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MODERNIZATION OF MECHATRONICS AND ROBOTICS FOR BACHELOR DEGREE IN UZBEKISTAN THROUGH INNOVATIVE IDEAS AND DIGITAL TECHNOLOGY
609564-EPP-1-2019-1-EL-EPPKA2-CBHE-JP

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Principles of Mobile Robotics

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Tashkent, Uzbekistan, 15-19 May 2023

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Outline

1. The very basics: What is a robot, categories and classifications, the technology
2. Sensing the environment: What are sensors, types of sensors
3. Acting in the environment: Degrees of Freedom, mobile robot types, mathematical models of robotics
4. Adding a brain: AI in robotics, localisation problem, motion planning
5. Case studies

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Stage 1:

What and why

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What is a Robot?

- Draw a robot in 5 minutes.
- How do we visualize a Robot?
  - Human-like
  - Animal-like
  - Vehicle-like
  - Arm-like
- But what is it?
- “Robota” is Czech for worker or labourer
  - First used by Czech dramatist Karel Capek in his theatrical play “Rossum’s Universal Robots”

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Robotics?

- Robotics ~ the art, knowledge and the know-how of designing and applying robots (inter-disciplinary fields) .
- McKerrow (1986) defines robotics as:
  - The design, manufacture, control & programming of robots.
  - The use of robots to solve problems.
  - ***The study of control processes, sensors and algorithms used in biological counterparts.***
  - ***The applications of these control processes and algorithms to the design of robots.***

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Classification of Robots

According to Japanese Industrial Robot Assoc. (JIRA)

- Classification by **task**
  - (*manual handling, fixed sequence, variable sequence, playback, numerical control , intelligent robot*).
- Classification by **coordinate system**
  - (*cartesian, cylindrical, spherical, articulated , SCARA @ selective compliance assembly robot arm*.)
- Classification by **control method**
  - (*non-servo controlled, servo controlled*)
- Classification by means of **actuation**
  - (*hydraulic ~ liquid pressure, pneumatic ~ compressed air, electric drive, or any combination*)

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Other Categories of Robots

- According to **form**:
  - Anthropomorphic, zoo-omorphic, mobile platforms, manipulators, etc
- According to **function**
  - Toy (entertainment), industrial, space, home (domestic), pet, educational, security, military, medical, sex, etc.
- According to **autonomy**
  - Tele-operated, automatic, autonomous, perceptive, emotional, intelligent
- According to **existence**
  - SciFi, Real, Virtual
- You can find more…
- Most of these have subcategories as well…

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According to Autonomy

- Intelligent
- Emotional
- Perceptive

- AI
- Basic intelligence
- Making sense of the Environment

Strong AI

AI boundary

- Autonomous
- Automatic
- Tele-operated

- Reflexes
- Repetitive tasks
- Remote controlled

Achieved

Basic sensors

Simple Programming

RC models

Weak AI on sensors

Weak AI on responses

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Technology behind robots

- Three main components:
  - Sensors: devices capable of translating external stimuli to voltage variations.
  - Brain: usually a computer, or a Programmable Logical Controller (PLC), that is used to run a program.
  - Actuators: devices that translate electrical signals to other forms (mechanical, optical, sound, etc).

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Section 2:

Sensing the environment

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Senses and devices

Sense	In Animals	In the Machine
Vision / light	Eyes	Camera, Photovoltaic, LDR (Light Dependant Resistors)
Audition	Ears	Microphones
Taste	Taste buds	Chemical analysis sensors
Smell	Smell buds	Chemical analysis sensors
Touch (pressure)	Skin	Contact sensors, Piezo-electric crystals
Touch (heat)	Skin	Thermocouple
Balance	Ears	Accelerometer
Pain	Skin	???
(Body) Awareness	Muscle joints	Encoders and rotational resistors
Acceleration	Ears	Accelerometer
Magnetic fields	Eyes	Magnetometer, compasses
Electric fields	Nose	Magnetometer, compasses
Distance	Sonar, echo location	Ultra-sonic, laser, Infra

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What does a Sensor do?

- A sensor is a device that transforms a measured physical property into some form of electrical property
  - Voltage, resistance, capacitance, inductance, etc)
- This phenomenon is call Transduction.
- We then have to measure the electrical property. Usually this is done by measuring a voltage.

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Categories of Sensors

- We categorise Sensors according to two functional axis:
- *Active / Passive*
  - Passive receive ambient energy from the environment
  - Active transmit energy to the environment and measure the reflected energy
- *Proprioceptive / Exteroceptive*
  - Proprioceptive measure values internal to the robot (motor speed / location), battery voltage
  - Exteroceptive measure properties from the Environment.

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Complex Sensors

- Ultrasonic measures distance from object:
  - First an ultrasonic sound is emitted
  - At the same time the sensor starts counting.
  - When the echo is returned, we multiply the time with the speed of sound in air (approx. 340.26 m/s) to get the distance.
- Some sensors are capable of measuring multiple echoes!
  - Thus many objects at different distances

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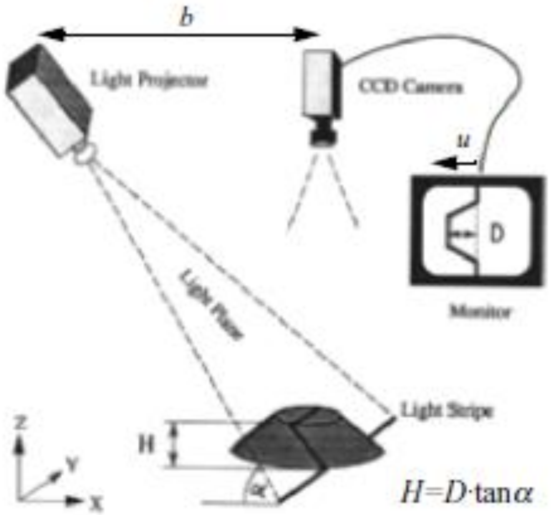
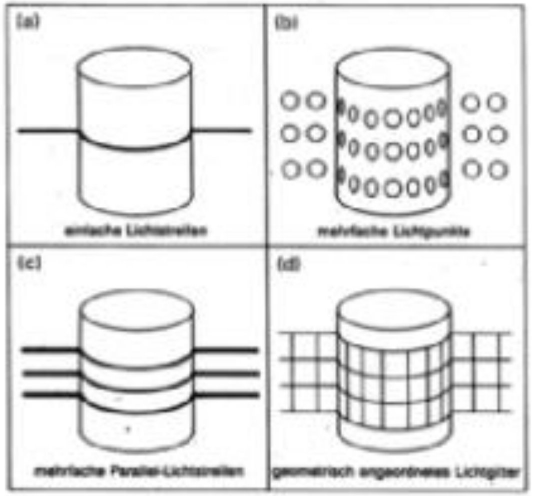
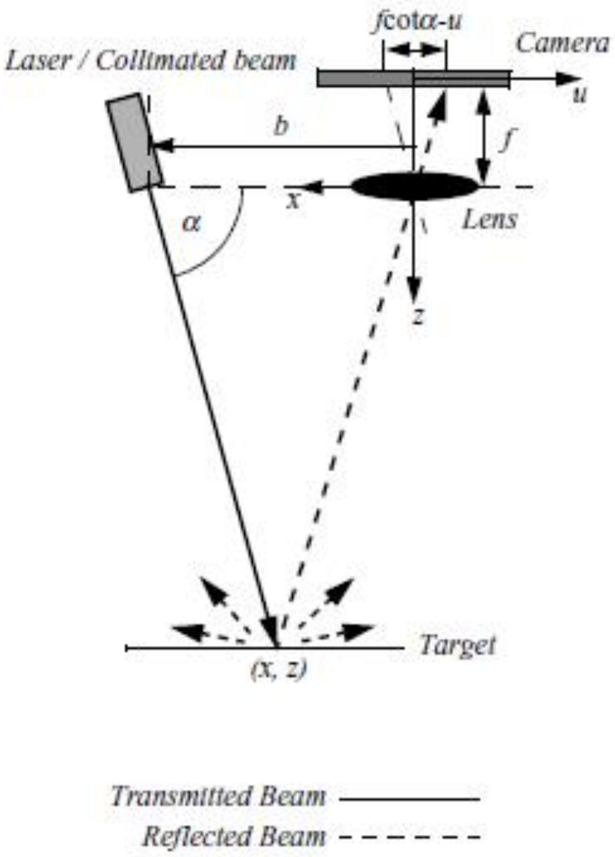
Vision

- CCD cameras
- Frames per second
- Image processing







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Radio Frequency IDentification

- The RFID device serves the same purpose as a bar code or a magnetic strip on the back of a credit card or ATM card; it provides a unique identifier for that object.
- RFID devices will work within a few feet (up to 20 feet for high-frequency devices) of the scanner and does not need to be positioned precisely relative to the scanner.

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How RFID works

- The scanning antenna puts out radio-frequency signals in a relatively short range. The RF radiation does two things:
  - It provides a means of communicating with the transponder (the RFID tag) AND
  - It provides the RFID tag with the energy to communicate (in the case of passive RFID tags).
- When an RFID tag passes through the field of the scanning antenna, it detects the activation signal from the antenna. That "wakes up" the RFID chip, and it transmits the information on its microchip to be picked up by the scanning antenna.

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Types of RFID

- RFID tag may be of one of two types.
  - **Active RFID tags** have their own power source; the advantage of these tags is that the reader can be much farther away and still get the signal. Even though some of these devices are built to have up to a 10 year life span, they have limited life spans.
  - **Passive RFID tags**, however, do not require batteries, and can be much smaller and have a virtually unlimited life span.

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Advantages of RFID

- Do not need to contain batteries, and can therefore remain usable for very long periods of time (maybe decades).
- Antennas and tags can have any form.
- Tags need not be on the surface of the object (and is therefore not subject to wear).
- Large numbers of tags can be read at once rather than item by item.
- The read time is typically less than 100 milliseconds.
- RFID tag does not need to be positioned precisely relative to the scanner (like barcodes).

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Ethical Problems with RFIDs

- RFID tags are difficult to for consumers to remove; some are very small - others may be hidden or embedded inside a product where consumers cannot see them.
- Since the tags can be read without being swiped or obviously scanned, anyone with an RFID tag reader can read the tags embedded in your clothes and other consumer products without your knowledge.
- A high-gain antenna can be used to read the tags from much further away, leading to privacy problems.
- Work is proceeding on a global system of product identification that would allow *each individual item* to have its own number. When the item is scanned for purchase and is paid for, the RFID tag number for a particular item can be associated with a credit card number.

