Lecture slides for

Automated Planning: Theory and Practice

Chapter 20
Planning in Robotics

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What is a Robot?

- A machine to perform tasks
  - Some level of autonomy and flexibility, in some type of environment
  - Sensory-motor functions
    - » Locomotion on wheels, legs, or wings
    - » Manipulation with mechanical arms, grippers, and hands
  - Communication and information-processing capabilities
    - » Localization with odometers, sonars, lasers, inertial sensors, GPS, etc.
    - » Scene analysis and environment modeling with a stereovision system on a pan-and-tilt platform

Examples of Tasks and Environments

- Manufacturing tasks
  - painting, welding, loading/unloading a machine tool, assembling parts
- Servicing stores, warehouses, and factories
  - maintaining, surveying, cleaning, transporting objects.
- Exploring unknown natural areas, e.g., planetary exploration
  - building a map with characterized landmarks, extracting samples, setting various measurement devices.
- Assisting people in offices, public areas, and homes.
- Helping in tele-operated surgical operations

Status

- Reasonably mature technology when robots restricted to either
  - well-known, well-engineered environments
    - » e.g., manufacturing robotics
  - performing single simple tasks
    - » e.g., vacuum cleaning or lawn mowing
- For more diverse tasks and open-ended environments, robotics remains a very active research field

Robots without Planning Capabilities

- Requires hand-coding the environment model and the robot's skills and strategies into a reactive controller
- The hand-coding needs to be inexpensive and reliable enough for the application at hand
  - well-structured, stable environment
  - robot's tasks are restricted in scope and diversity
  - only a limited human-robot interaction
- Developing the reactive controller
  - Devices to memorize motion of a pantomime
  - Graphical programming interfaces

Requirements for Planning in Robotics

- online input from sensors and communication channels
- heterogeneous partial models of the environment and of the robot
- noisy and partial knowledge of the state from information acquired through sensors and communication channels
- direct integration of planning with acting, sensing, and learning

Types of Planning

- Domain-independent planning is not widely used in robotics
  - Classical planning framework too restrictive
- Instead, several specialized types of planning
  - Path and motion planning
    - Computational geometry and probabilistic algorithms
    - Mature; deployed in areas such as CAD and computer animation
  - Perception planning
    - Younger, much more open area
  - Navigation planning
  - Manipulation planning

