments," *IEEE/RSJ International Conference on Intelligent Robots and Systems,* Oct. 2007.
- R. Vatcha and J. Xiao, "Perceived CT-Space for Motion Planning in Unknown and Unpredictable Environments," *Proceedings of the 8th International Workshop on Algorithmic Foundations of Robotics (WAFR), Guanajuato, Mexico, Dec. 7--9, 2008.*
- Y. Li and J. Xiao, "On-line Planning of Nonholonomic Trajectories in Crowded and Geometrically Unknown Environments," *IEEE International Conference on Robotics and Automation, Kobe, Japan,* May 2009.
- J. Annas and J. Xiao, "Intelligent Pursuit & Evasion in an Unknown Environment," *IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, MO, Oct. 2009.*