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Technological Obstacles: -Sensor Limitations

- Today, sensing devices are limited: The information from Sensors is very primitive.
  - Although the data from many sensors are very accurate, it is not sufficient information.
  - An insect understands its environment much better than an average robot today.
- Possible solutions:
  - Better sensors and / or better processing software (AI?).
  - Hybrid Sensors have multiple sensors and multiple processing techniques to obtain more information than one could achieve from independent sensors

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Section 3:

Acting in the environment

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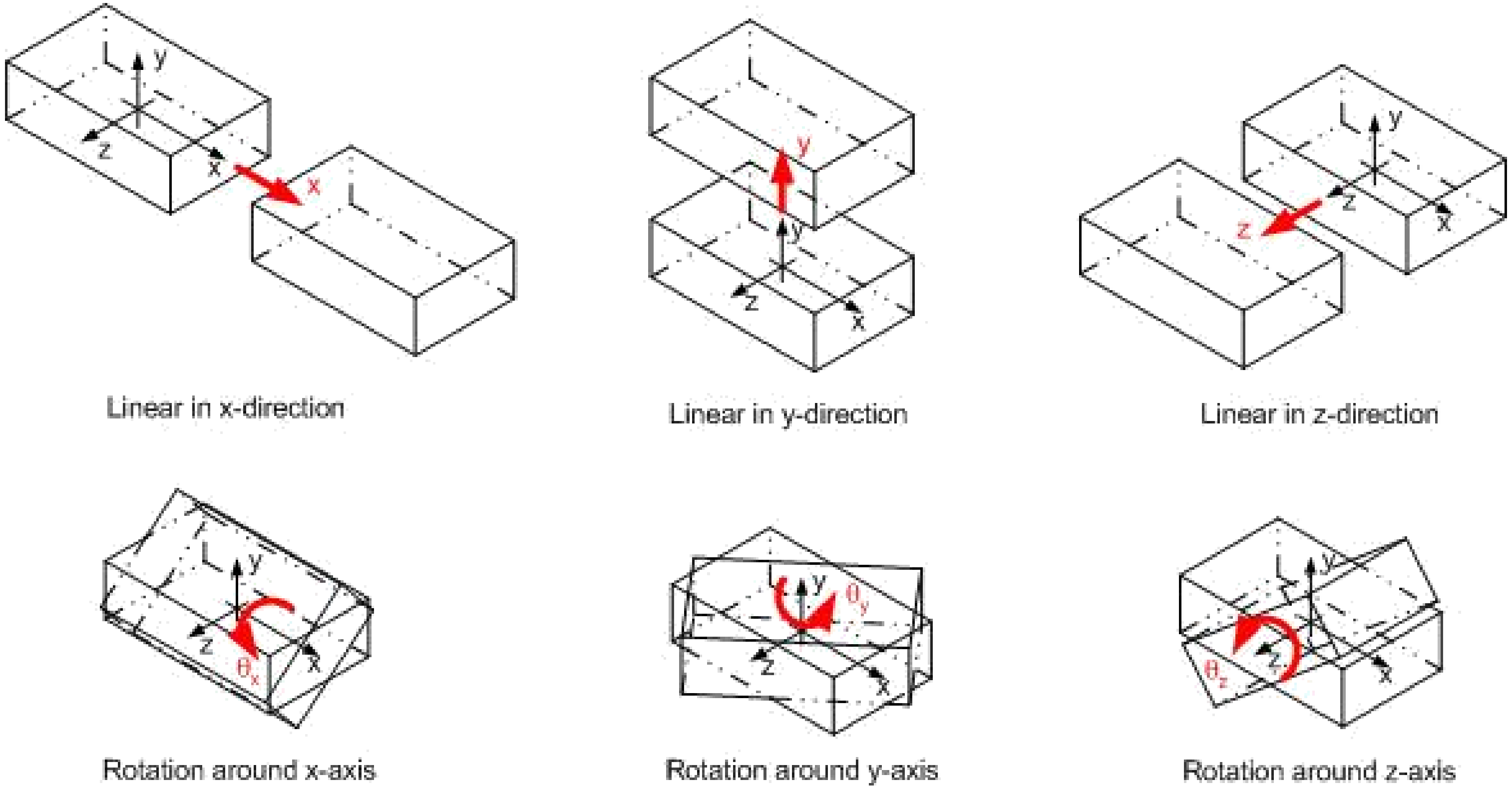
Degrees of Freedom

- Degrees of Freedom refer to the movement range available for a given piece of equipment within three dimensions.



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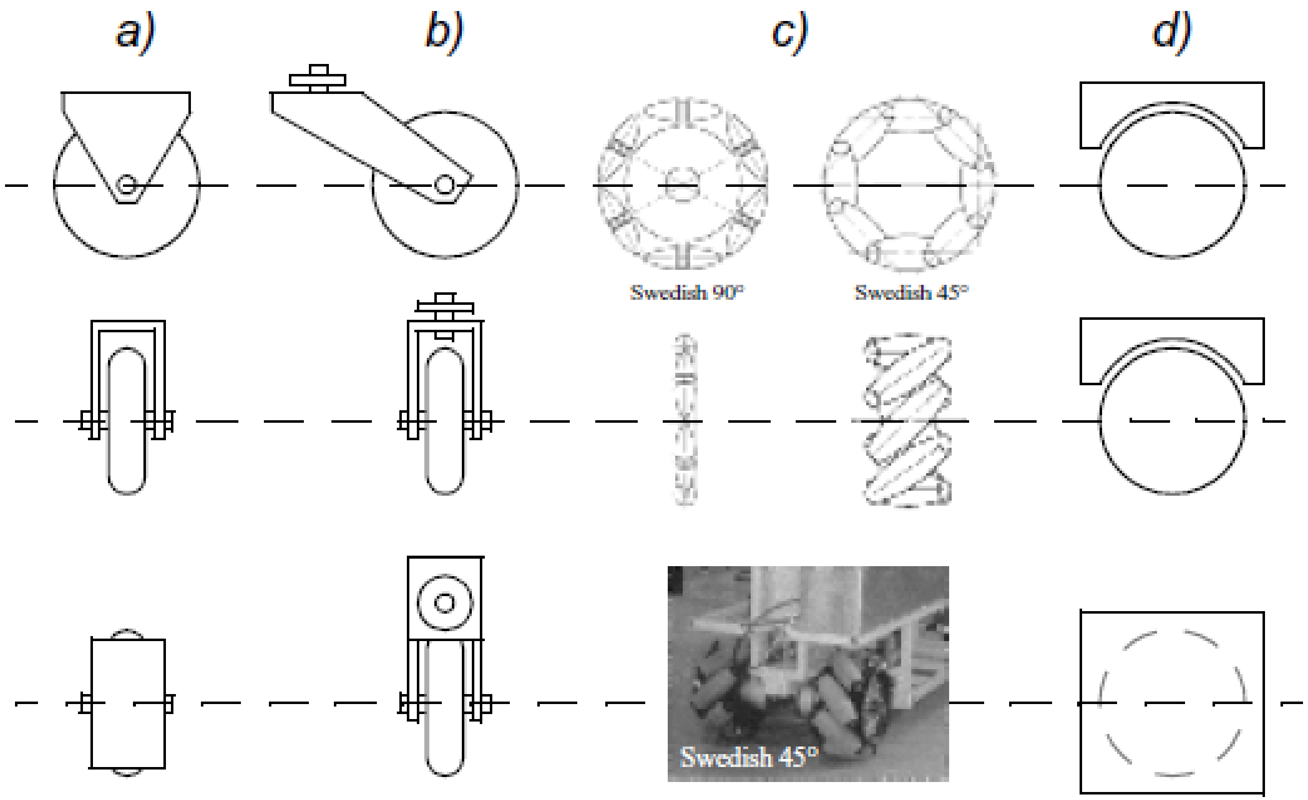
Wheeled locomotion

a) Standard wheel – 2 DoF motorised axle

b) Castor (free) wheel – 2DoF

c) Swedish model (90 and 45 degrees) – 3DoF

d) Ball or spherical wheel - 3



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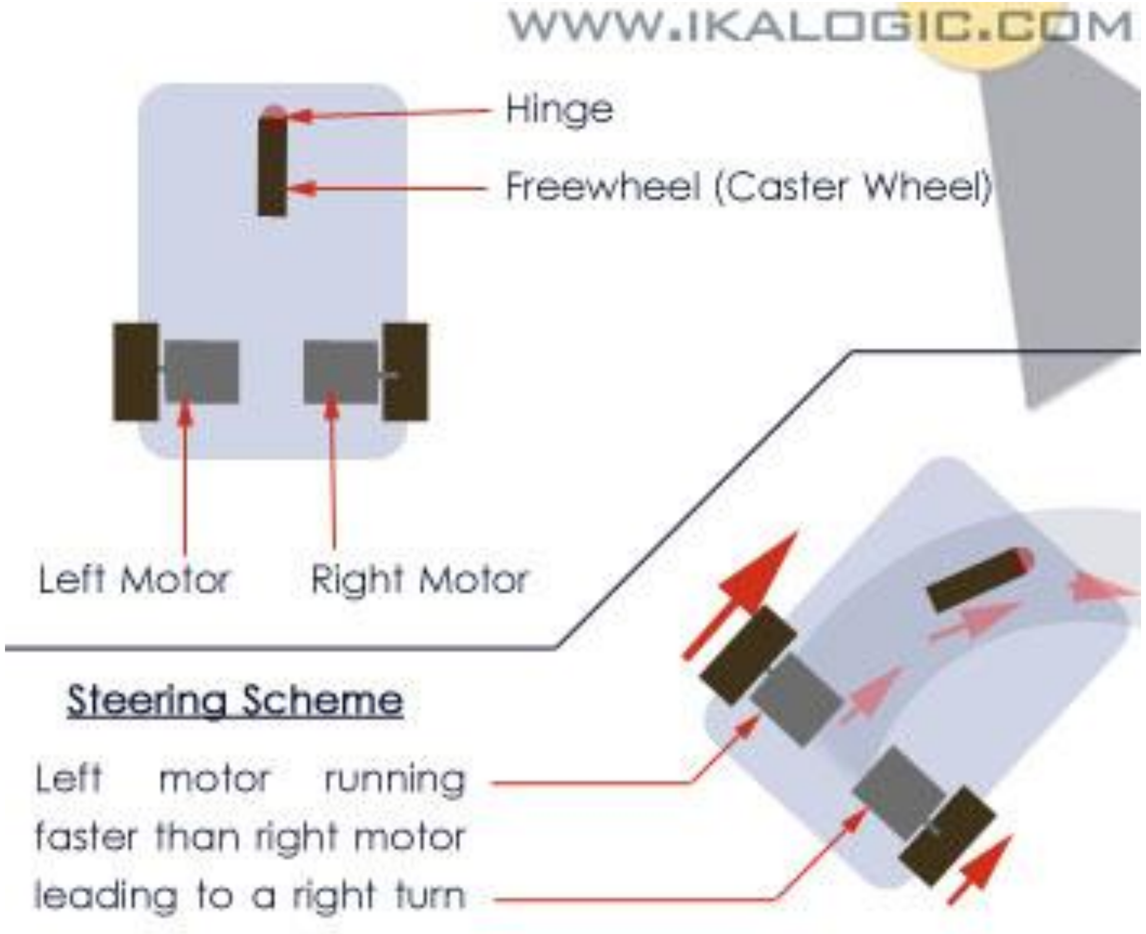
Differential drive

- Controlled variables:
  - Left wheel rotation
  - Right wheel rotation
- DoF = 2:
  - Forward/Backward translation
  - Clockwise / anticlockwise rotation
- Advantages:
  - Cheap to build
  - Easy to implement
  - Simple design
- Disadvantages:
  - Difficult to move in a straight line



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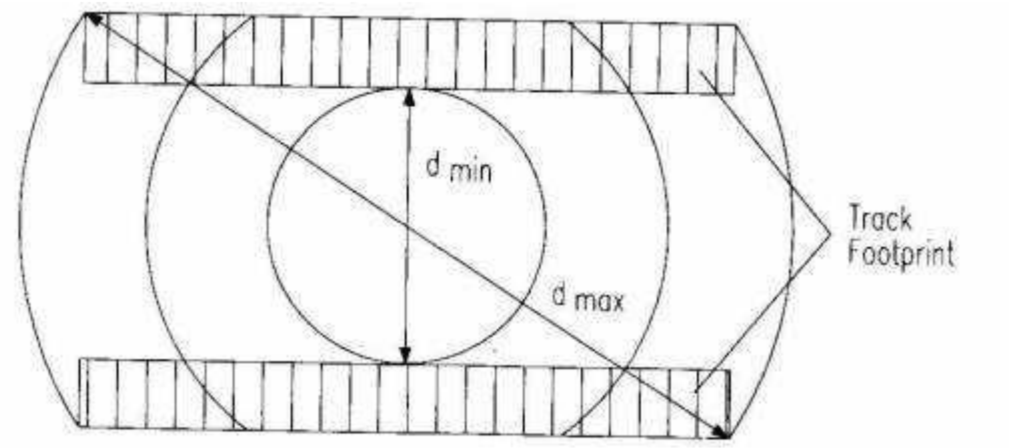
Skid Steering

- Advantages:
  - Simple drive system
- Disadvantages:
  - Slippage and poor odometry results
  - Requires a large amount of power to turn



- Controlled variables:
  - Left track rotation
  - Right track rotation
- DoF = 2:
  - Forward/Backward translation
  - Clockwise / anticlockwise rotation

