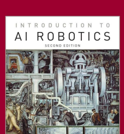
9a

Locomotion

How do you actually make a robot move?

Why don’t more robots have legs?

How does walking compare to tracks and wheels?



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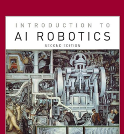
Objectives

Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

- General locomotion
  - Describe the difference between Ackerman and differential steering; explicit and skid steering; holonomic and non-holonomic vehicles
  - Rank the following list in order of power demands: crawling/sliding, running, tires on soft ground, walking, railway wheels
- Legs and walking
  - Given the number of legs, give the formula and compute the number of possible leg events
  - Describe the difference between static and dynamic balance
  - Define the zero moment point (ZPM)
  - Define the role of reference trajectory and central pattern generators in locomotion
  - List the three virtual biped gaits



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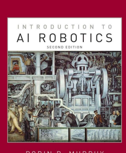
Motivation

Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

- By this point, familiar with principles of organizing the software behind a reactive or behavioral robot system
- But what about the *mobility* part?
  - Not a control course, but do need some familiarity

AI research in locomotion typically focuses on generating the reference trajectory (where it should go) and at what velocity to execute that trajectory (when to run, not walk).

Explorations into learning to walk

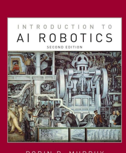


9a

General outline

Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

- Mechanical locomotion
  - Types of Steering
  - Holonomic vs. non-Holonomic vehicles
- Biomimetic locomotion
  - Crawlers
  - Snakes
  - Legs



9a

4 Steering types

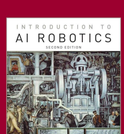
Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

1. Skid steering (differential)
    1. Tracks (common)
    2. 2 wheels + castor (variant)
2. Omnidirectional wheels
3. Ackerman steering (e.g., car)
4. Synchro-drive: wheels must turn together

skid steering:
-More power
-Less accurate

Explicit steering:
- physically turn

Typical Mechanical Locomotion
Using either Wheels or Tracks



9a Wheels: 4 Steering types

Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

1. **Skid steering (differential)**
   1. **Tracks (common)**
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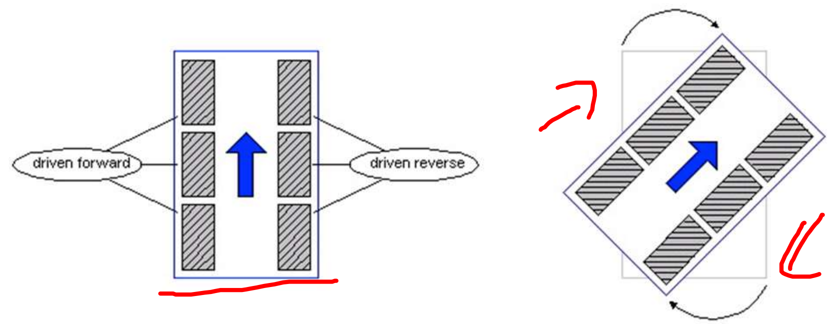
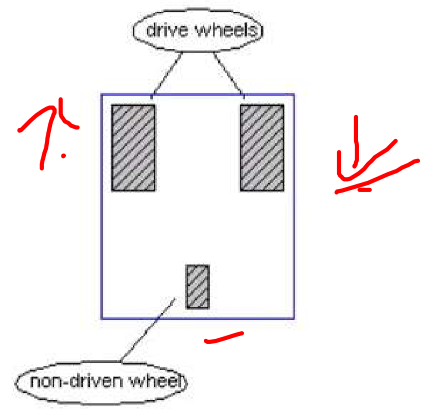
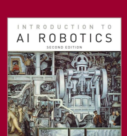
http://groups.csail.mit.edu/drl/courses/cs54-2001s/skidsteer.html





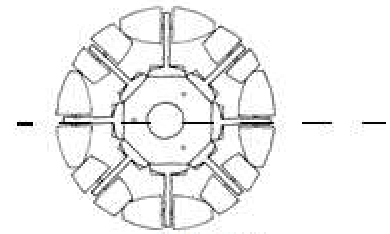


Wheels: 4 Steering types

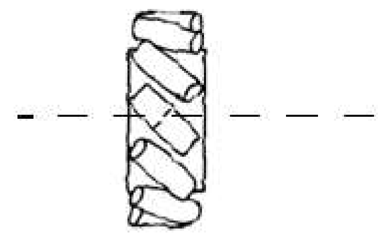
Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