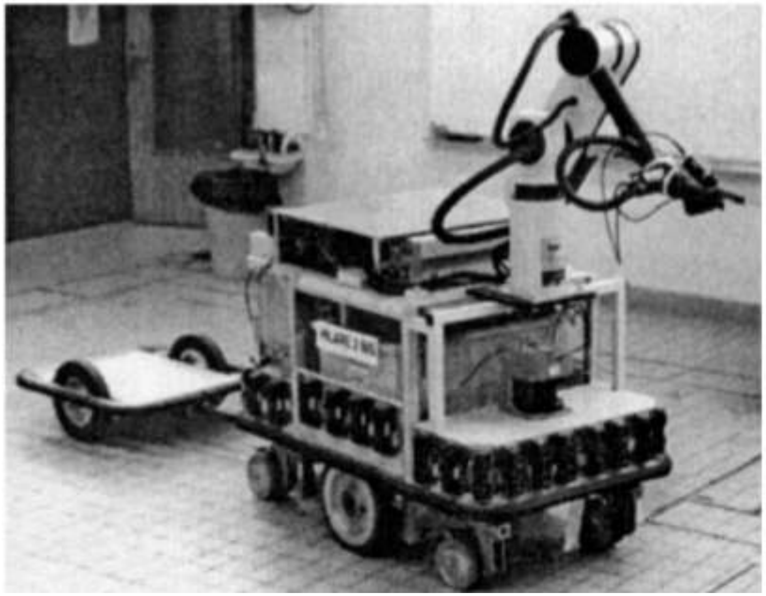
Path and Motion Planning

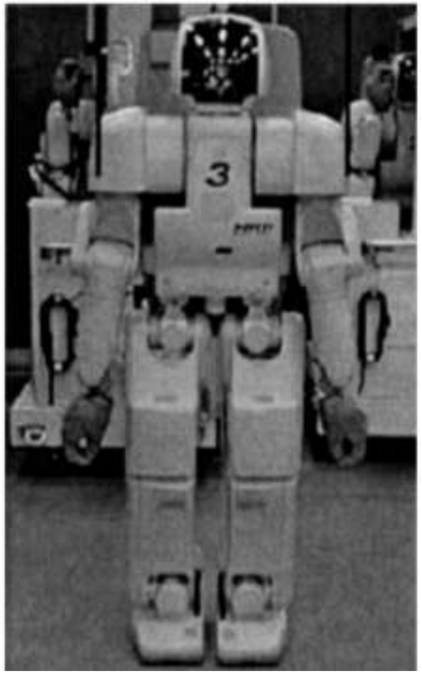
- Path planning:
  - Find a feasible geometric path for moving a mobile system from a starting position to a goal position
  - Given a geometric CAD model of the environment with the obstacles and the free space
  - A path is feasible if it meets the kinematic constraints of the mobile system and avoids collision with obstacles
- Motion planning:
  - Find a feasible trajectory in space and time
    - feasible path and a control law along that path that meets the mobile system's dynamic constraints (speed and acceleration)
    - Relies on path planning

Configuration Parameters

- Car-like robot
  - Three configuration parameters are needed to characterize its position: x, y, θ
    - » Path planning defines a path in this space
  - The parameters are not independent
    - » E.g., unless the robot can turn in one place, changing theta requires changing x and y
- Mechanical arm with n rotational joints
  - n configuration parameters
    - » Each gives the amount of rotation for one of the joints
  - Hence, n-dimensional space
  - Also, min/max rotational constraints for each joint

Examples





- The robot *Hilare*
- 10 configuration parameters:
  - 6 for arm
  - 4 for platform & trailer

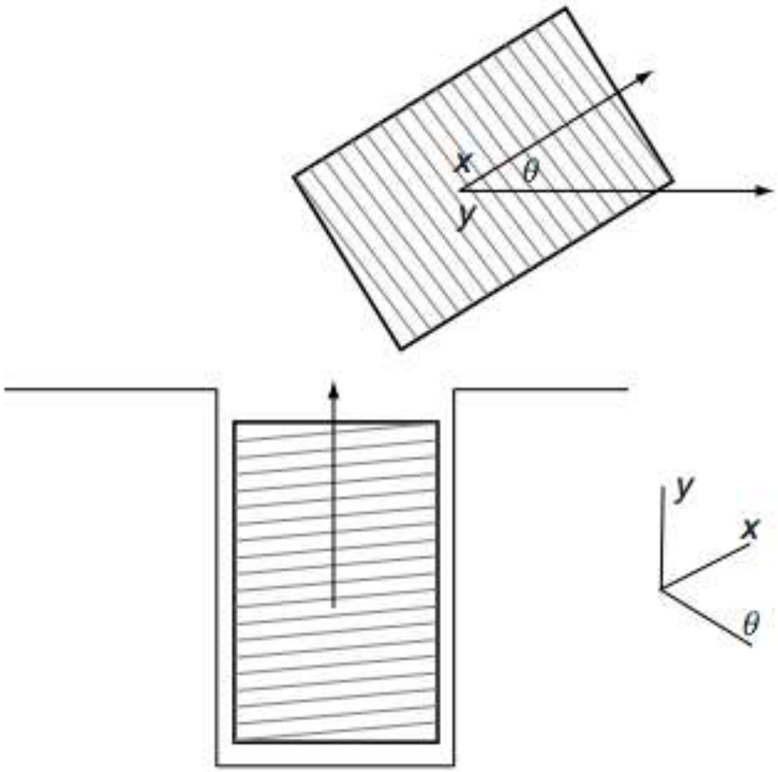
- 52 configuration parameters
  - 2 for the head,
  - 7 for each arm
  - 6 for each leg
  - 12 for each hand

Path Planning

- Definitions
  - q = the configuration of the robot = an n-tuple of reals
  - CS = the configuration space of the robot
    = {all possible values for q}
  - $CSfree$ = the free configuration space
    - » {configurations in CS that don't collide with the obstacles}
- Path planning is the problem of finding a path in $CSfree$ between an initial configuration q_i and a final configuration q_g

- Very efficient probabilistic techniques to solve path planning problems
  - Kinematic steering finds a path between two configurations q and q' that meets the kinematic constraints, ignoring the obstacles
  - Collision checking checks whether a configuration or path between two configurations is collision-free (i.e., entirely in $CSfree$)