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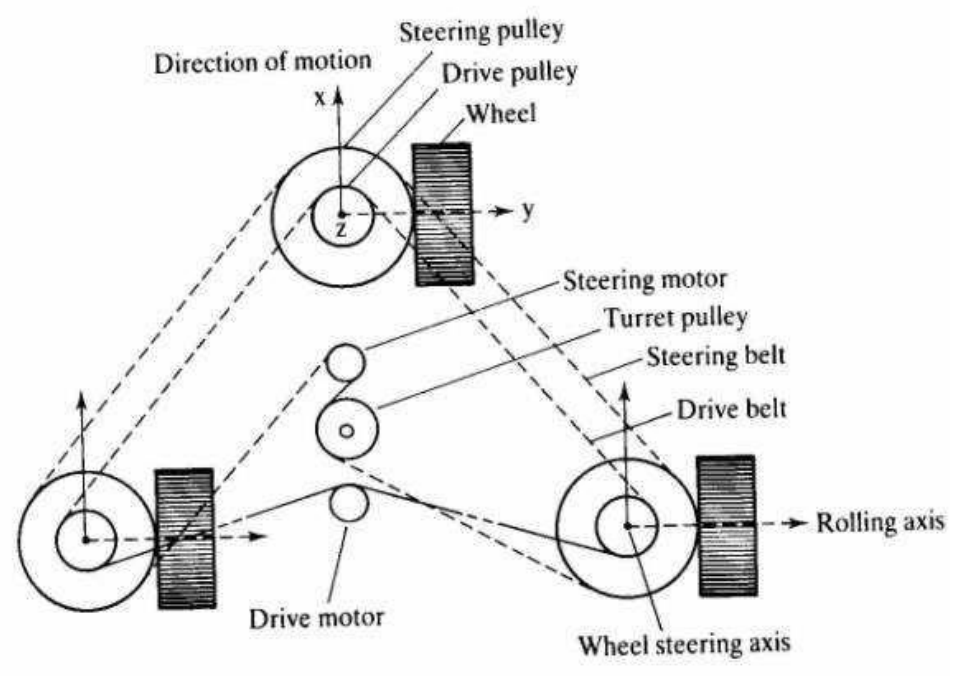
Synchro Drive

- Advantages:
  - Separate motors for translation and
  - rotation makes control easier
  - Straight-line motion is guaranteed mechanically
- Disadvantages:
  - Complex design and implementation



- Controlled variables:
  - wheel rotation
  - wheel direction
- DoF = 2:
  - Forward/Backward translation
  - Left/Right translation

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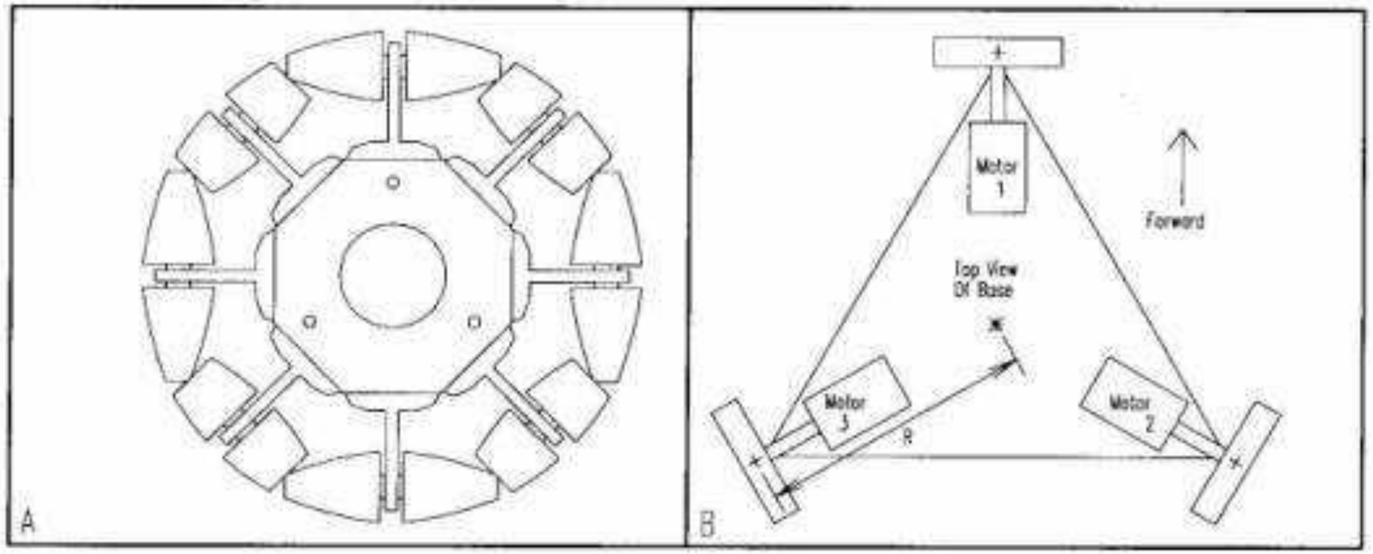
Omniwheels (holonomic)

- Advantages:
  - Allows complicated motions
- Disadvantages:
  - No mechanical constraints to require straight-line motion
  - Complicated implementation



- Controlled variables:
  - wheel 1 rotation
  - wheel 2 rotation
  - wheel 3 rotation
- DoF = 3:
  - Forward/Backward translation
  - Left/Right translation
  - Clockwise / anticlockwise rotation

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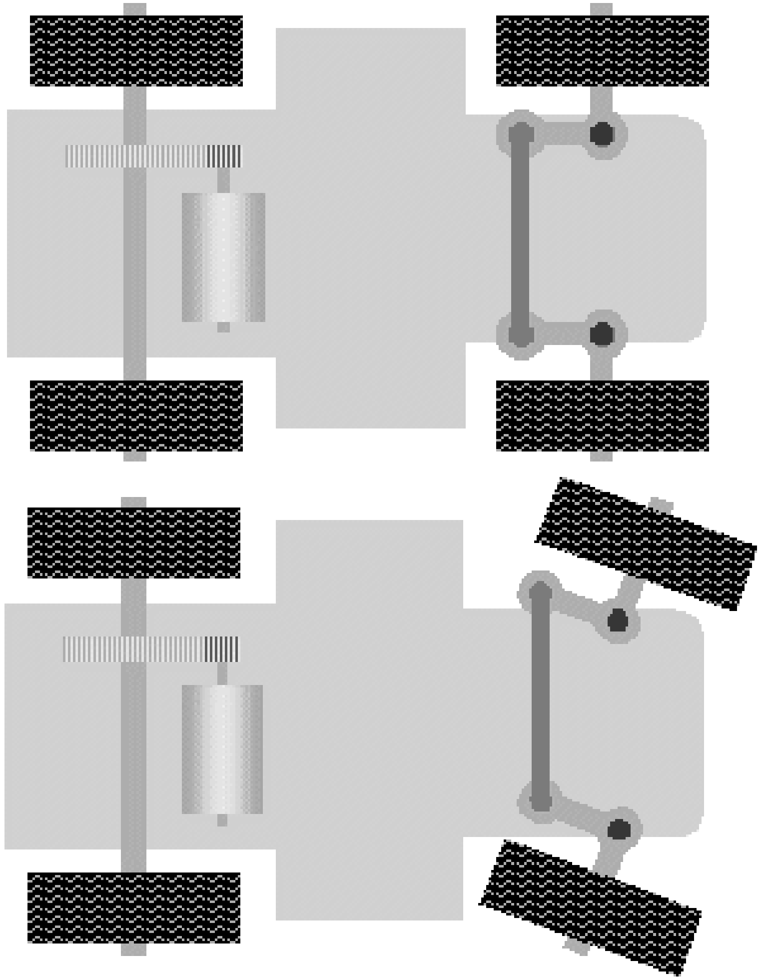
Ackerman Steering

- Advantages:
  - Simple to implement
  - Simple 4 bar linkage controls
  - front wheels
- Disadvantages:
  - Non-holonomic planning required
- Controlled variables:
  - Steering
  - Motor speed
- DoF 2:
  - Forwards/Backwards translation
  - Wheel rotation



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Snake robots

- Advantages:
  - Many applications
  - Hyper-redundant
- Disadvantages:
  - •Complex control and planning

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Legged robots

- Advantages:
  - Can traverse any terrain a human can
- Disadvantages:
  - Large number of degrees of freedom
  - Maintaining stability is complicated

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Forward Kinematic Model

- A robot is a machine that the computer drives the motors, and the robot moves.
- Therefore as a system the robot has as its input (cause) rotation of its motors (more precise voltage to the motors) and as outputs (effect) movement (position and speed in 3D space).
- The mathematical model that connects the properties of motor rotation to position in space is known as the forward kinematic model.
- The forward kinematic model is a set of equations that accept as variables the position of the motors (angle of rotation) and calculate the position of the robot (in the case of a manipulator, the position of the gripper).
- $(x,y,z) = f(\theta_1, \theta_2 \ldots \theta_n)$.
- The construction of this model is a simple geometrical problem

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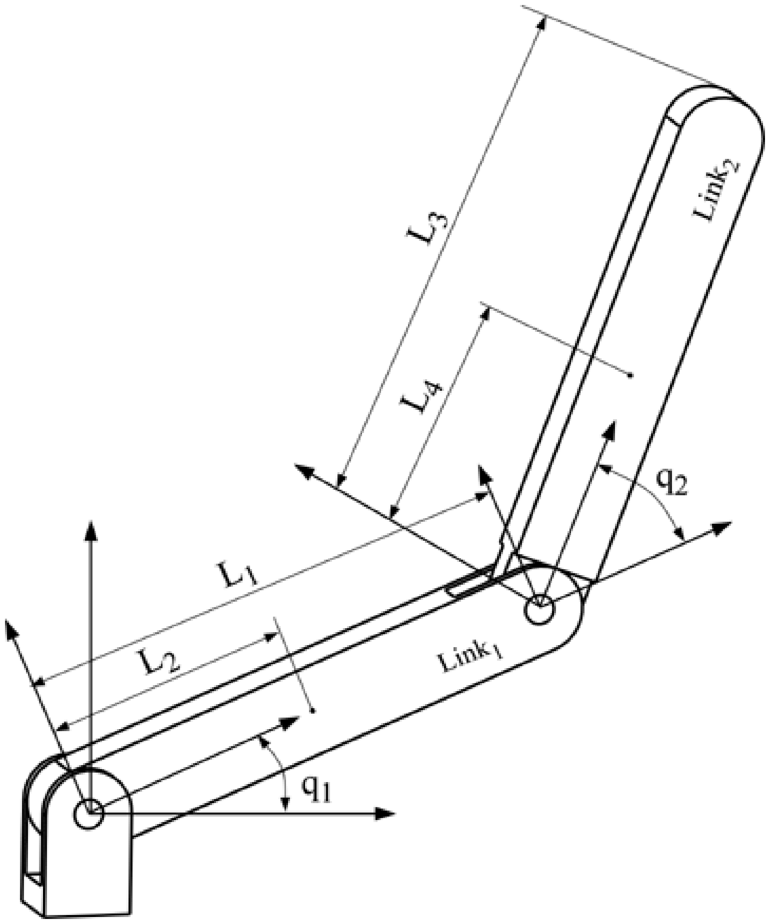
Manipulator Example

- Gripper position:
- X = L1*cos(q1)+L3*cos(q1+q2)
- Y = L1*sin(q1)+L3*sin(q1+q2)

- Angles are always measured anticlockwise from X axis
- At each joint a new frame of reference is used with the X axis parallel to the previous link
- Changing coordinate systems from frame of reference to the end effector is done by consecutive translations and rotations of the frame of reference to each joint.



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Mobile robot example

- Establish the robot speed as a function of the wheel speeds, steering angles, steering speeds and the geometric parameters of the robot (configuration coordinates).