1. Skid steering (differential)
   1. Tracks (common)
   2. 2 wheels + castor (variant)

2. **Omnidirectional wheels**



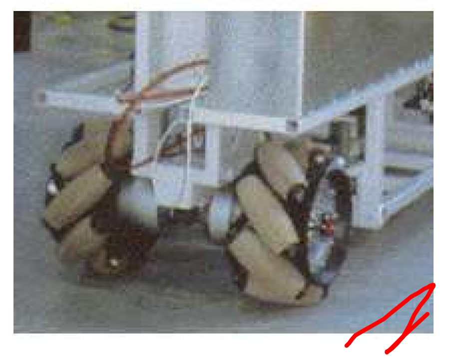
swedish 90°

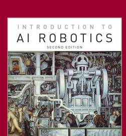


swedish 45°

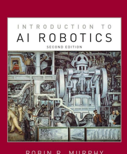
Swedish wheel: Three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers and around the contact point

4. Synchro-drive: wheels must turn together





9a Wheels: 4 Steering types



Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

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3. **Ackerman steering (e.g., car)**
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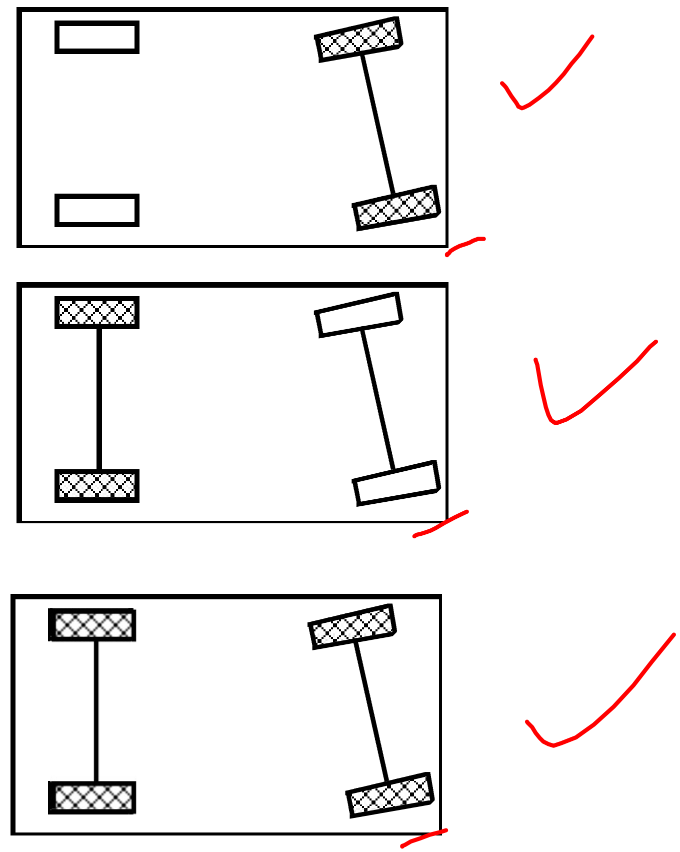

9a Wheels: 4 Steering types

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-Omnidirectional
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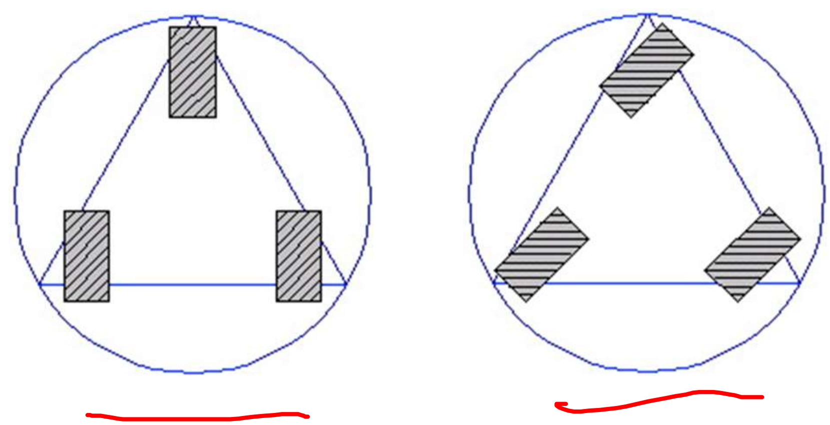
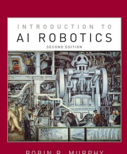
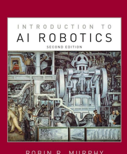
http://groups.csail.mit.edu/drl/courses/cs54-2001s/synchro.html