- Explicit definition of *CSfree* is computationally difficult
  - Exponential in the dimension of *CS*



Car-like robot and environment

Configuration space

Roadmaps

- Let $L(q,q')$ be the path in CS computed by the kinematic steering algorithm
- A *roadmap* for $CSfree$ is any finite graph R whose vertices are configurations in $CSfree$
  - two vertices q and q' in R are adjacent in only if $L(q,q')$ is in $CSfree$
- Note:
  - Every pair of adjacent vertices in R is connected by a path in $CSfree$
  - The converse is not necessarily true

Planning with Roadmaps

- Given an adequate roadmap for *CSfree* and two configurations q_i and q_g in *CSfree*, a feasible path from q_i to q_g can be found as follows:
  - Find configuration q'_i in R such that $L(q_i, q_i')$ is in *CSfree*
  - Find configuration q' in R such that $L(q_g, q_g')$ is in *CSfree*
  - In *R*, find a sequence of adjacent configurations from q_i' to q_g'
- The planned path is the finite sequence of subpaths

  $L(q_i, q_i'), \ldots, L(q_g, q_g')$
  - Postprocessing to optimize and smooth the path
- This reduces path planning to a simple graph-search problem, plus collision checking and kinematic steering
  - How to find an adequate roadmap?

Coverage

- Need to find a roadmap that *covers CSfree*
  - Whenever there is a path in *CSfree* between two configurations, there is also a path in the roadmap
  - Easier to use probabilistic techniques than to compute *CSfree* explicitly
- The *coverage domain* of a configuration q is
  - $D(q) = \{q' \in CSfree \mid L(q,q') \subseteq CSfree\}$
- A set of configurations $Q = \{q_1, q_2, \ldots, q_n\}$ *covers CSfree* if
  - $D(q_1) \cup D(q_2) \cup \ldots \cup D(q_n) = CSfree$

Probabilistic Roadmap Algorithm

- Probabilistic-Roadmap
  - Start with an empty roadmap *R*
  - Until (termination condition), do
    - » Randomly generate a configuration *q* in *CSfree*
    - » Add *q* to *R* iff either
      - *q* extends the coverage of *R*
        - e.g., there's no configuration *q′* in *R* such that *D*(*q′*) includes *q*
      - *q* extends the connectivity of *R*
        - i.e., q connects two configurations in *R* that aren't already connected in *R*

Termination Condition

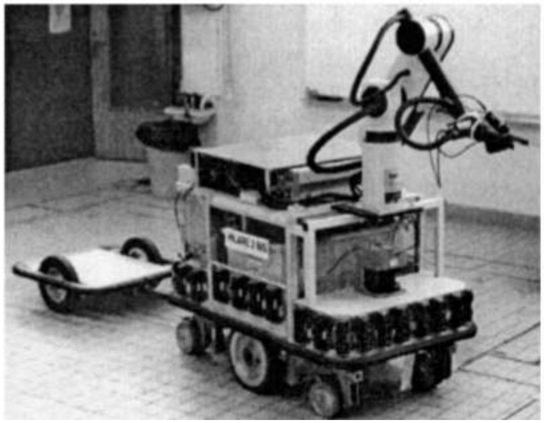
- Termination condition:
  - Let k = number of random draws since the last time a configuration was added to the roadmap
  - Stop when k reaches some value k_{max}
- $1/k_{max}$ is a probabilistic estimate of the ratio between the part of *CSfree* not covered by R and the total *CSfree*
  - For k_{max} = 1000, the algorithm generates a roadmap that covers *CSfree* with probability 0.999