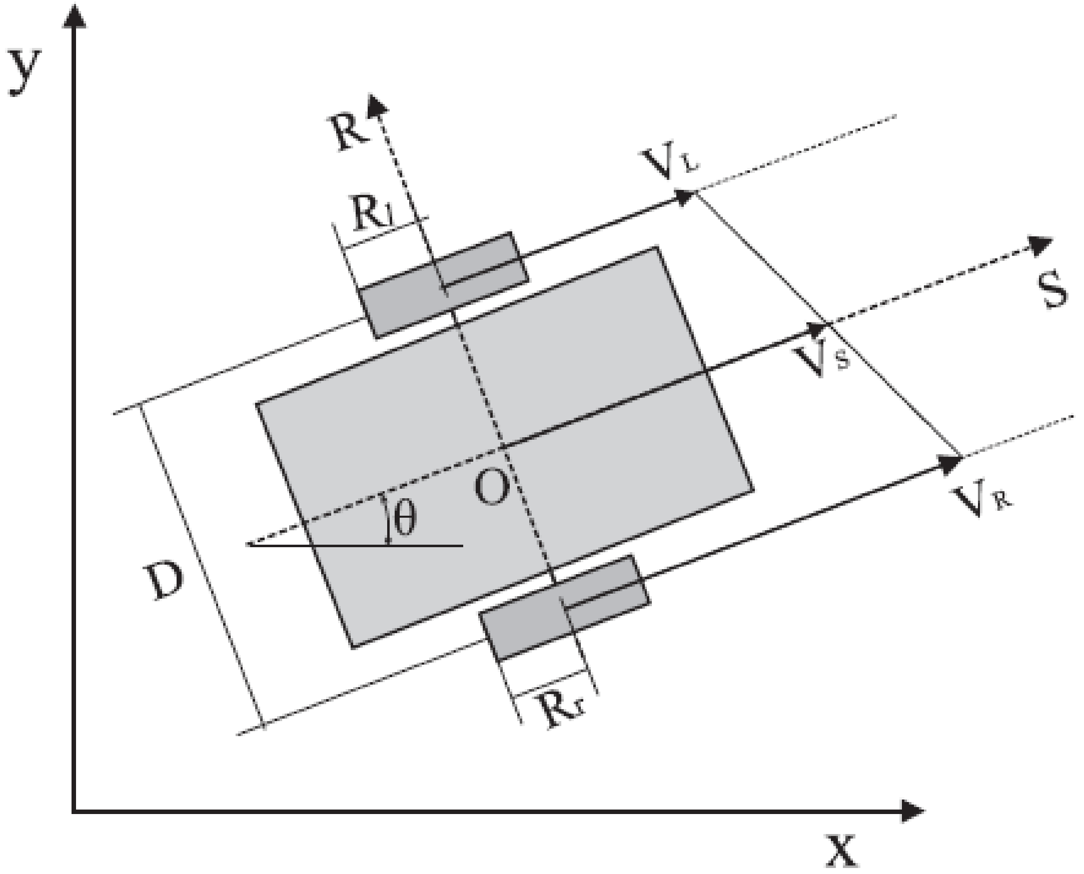
$$\dot{x} = V_S \cdot \cos\theta$$

$$\dot{y} = V_S \cdot \sin\theta$$

$$\dot{\theta} = \omega$$

$$V_S = \frac{\omega_r \cdot R_r + \omega_l \cdot R_l}{2}$$

$$\omega = \frac{\omega_r \cdot R_r - \omega_l \cdot R_l}{D}$$



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Inverse Kinematics

- The mathematical model that connects the properties of position in space to motor rotation is known as the inverse kinematic model.
- The inverse kinematic model is a set of equations that accept as variables the position of the motors (angle of rotation) and calculate the position of the robot (in the case of a manipulator, the position of the gripper).
- $(\theta_1, \theta_2 \ldots \theta_n) = g(x,y,z)$.
- The construction of this model is more difficult as it can have multiple solutions.

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Dynamics

- **Robot** dynamics is concerned with the relationship between the forces acting on a robot mechanism and the accelerations they produce. Typically, the robot mechanism is modelled as a rigid-body system, in which case robot dynamics is the application of rigid-body dynamics to robots. The two main problems in robot dynamics are:
  - **Forward dynamics**: given the forces, work out the accelerations.
  - **Inverse dynamics**: given the accelerations, work out the forces.
- Forward dynamics is also known as "direct dynamics," or sometimes simply as "dynamics." It is mainly used for simulation. Inverse dynamics has various uses, including: on-line control of robot motions and forces, trajectory design and optimization, design of robot mechanisms, and as a component in some forward-dynamics algorithms.

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Localization

- Localization involves one question: Where is the robot now?
- Localization techniques that work fine on an outdoor robot wouldn't work very good or even at all for an indoor robot.
- All localization techniques have to provide 2 pieces of information:
  - what is the current position of the robot?
  - where is it heading to?

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Dead-reckoning

- Dead reckoning uses odometry to measure how far the robot moves. Trigonometry and the equations of kinematics are all that is needed to calculate its new position.
- This method has 2 flaws:
  - It needs a way to determine its initial position.
  - its accuracy decreases over time as every measurement has an error, and all the inaccuracies add up.
- Dead reckoning is often used with other methods to increase their accuracy.

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Line-following

- Probably the easiest way: Draw a line on the ground and use IR reflection sensors to follow it. Useful as a track or to mark the edges of the robot's work area.
- Problems:
  - Limits the robot movement only on lines

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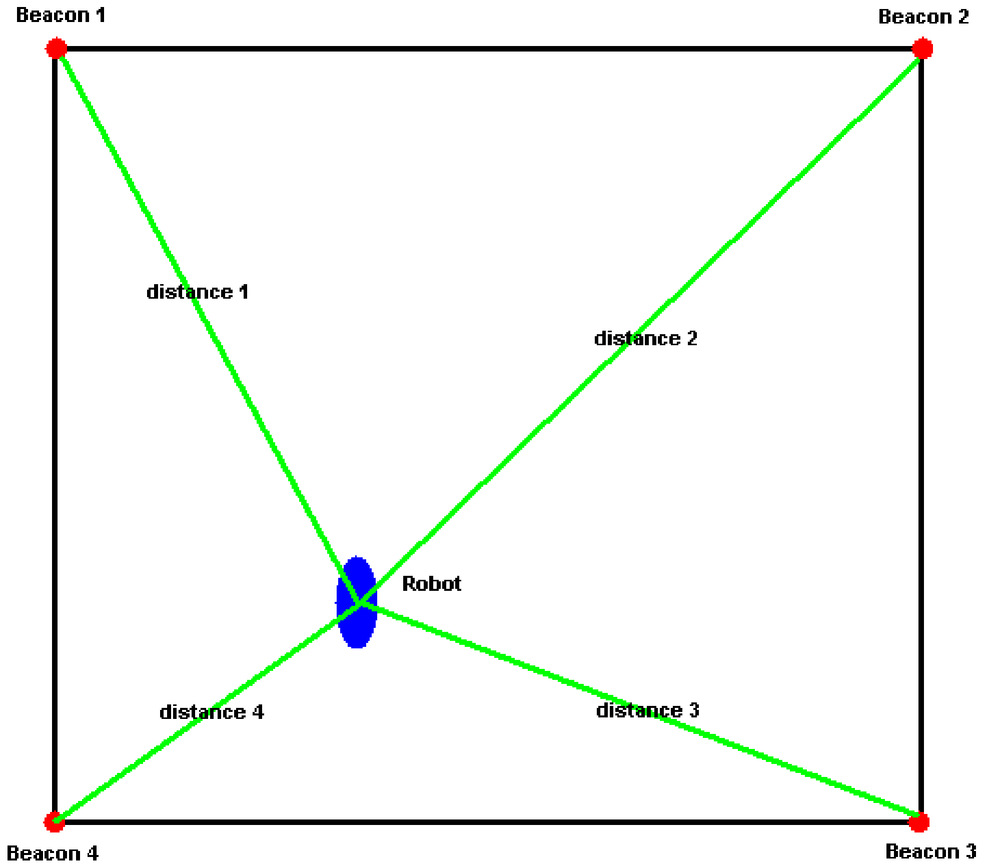
GPS like devices

- Although GPS isn't very useful indoors, similar techniques as those used in GPS can be used indoors.
- All a robot needs is to measure it's distance to 3 fixed beacons. Each of these distances describe a circle with the beacon in its center. 3 circles will only intersect in one point.



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Landmarks

- Placing landmarks is another way to help your robot to navigate through its environment. Landmarks can be active beacons (IR or sound) or passive (reflectors). Using bar code scanners is another possibility.
- A special trick, if the environment is known beforehand, is to use collision detection (i.e. sensor bumpers or similar) with known objects. Together with dead reckoning the precision can be extraordinary even when using cheap equipment.
- In new environments landmarks often need to be determined by the robot itself. Through the use of sensor data collected by laser, sonar or camera, specific landmark types (e.g. walls, doors, corridors) can be recognised and used for localization.

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Section 4:

Putting a brain to the robot

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AI & Robotics?

- Conventional robot deals with a very rigid, structural (controlled) environment and too simple.
- Real world is messy! ~ robot should be able to handle this! (with goals, information and behavior adaptation).
- Real world environments provide rich information BUT hard to understand by robot. AI provides some help to cope with this.
- Basically AI provides flexibility, automation and autonomy (possibly less human intervention) ~ through algorithms, concepts and devices.

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Intelligent Robots

- Mechanical species : capable to learn, to adapt and to “understand” the environment (or completing the mission) with less (or no more) human interference.
- Basically have digital “brain” on its own. Two approach ~ either central coordination or decomposition coordination.
  - **Central coordination**: there is a single processor did all things (more processing power).
  - **Decomposition coordination**: processing elements are distributed according to their functions. Interaction among each function is critical and crucial.

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Biological Inspired Robots (Biomimetic)

- **Essence: behavioral based robots**: mapping of sensory inputs to a pattern of motor actions which then used to achieve a task (robust to unstructured environment).
- Categories of behaviors:
  - **Reflexive behaviors**: stimulus response (typically hardwired).
  - **Reactive behaviors**: learned and executed without "conscious" thought → muscle memory for athletes.
  - **Conscious behavior**: high level and deliberated!

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The Example of Biomimetic Program

(innate releasing mechanism)

```
#define T LONG_TIME
Enum Releaser = {present, not_present}
WHILE (TRUE) {
      predator = sensePredator();
      IF (predator == present)
            for(time = T; time > 0; time --) {
                  flee();

            }
            food = senseFood();

            hungry = checkStateHungry();
            IF (hungry == present && food == present)
                  feed();
            IF (hungry == present && food == not_present)
                  searchForFood();

      }

}
```


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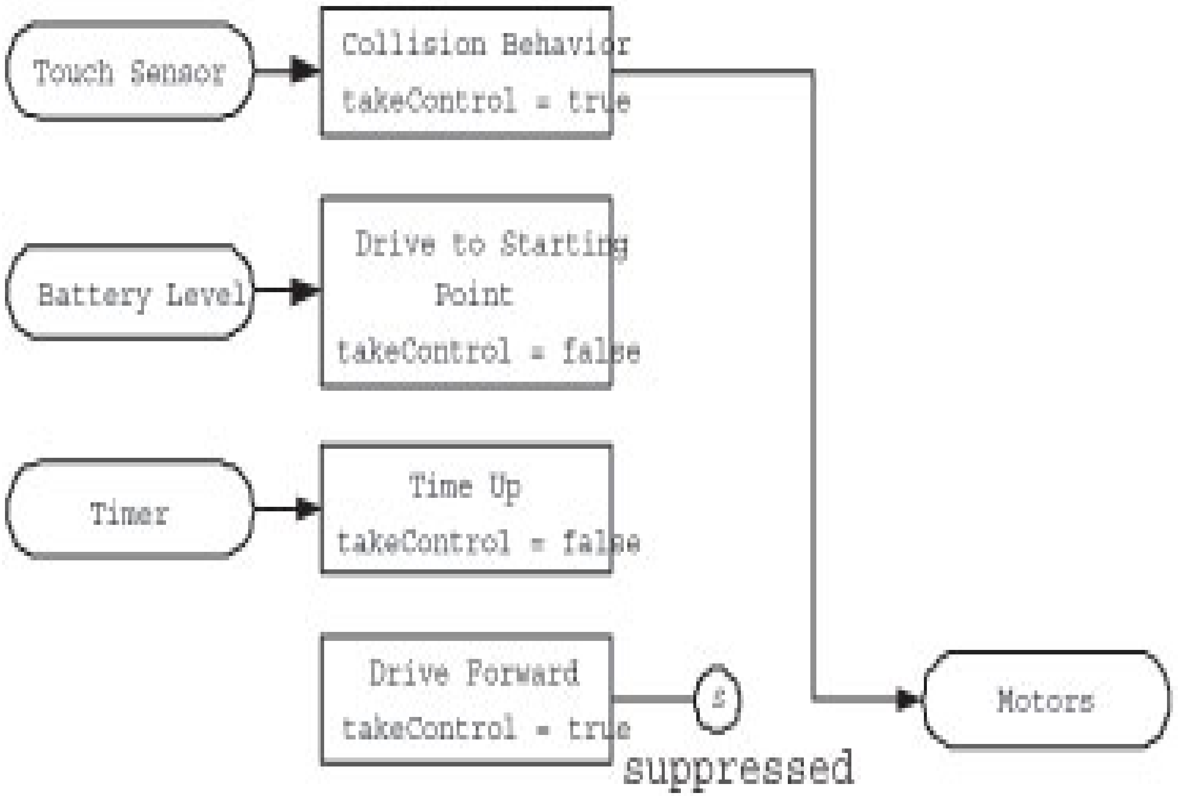
Subsumption Architecture