9a Holonomic/Non-holonomic

- *Holonomic* vehicle means that the vehicle can be treated as a massless point capable of instantaneous turning in any direction (e.g., spin on a dime)
  - Mechanical/control complexity simplifies motion
  - Easy to avoid, park (esp. if round robot)
  - Advantages for path-planning and localization (see later)
- In reality, always have some slippage that is hard to model due to dependency on the surface
- Non-holonomic
  - Ackerman steering
  - Skid steering (though sometimes approximate as holonomic)
- Holonomic (reasonable assumption for benign conditions)
  - Synchro-drive
  - Omnidirectional wheels

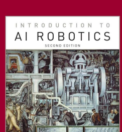


9a

Denning DRV-1 robot and iRobot

Holonomic

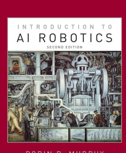
Differential Steering



9a Controlling Wheeled & Tracked Systems

Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

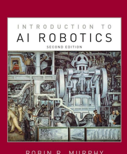
- Need to know how far, how fast
  - Generally have shaft or optical encoders to count how shaft or wheel turns
  - Tracked vehicles are notorious hard to infer the actual distance traveled
  - Rotation accrues errors more rapidly than translation
- You may need to consider the acceleration and velocity profiles to avoid jerky motion



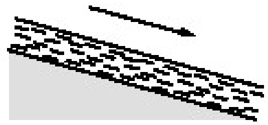
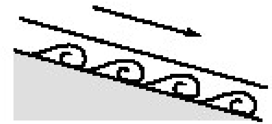
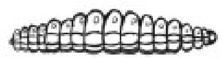
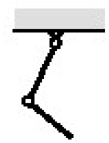
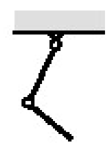
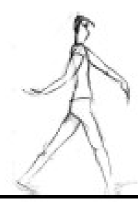
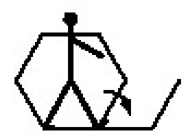
9a Summary: Mechanical Locomotion

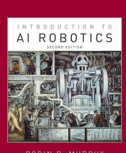
Steering
-Skid
-Omnidirectional
-Ackerman
-Synchro-drive
Holonomic

- Ground mobility generally uses wheels or tracks
- Steering is either skid (or differential) or explicit
- Two common skid steering mechanisms are differential, omnidirectional treads
- Two common explicit steering mechanisms are Ackerman and synchro-drive
- Holonomic vehicles can "turn on a dime" and change orientation in place but in practice, there is always "skitter"



9a Locomotion Concepts: Principles Found in Nature

Type of motion	Resistance to motion	Basic kinematics of motion
Flow in a Channel 	Hydrodynamic forces	Eddies 
Crawl 	Friction forces	 Longitudinal vibration
Sliding 	Friction forces	 Transverse vibration
Running 	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum 
Jumping 	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum 
Walking 	Gravitational forces	Rolling of a polygon (see figure 2.2) 



General outline

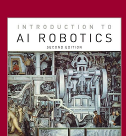
- Biomimetic locomotion
  - Why
  - Types
  - Patterns
    - Leg events- why CPG
    - CPG
  - Gaits
    - Support polygon, zmp
    - Static
    - Dynamic

9a Wheels v. Biomimetic Locomotion

Types
Crawling
Sliding
Legs
-Balance
-Leg events
Summary

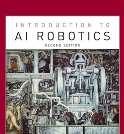
- Only half earth is accessible by wheels
- Leg advantages
  - can find isolated footholds, whereas wheels are continuous
  - Provide active suspension
- Walking not as energy intensive as other biological modes
  - Crawling/sliding
  - Running
  - Tires on soft ground
  - Walking
  - Railway wheels

Increasing power demand



9a Biological Locomotion (Sweigert, Nourbakhsh)