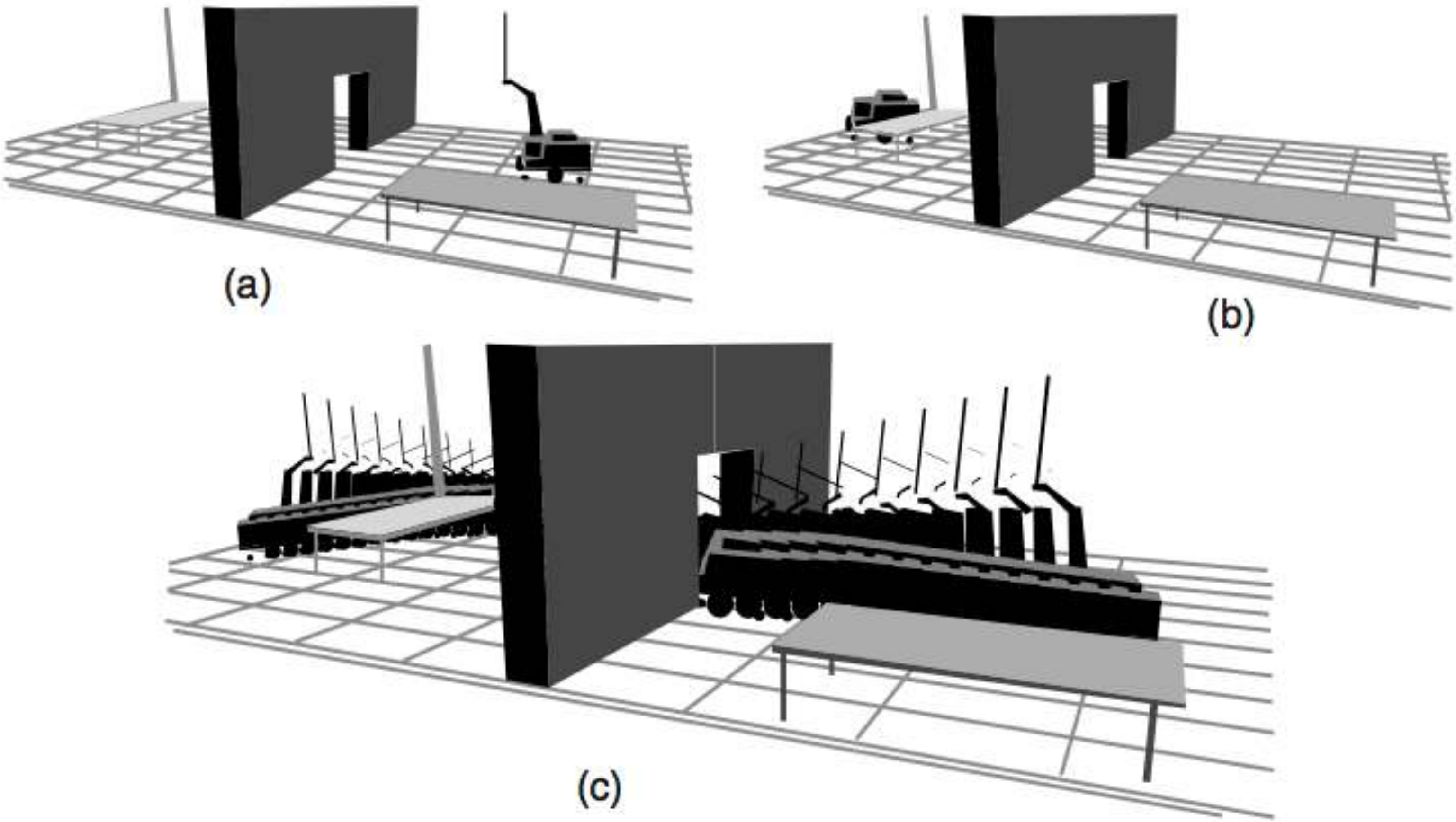
Implementation

- Very efficient implementations
- Marketed products used in
  - Robotics
  - Computer animation
  - CAD
  - Manufacturing

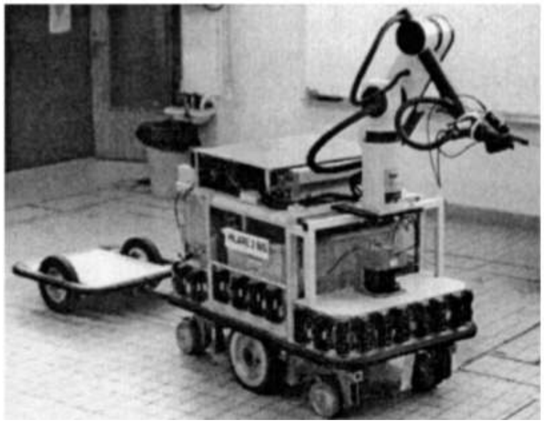
Example

- Task: carry a long rod through the door
  - Roadmap: about 100 vertices in 9-dimensional space
  - Generated in less than 1 minute on a normal desktop machine