- Decomposing complicated intelligent behaviour into many "simple" behaviour modules, which are in turn organized into layers.
- Each layer implements a particular goal of the robot, and higher layers are increasingly abstract.
- Each layer's goal subsumes that of the underlying layers, e.g. the decision to move forward by the eat-food layer takes into account the decision of the lowest obstacle-avoidance layer.



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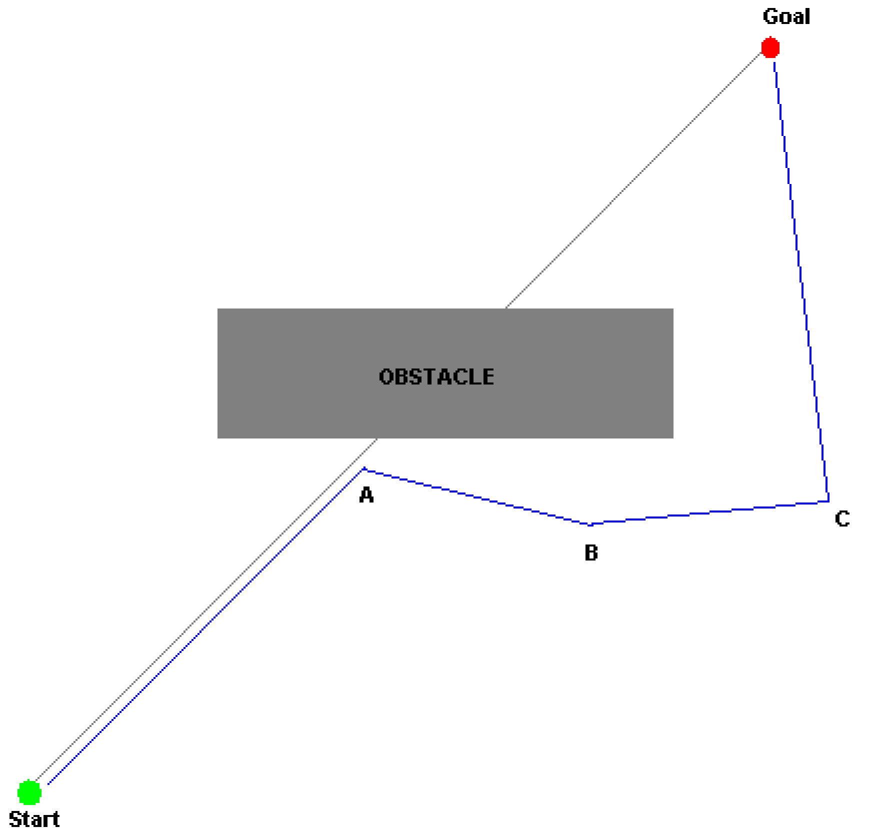
Subsumption example

- Robots moves towards goal (go to beh
- At point A detects obstacles, and avoid
- At B it still detects obstacles and avoid
- At C it no longer detects obstacles so r



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Motion Planning

- The World consists of:
  - Obstacles
    - Already occupied spaces of the world
    - In other words, robots can't go there
  - Free Space
    - Unoccupied space within the world
    - Robots "might" be able to go here
    - To determine where a robot can go, we need to discuss what a *Configuration Space* is

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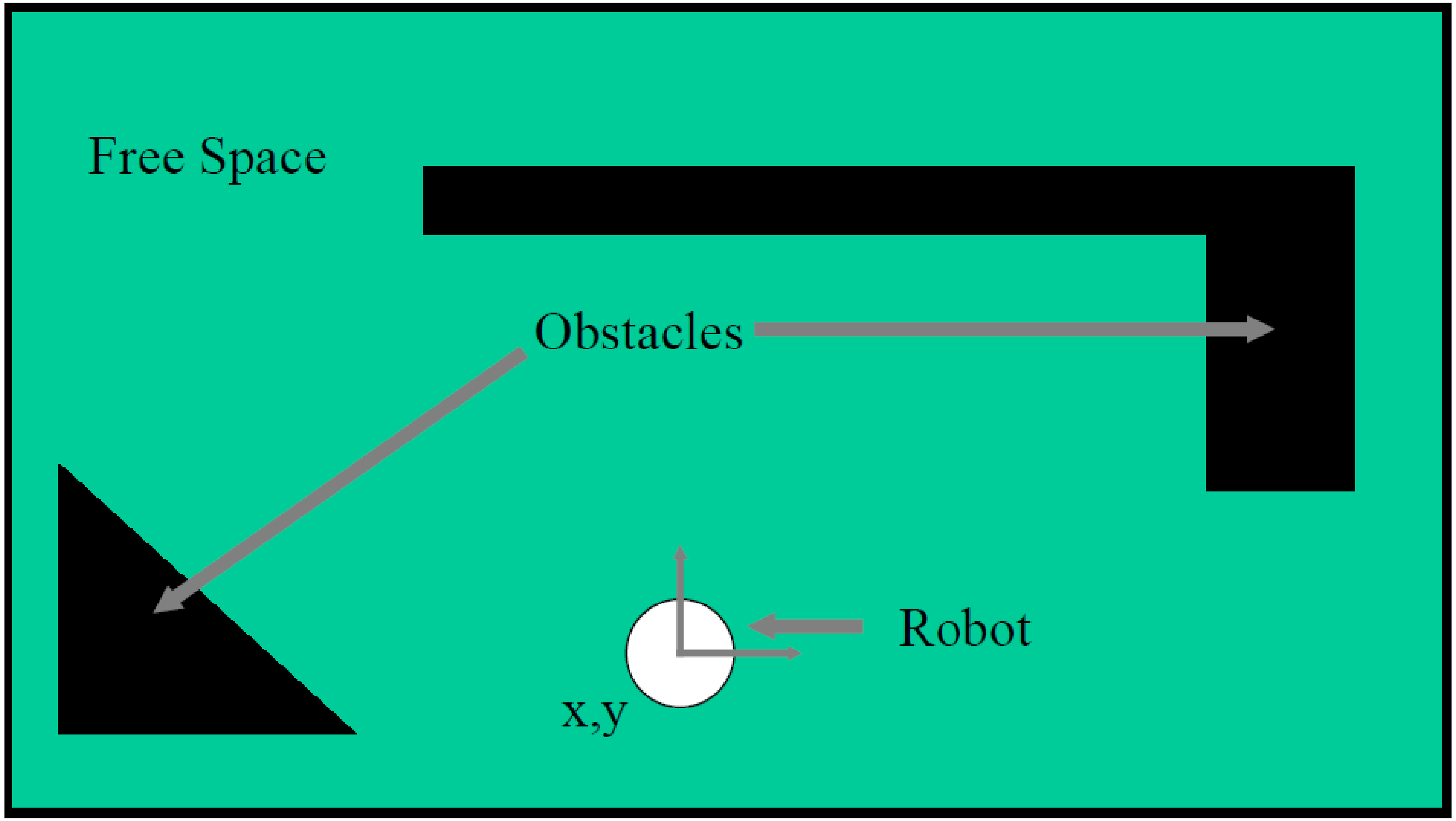
Example of a World (and Robot)



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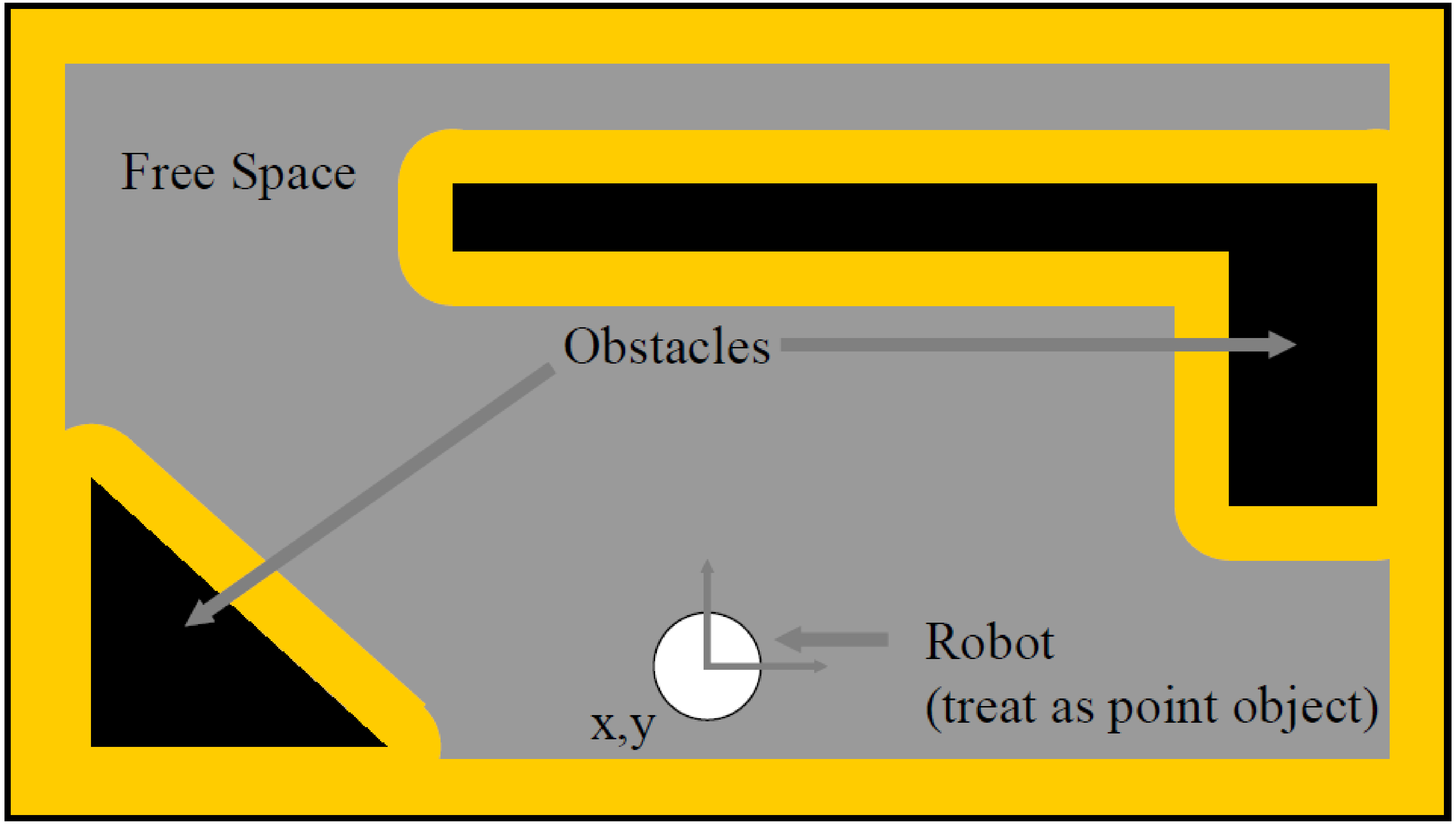
Configuration Space: Accommodate for the size of the robot.