- The central concept in biomimetic locomotion is that there is a periodic, or repetitive, motion, either a vibration of the body or an oscillation of limbs
  - **Crawl**- overcome friction through longitudinal vibration or movement (e.g. caterpillar)
  - **Sliding**- overcome friction through transverse vibration or movement (e.g. snake)
  - **Running**- overcome kinetic energy with oscillatory movement of multi-link pendulum that leads to a predominately horizontal motion
  - **Jumping**- overcome kinetic energy with oscillatory movement of multi-link pendulum that leads to a predominately vertical motion
  - **Walking**- overcome gravity by rolling like a polygon



9a Biological Locomotion (Sweigert, Nourbakhsh)

Types
Crawling
Sliding
Legs
-Balance
-Leg events
Summary

- The central concept in biomimetic locomotion is that there is a periodic, or repetitive, motion, either a vibration of the body or an oscillation of limbs
  - **Cra** l vibration or mov

  LEGGED LOCOMOTION

  - **Slid** e vibration or movement (e.g. snake)
  - **Running**- overcome kinetic energy with oscillatory movement of multi-link pendulum that leads to a predominately horizontal motion
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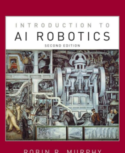
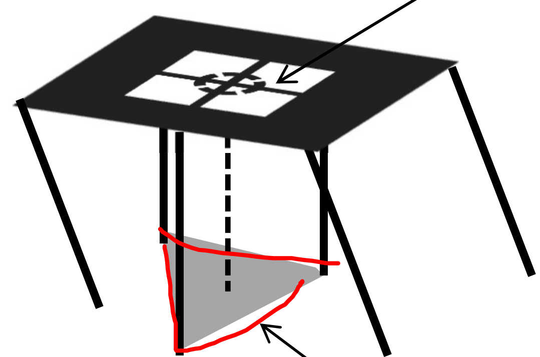
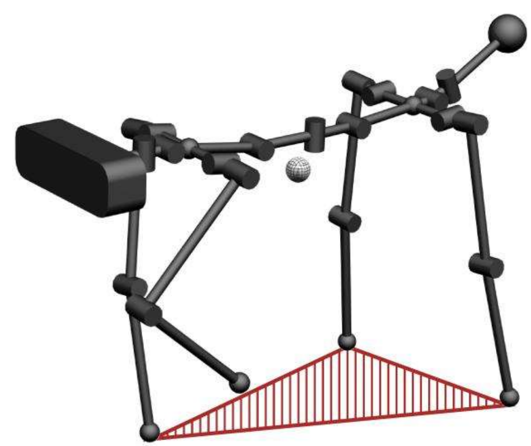


9a Legged Locomotion

- Where to place the foot and how to stay balanced
- **Support polygon**
  - Convex hull of the contact points
- If COM is always in the support polygon, then **statically balanced**
- First legged robots were statically balanced



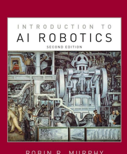


9a It's All A Matter of Balance

- "Static stability" means balance is always maintained with no need for motion for passive correction. Fairly rare in nature.

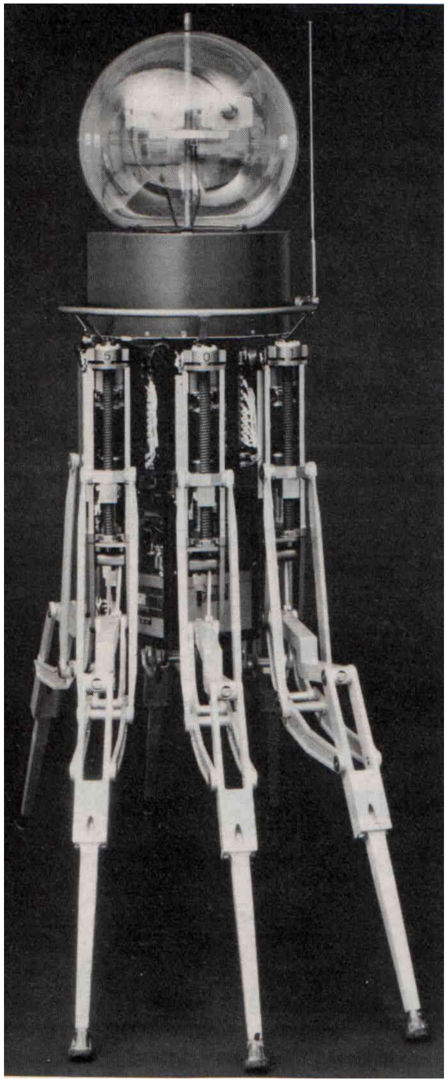
- Static walking
  - Maintaining static stability while walking
    - Usually has >= 6 legs, since must lift legs
    - Ex. Lobster
    - Ex. OSU hexapod, Odetics, Dante