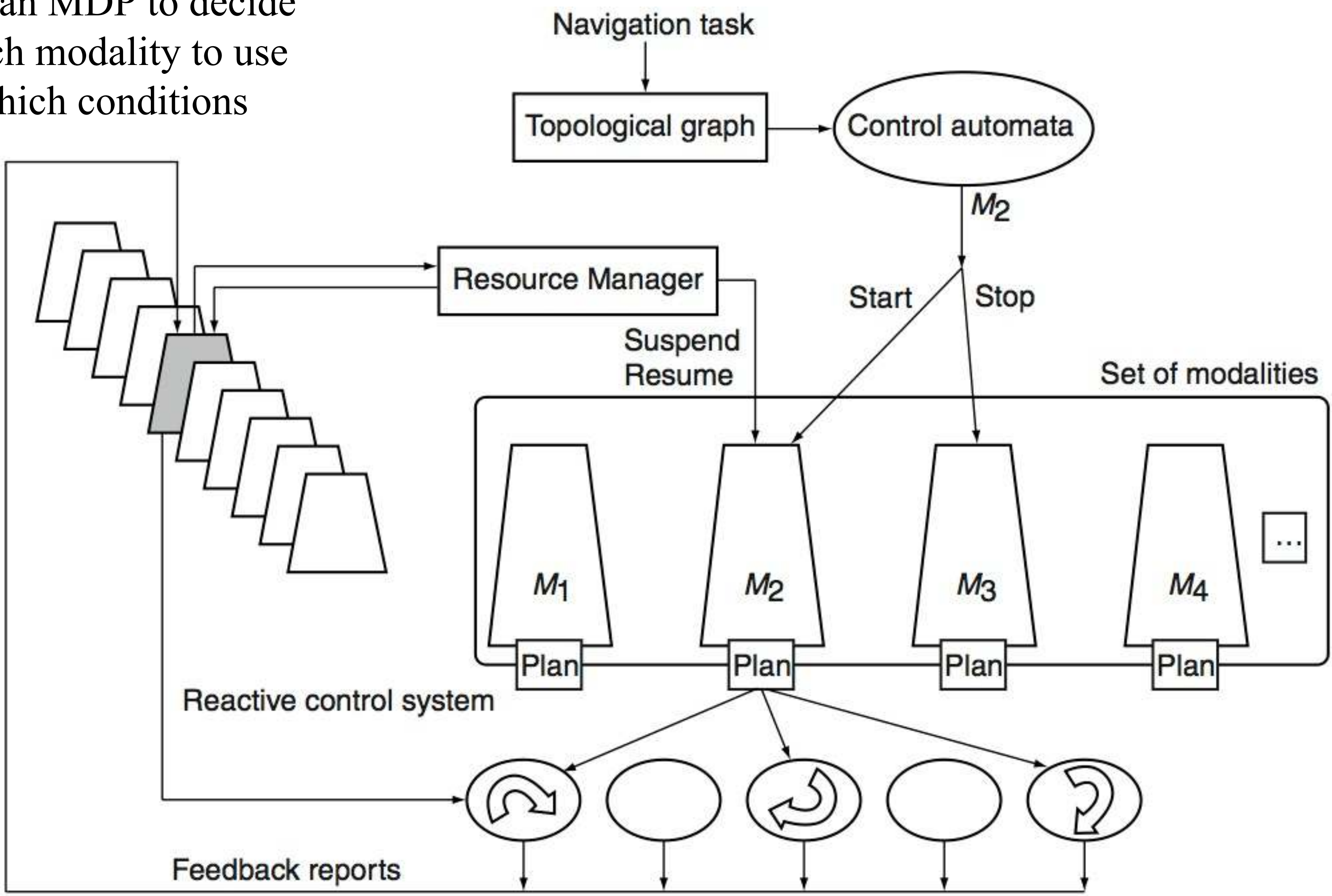


Planning for the Design of a Robust Controller



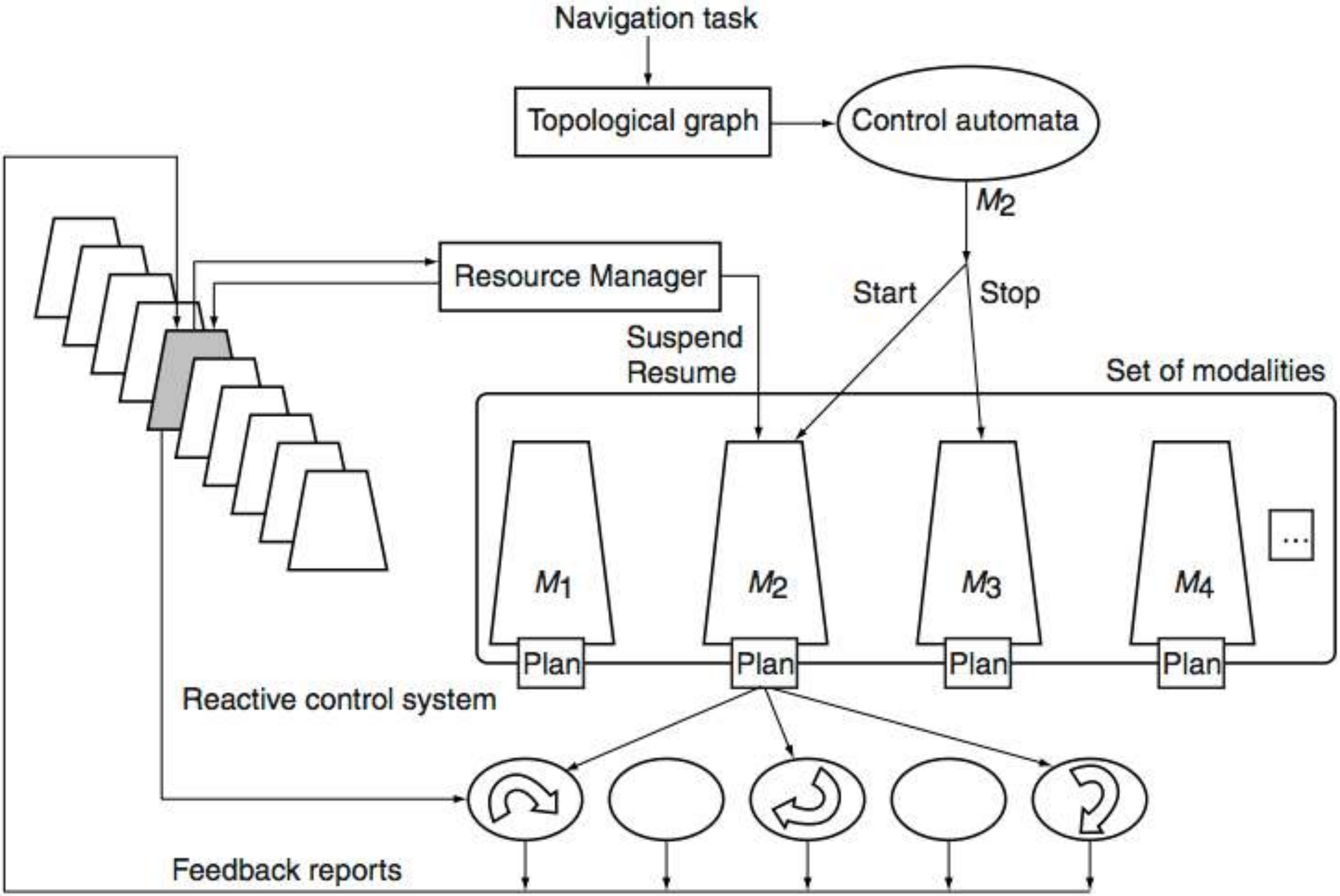
- Several sensors (sonar, laser, vision), actuators, arm
- Several redundant software modules for each sensory-motor (sm) function
  - Localizations
  - map building and updating
  - Motion planning and control
- Redundancy needed for robustness
  - No single method or sensor has universal coverage
  - Each has weak points and drawbacks
- Example: planning techniques

- Hilare has several Modes of Behavior (or *Modalities*)
- Each modality is an HTN whose primitives are *sm* functions
  - i.e., a way to combine some of the *sm* functions to achieve the desired task
- Use an MDP to decide which modality to use in which conditions