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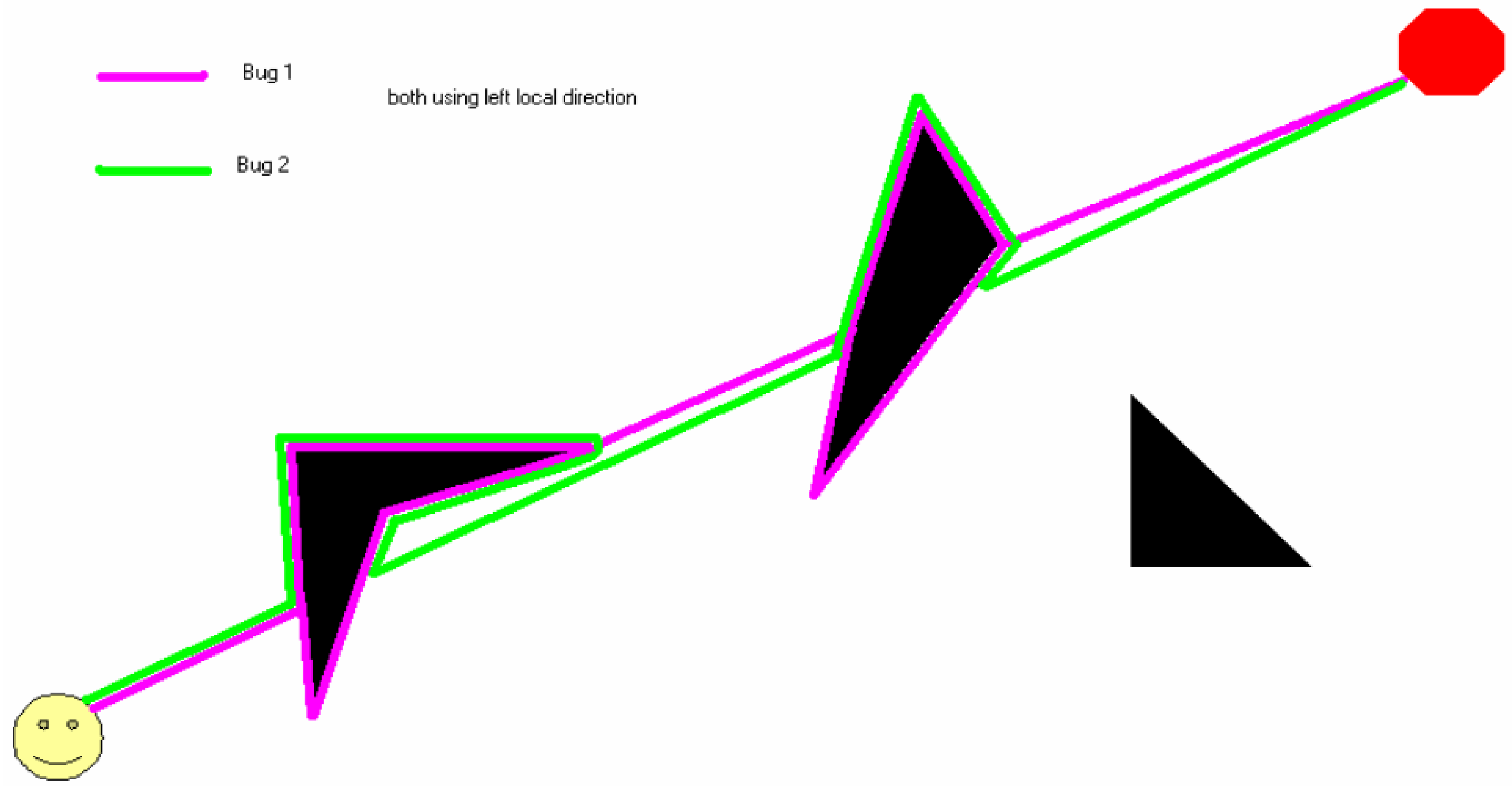
Lumelsky Bug Algorithms



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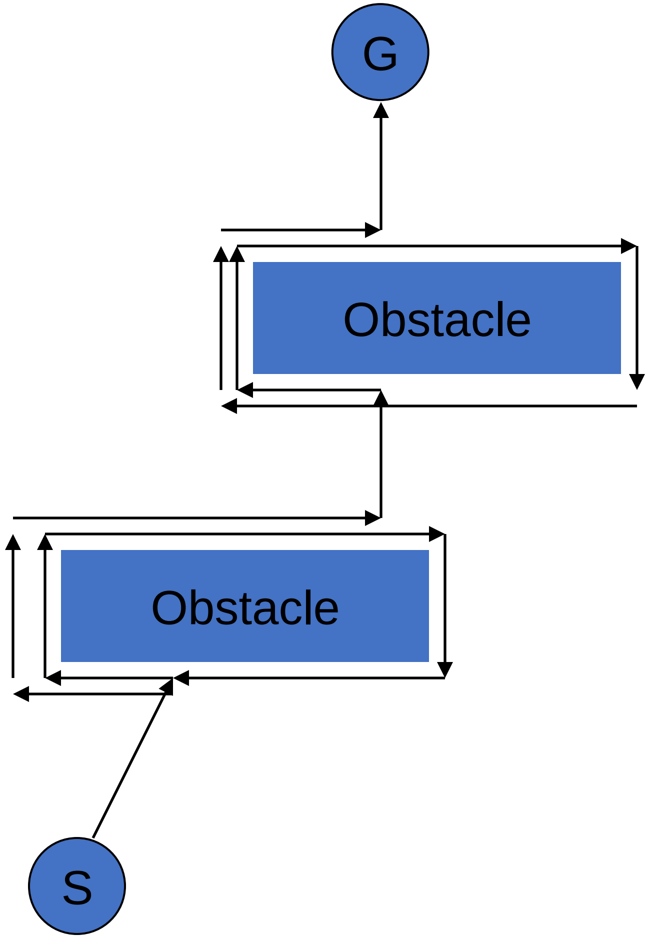
Bug 1 algorithm

- Requires:
  - known direction to goal
  - otherwise local sensing

1. head toward goal
2. if an obstacle is encountered, circumnavigate it and remember how close you get to the goal
3. return to that closest point (by wall-following) and continue

- We assume left local direction (turning left when see obstacle)



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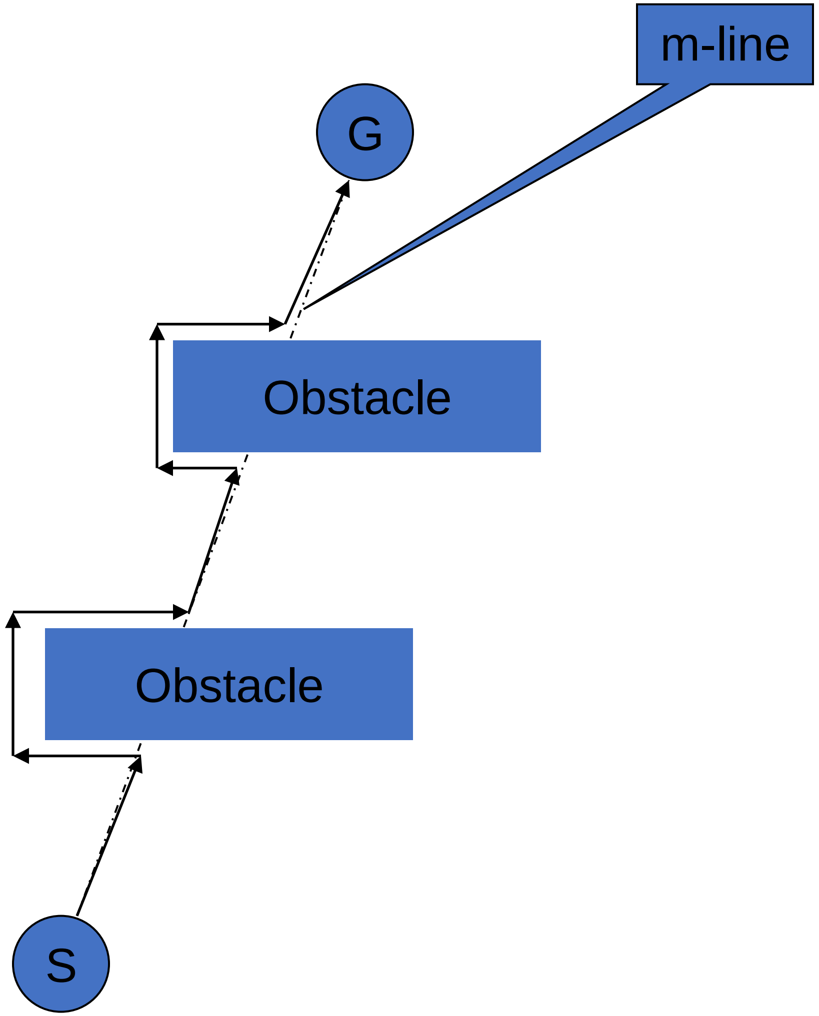
Bug 2 algorithm

1. head toward goal on the *m-line*
2. if an obstacle is in the way, follow it until you encounter the m-line again.
3. Leave the obstacle and continue toward the goal



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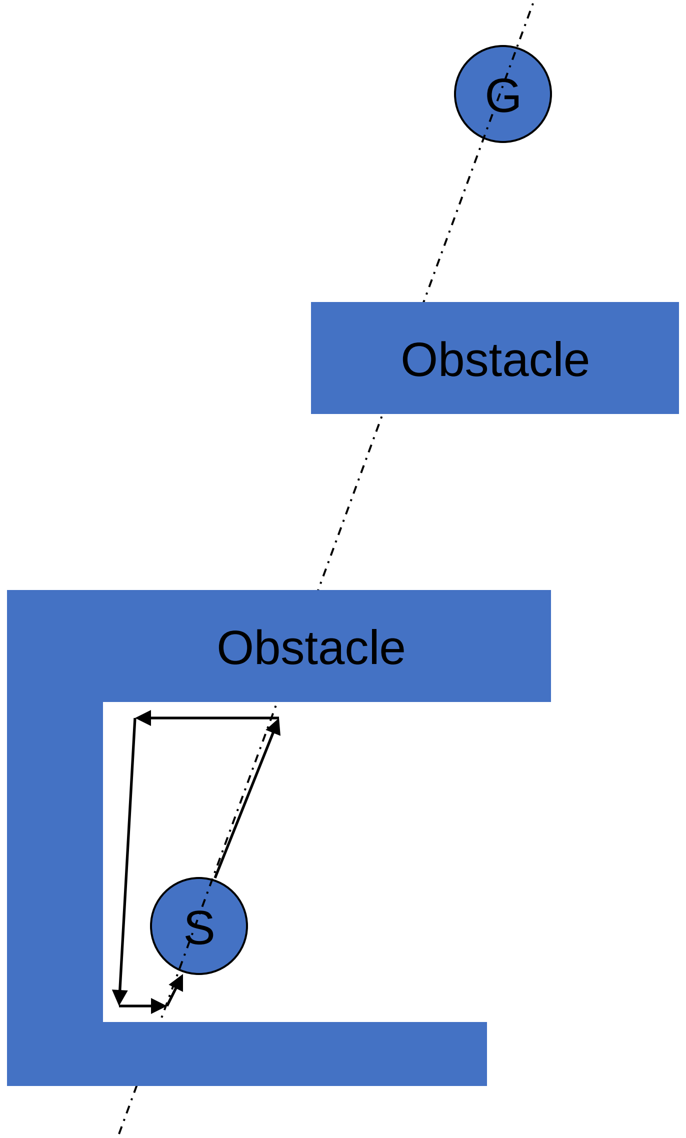
A bug in Bug 2?