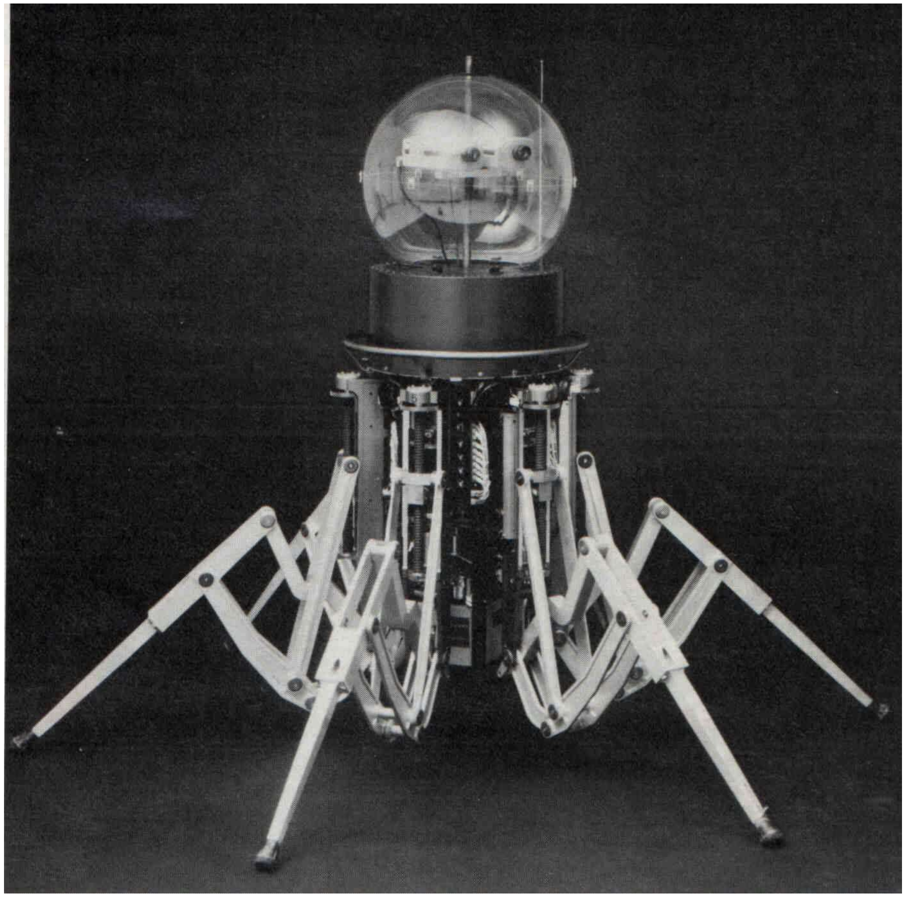
- Note also the body is always moving on a horizontal plane, no pushing up or down. This simplifies the control