Sensory-Motor Functions

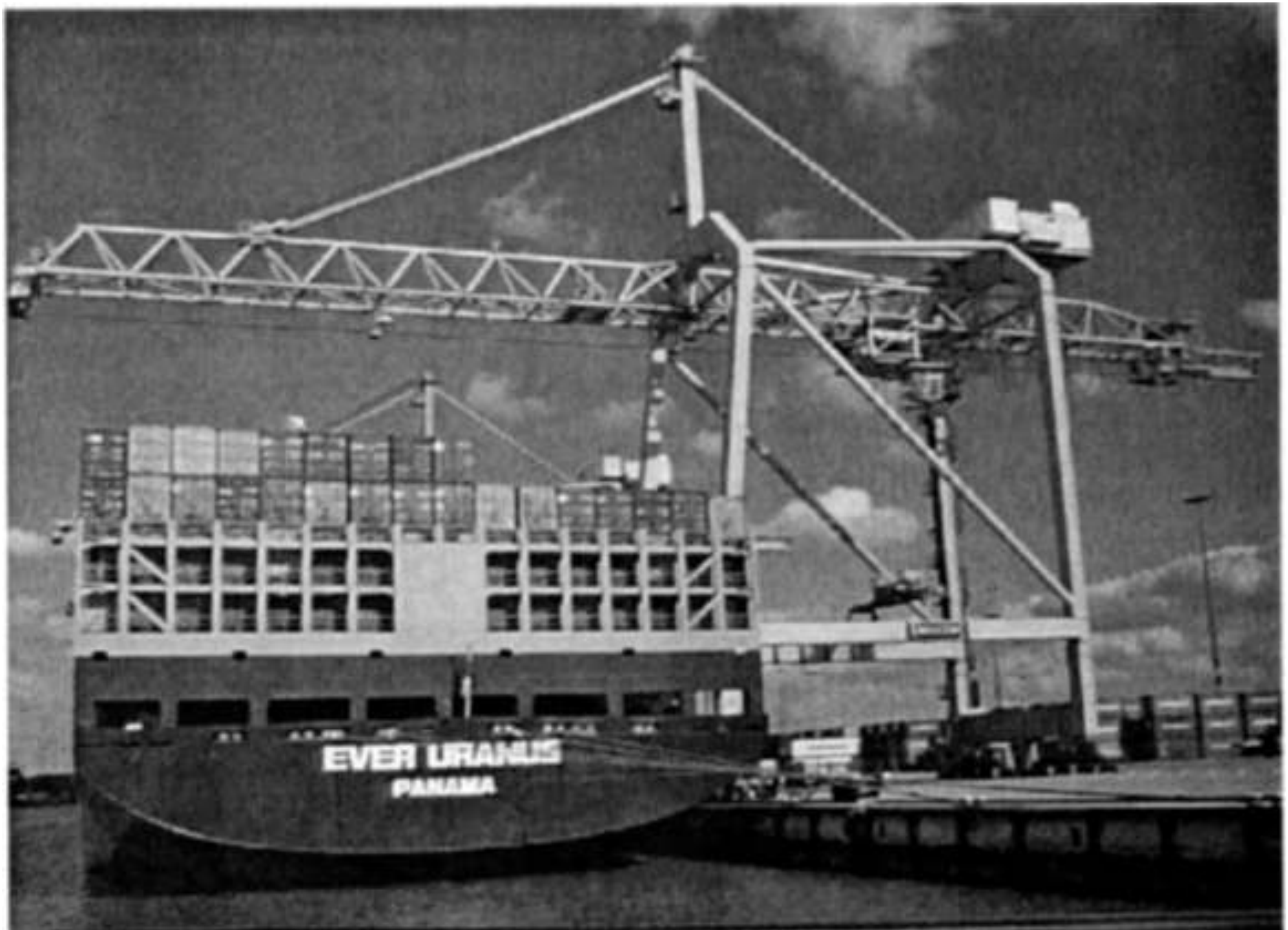
- Segment-based localization
  - Laser range data, extended Kalman filtering
  - Has problems when there are obstacles and/or long corridors
- Absolute localization
  - Infrared reflectors, cameras, GPS
  - Only works when in an area covered by the devices
- Elastic Band for Plan Execution
  - Dynamically update and maintain a flexible trajectory


Navigation task
Topological graph
Control automata
M_2
Resource Manager
Start
Stop
Suspend
Resume
Set of modalities
M_1
M_2
M_3
M_4
...
Plan
Plan
Plan
Plan
Reactive control system
Feedback reports

Some Pictures You Might Like

- Here are some pictures of real dock environments

Loading the *Ever Uranus* in Rotterdam Harbor



A Dock Work Environment