1. head toward goal on the *m-line*
2. if an obstacle is in the way, follow it until you encounter the m-line again.
3. Leave the obstacle and continue toward the goal



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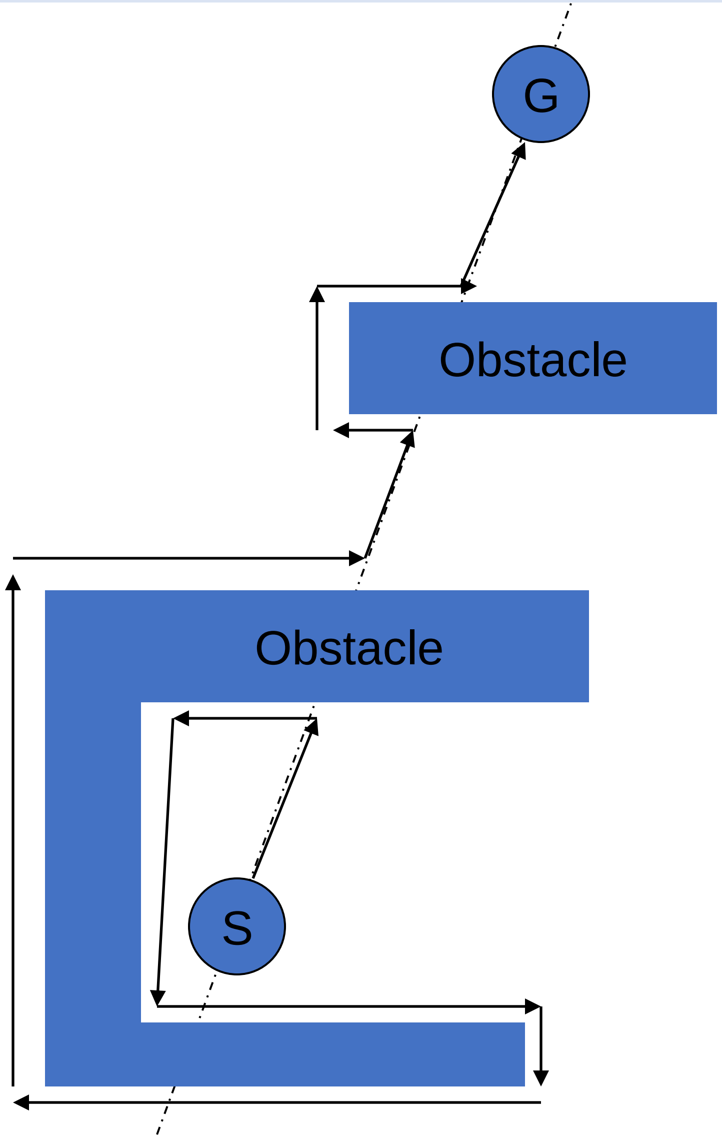
Fixing the bug in Bug 2

1. head toward goal on the *m-line*
2. if an obstacle is in the way, follow it until you encounter the m-line closer to the goal.
3. Leave the obstacle and continue toward the goal



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Wavefront (Overview)

- Divide the space into a grid.
  - Number the squares starting at the start in either 4 or 8 point connectivity starting at the goal, increasing till you reach the start.
- Your path is defined by any uninterrupted sequence of decreasing numbers that lead to the goal.

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Setup

7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
3	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

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Step 1

- Starting with the goal, set all adjacent cells with "0" to the current cell + 1
  - 4-Point Connectivity or 8-Point Connectivity?
  - Your Choice. We'll use 8-Point Connectivity in our example

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
3	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2

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Step 2

- Now repeat with the modified cells
  - This will be repeated until no 0's are adjacent to cells with values >= 2
    - 0's will only remain when regions are unreachable

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
3	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	4
1	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3	2

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Repeating..

7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
3	0	0	0	0	1	1	1	1	1	1	1	1	5	5	5	5
2	0	0	0	0	0	0	0	0	0	0	0	0	5	4	4	4
1	0	0	0	0	0	0	0	0	0	0	0	0	5	4	3	3
0	0	0	0	0	0	0	0	0	0	0	0	0	5	4	3	2
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

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Until

- Zeros will only remain in unreachable regions

7	**18**	17	16	15	14	13	12	11	10	9	9	9	9	9	9	9
6	17	17	16	15	14	13	12	11	10	9	8	8	8	8	8	8
5	17	16	16	15	14	13	12	11	10	9	8	7	7	7	7	7
4	17	16	15	15	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	6	6	6	6
3	17	16	15	14	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	5	5	5	5
2	17	16	15	14	13	12	11	10	9	8	7	6	5	4	4	4
1	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	3
0	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	**2**
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

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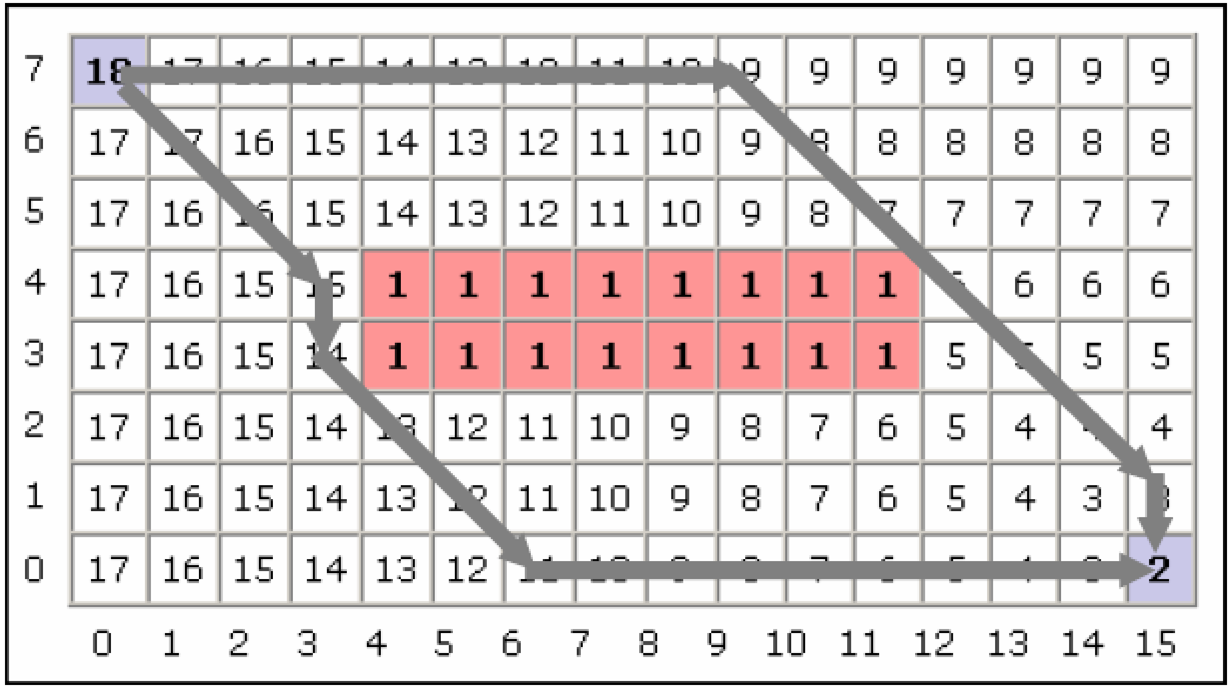
Finally,

- To find the shortest path, according to your metric, simply always move toward a cell with a lower number
  - The numbers generated by the Wavefront planner are roughly proportional to their distance from the goal



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Section 5

Case studies

Figure 6. A user giving rubbish to the robot. (Photo courtesy of Foto Silvi.)

The Robot DustCart

By Pericle Salvini, Giancarlo Teti, Enza Spadoni, Cecilia Laschi, Barbara Mazzolai, and Paolo Dario

Peccioli became one of the first places in the world where a robot was used (not demonstrated) to carry out a public service in the urban environment.

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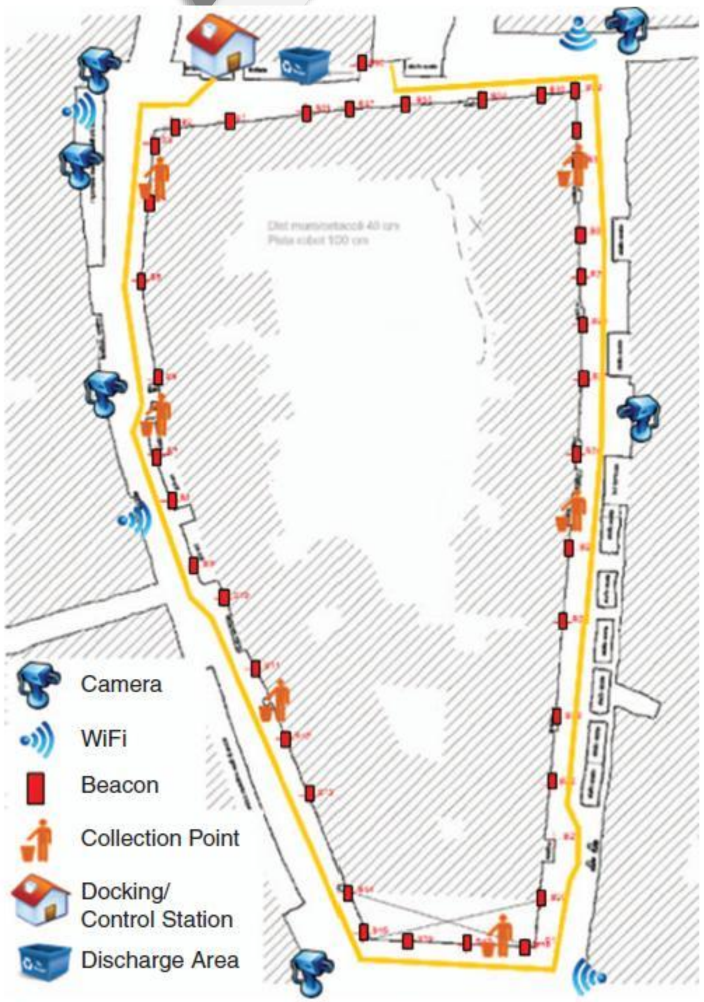

Figure 2. The experimental site with the location of the beacons, docking station, cameras, and access point of the wireless network. (Photo courtesy of Giancarlo Teti.)

Figure 4. DustCart discharging a rubbish bag. (Photo courtesy of Giancarlo Teti.)

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To determine the overall level of acceptance of innovations such as DustCart, it should also be necessary to include ethical, social, and legal issues.

http://www.youtube.com/watch?v=wtpNCnfkKE8

http://www.youtube.com/watch?v=4gt09873luI

Figure 8. The robot lane (right-hand side of the picture). (Photo courtesy of Giancarlo Teti.)

Figure 9. A curious and interested group of people.

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Programmable matter aims to bring machines and materials closer together by creating machines that become more like materials and materials that behave more like machines. This is a considerable challenge with exciting potential for future payoffs.