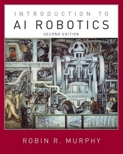


9a Odetics Odex 1: Example legged robot

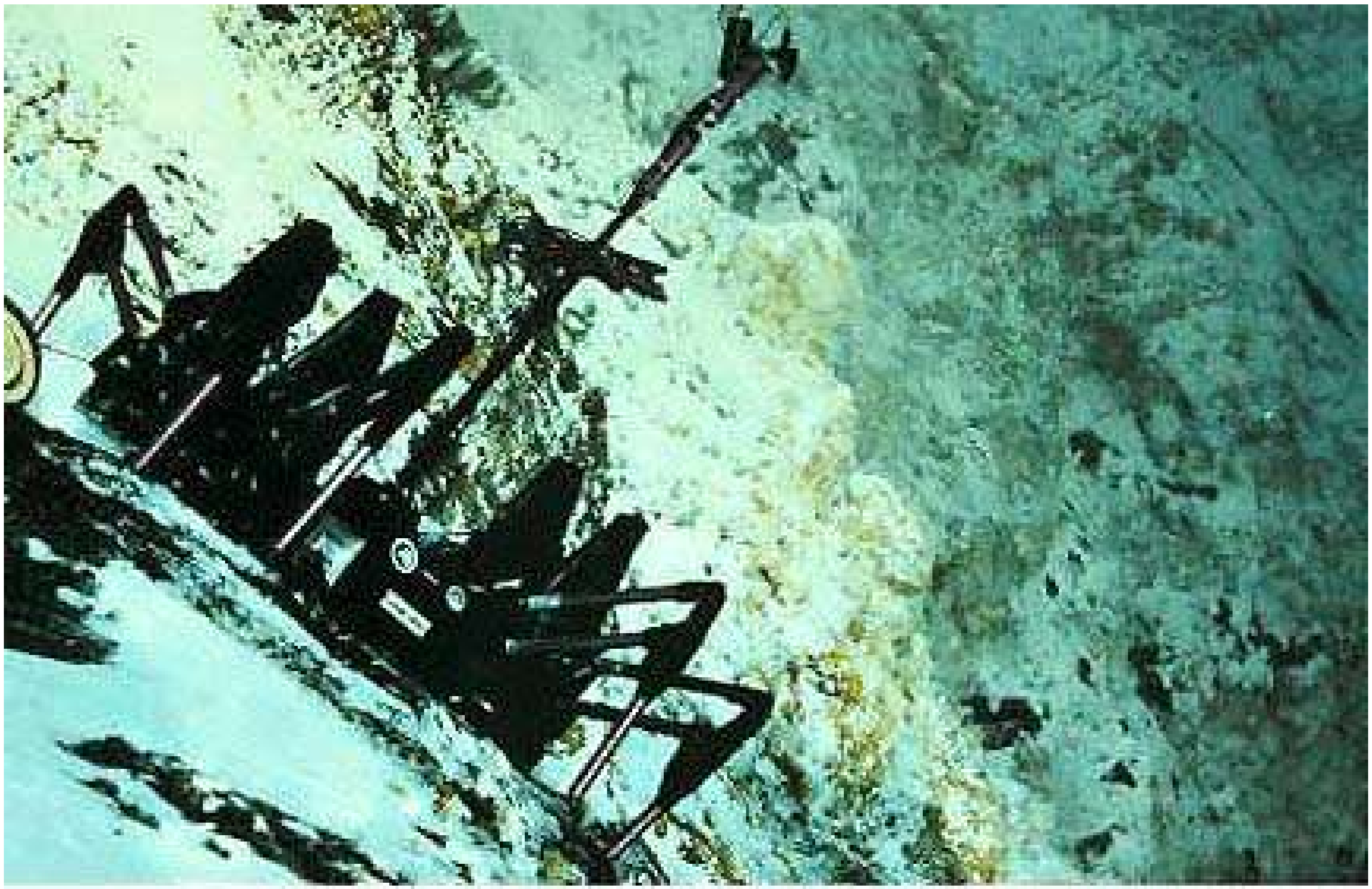
Types
Crawling
Sliding
Legs
-Balance
-Leg events
Summary



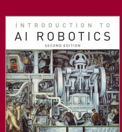




9a Dante I, II: Example legged robot



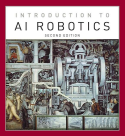
Dante I on the rim of Erebus.



9a

Dynamic Balance

- Most animals rely on dynamic balance
  - Focus on creating robots that do not have to maintain static stability as they move.
- A challenge in dynamic balance
  - Making sure that when a legged robot lands on its forward legs, the legs do not slip out from under causing a fall, and the legs are positioned such that the robot can spring off of them.



9a

Zero Moment Point

- Think of the leg as an inverted pendulum
  - where the leg can make contact with the ground within a range of angles.
- The zero moment point (zmp) is the angle
  - where the horizontal forces of momentum and friction are balanced and thus the robot should not fall.
- The ZMP is used to compute where to place a leg
  - but it is also influenced by friction and the type of foot on the leg.

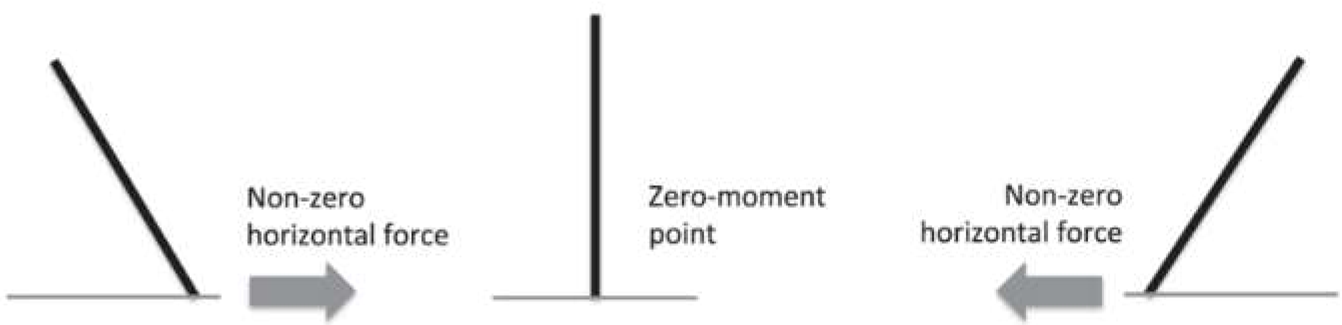
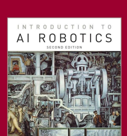


Figure 9.8 A leg as an inverted pendulum illustrating the zero moment point (ZMP).



9a

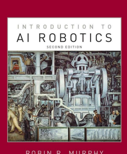
Number of Leg Events

Types
Crawling
Sliding
Legs
-Balance
-Leg events
Summary

- Leg Events
  - possible motions for the legs
- Large number of leg events (from S&I)
  - **N=(2k-1)!, where k = #legs**
  - Bipedal
    - K=2 N=6
  - 6 legs (hexapods like bees)
    - K=6 N=39,916,800
- Gets worse when consider joints

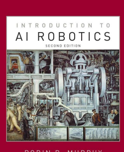
Left	Right
u	-
-	d
-	u
d	-
u	u
d	d

U: up, D: down, -: not at all



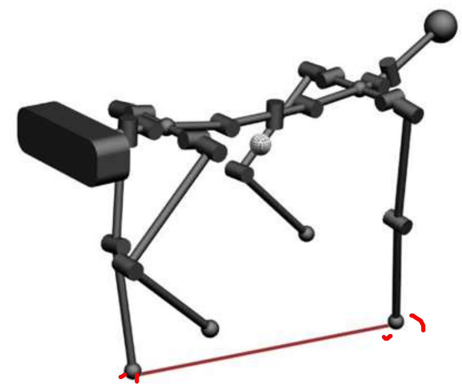
9a So gaits rather than leg events

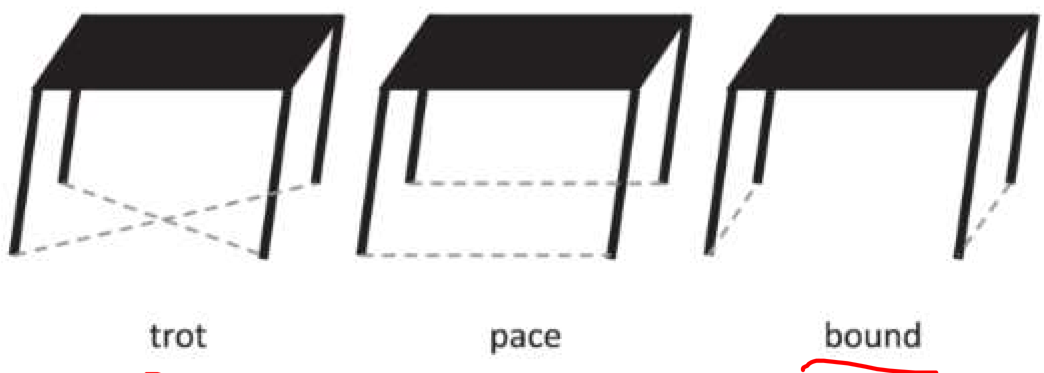
- As a result of the high number of leg events, the approach is to bundle the movements into a small set of precomputed coordinated movement called **gaits** (specific type of leg oscillation)
- Moving the agent along the reference trajectory then becomes
  - specifying the gait to get the desired velocity, and
  - then adding reactive control to adjust the actual footfall to the terrain.
  - If terrain is too difficult, control will revert to a “free gait” where the agent has to compute the legged movements manually.
- Approach: reference trajectory and oscillation (gait)

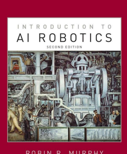


Virtual Gaits

- The idea in virtual gaits is that legs are collected into two sets, A and B, and all the legs in A move at the same time in the same way and then next all the legs in B move in the same way at the same time
- There are three basic gaits
  - Trot (diagonal pairs)
  - Pace (lateral pairs)
  - Bound (front, back pairs)

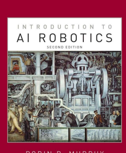






9a But what about legs with joints?

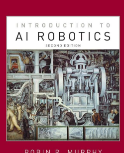
- The joints in a leg give the agent a mechanism by which to spring up with kinetic energy
  - Thus they increase the range of motion and the ability to adapt to terrain.
  - But they also reintroduce computational complexity.
- In biology, there are neural structures called central pattern generators (CPG) that produce oscillations, such as breathing, swallowing, and locomotion, which require synchronized movements.
  - Once the CPG is activated, the oscillations occur without the need for sensing or other additional inputs.
- Implementing CPGs in robotics for joints is one of methods for controlling legged robot locomotion.



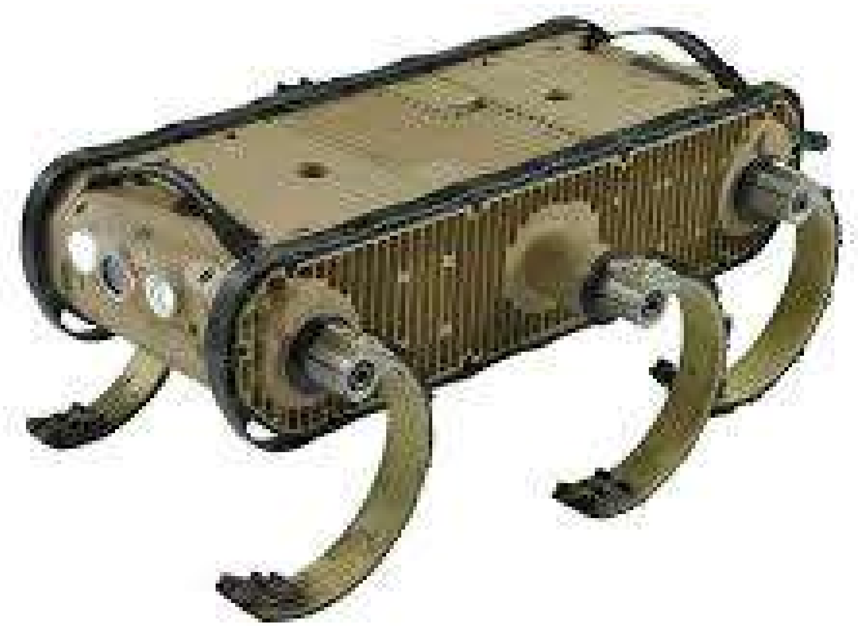
9a

Better Legs: Spring Flamingo

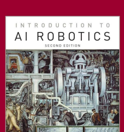
YouTube: Spring Flamingo robot



RHex Rough-Terrain Robot



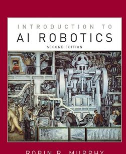
YouTube: RHex Rough-Terrain Robot



9a

Action Selection

- Action selection in AI robotics connotes how an agent chooses which behavior(s) to instantiate at a given time
  - Having a planner explicitly plan each step (free walking)
  - Using hard-wired patterns, such as gaits and central pattern generators (CPG)
  - Learning to assemble existing motor schemas so that an agent learns to locomote



9a Summary: Biological Locomotion

Types
Crawling
Sliding
Legs
-Balance
-Leg events
Summary

- If a robot has a degree of freedom, you want to be accurately measure it (proprioception) or you won't be able to control it
- Wheels remain the most energy efficient form of locomotion for ground robots but legs are the most versatile
- Legs don't have to look like legs (rHex, whegs)
- Gaits reduce the problem of planning of footfalls for dynamic balance