Modular Robot Systems

From Self-Assembly to Self-Disassembly

BY KYLE GILPIN AND DANIELA RUS

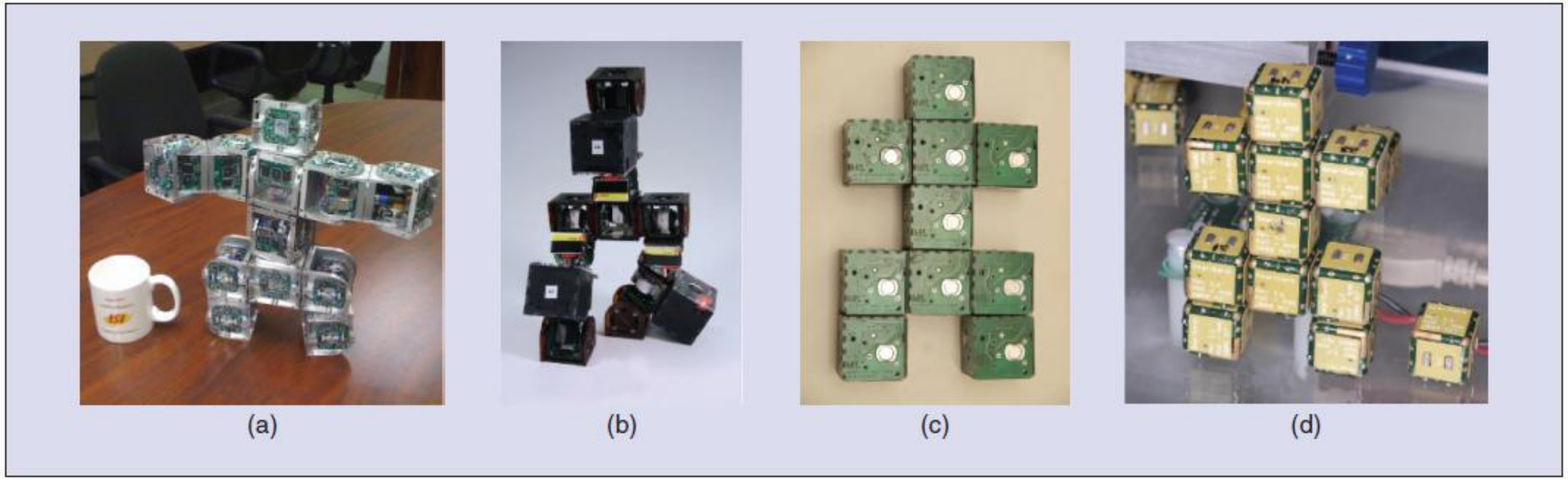

Figure 1. *(a) Six Superbot modules assembled by hand to form a humanoid. (b) CKBot modules forming a similar structure that is able to self-repair itself after being damaged. (c) The Miche system lacks internal degrees of freedom, but it was produced through the self-disassembly of a 3 × 5 block of modules. (d) The humanoid formed by the Smart Pebbles system. (SuperBot picture courtesy of Polymorphic Robotics Laboratory, University of Southern California, Dr. Wei-Min Shen. CKBot picture courtesy of Prof. Mark Yim, University of Pennsylvania.)*

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Some Modules

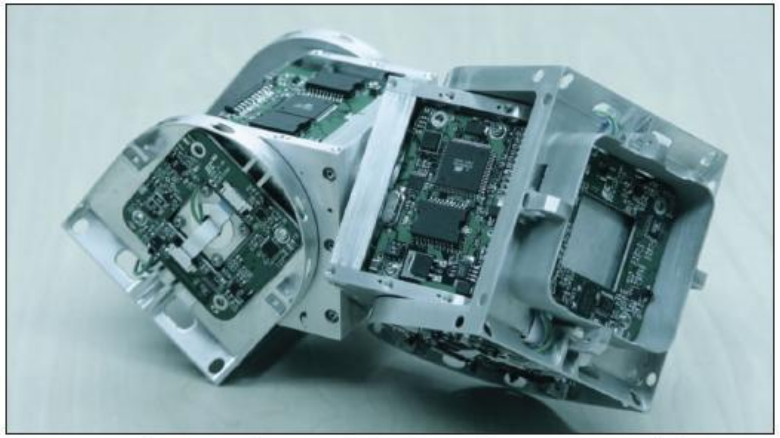

Figure 2. *The Superbot modules have three rotational degrees of freedom and are designed to operate in real-world scenarios. Each Superbot module fits within a 168 × 84 × 84 mm^3 rectangular box. (Picture courtesy of Polymorphic Robotics Laboratory, University of Southern California, Dr. Wei-Min Shen.)*

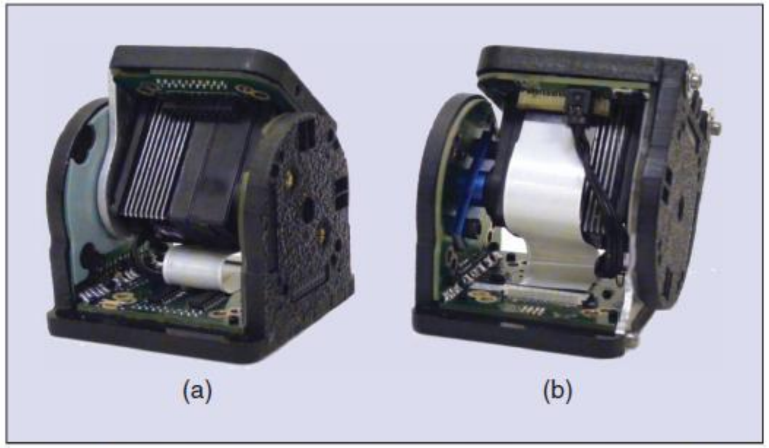

Figure 3. *The CKBot modules each contain one rotational degree of freedom and are capable of mating with other modules in a variety of configurations. Each module fits within a 60-mm cube. (Picture courtesy of Prof. Mark Yim, University of Pennsylvania.)*

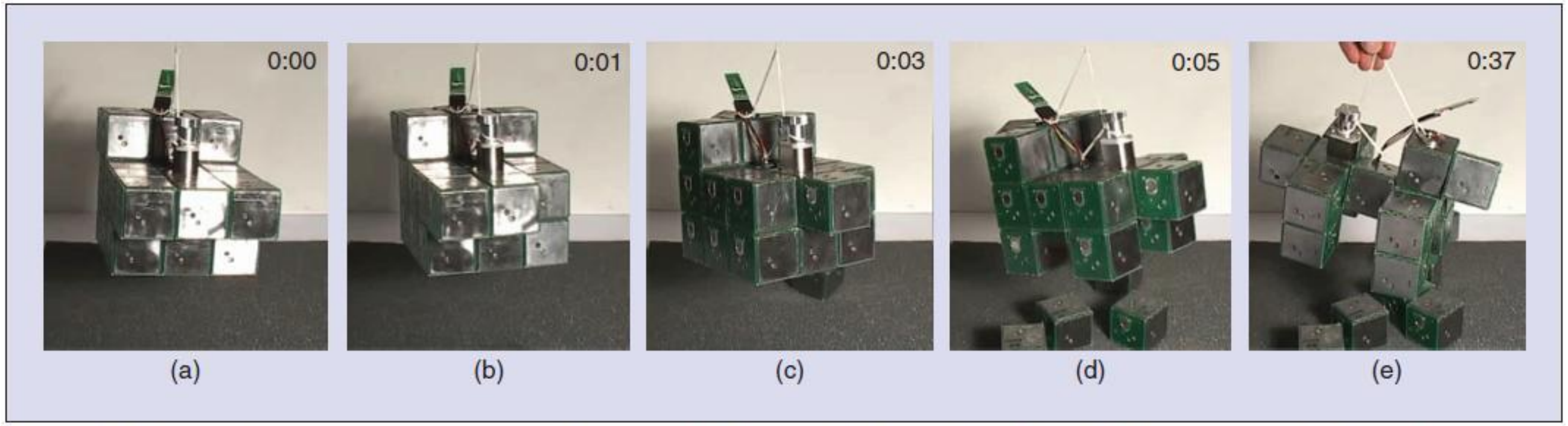

Figure 13. *A dog-shaped structure can be self-disassembled from an initial configuration of 27 suspended Miche modules (each 45-mm per side). (Picture courtesy of Daniela Rus, Distributed Robotics Laboratory at MIT.)*

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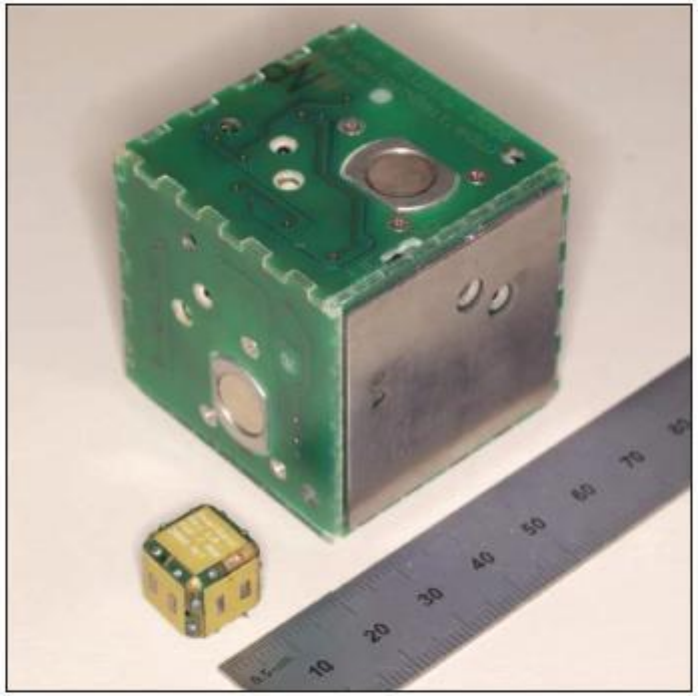

Figure 10. *The Pebble modules are 50 times smaller by volume (12 versus 45 mm per side) and five times stronger by weight. (Picture courtesy of Daniela Rus, Distributed Robotics Laboratory at MIT.)*

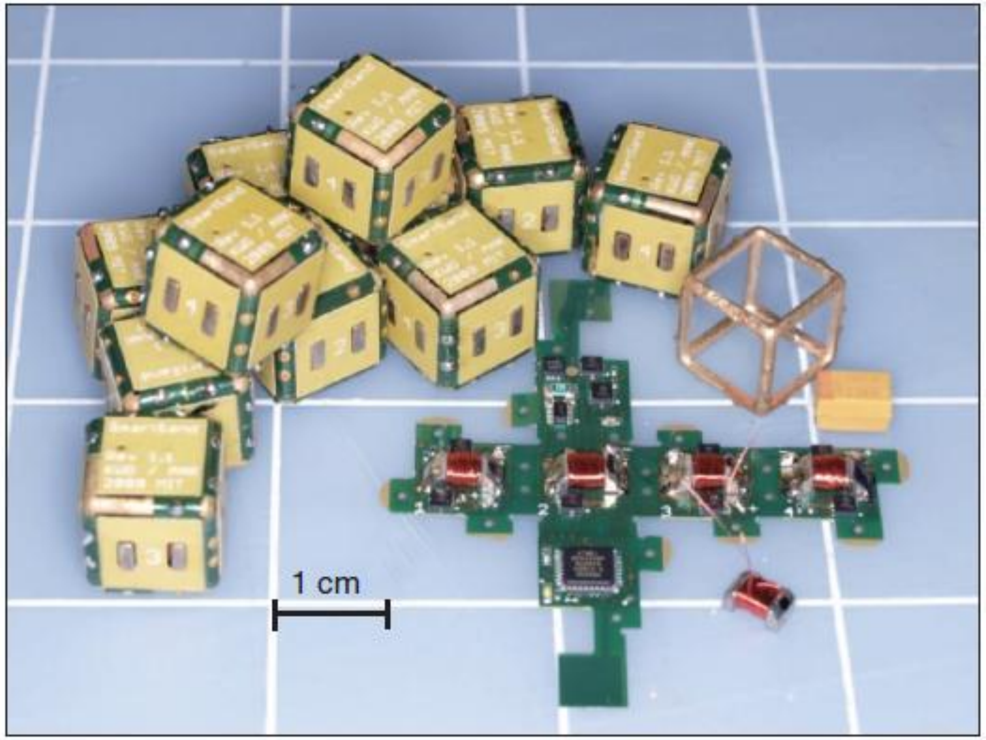

Figure 11. *Each programmable matter Smart Pebble is a cube with 12-mm sides. A collection of Smart Pebbles are able to form complex 2-D shapes using four EP magnets that are able to hold 85 times the individual module weight. The Pebbles are formed by wrapping a flexible circuit around a brass frame. An energy storage capacitor hangs between two tabs occupies the center of the module. (Picture courtesy of Daniela Rus, Distributed Robotics Laboratory at MIT.)*

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Roombots: Reconfigurable Robots for Adaptive Furniture

http://www.youtube.com/watch?v=vlXh8RvvcuI

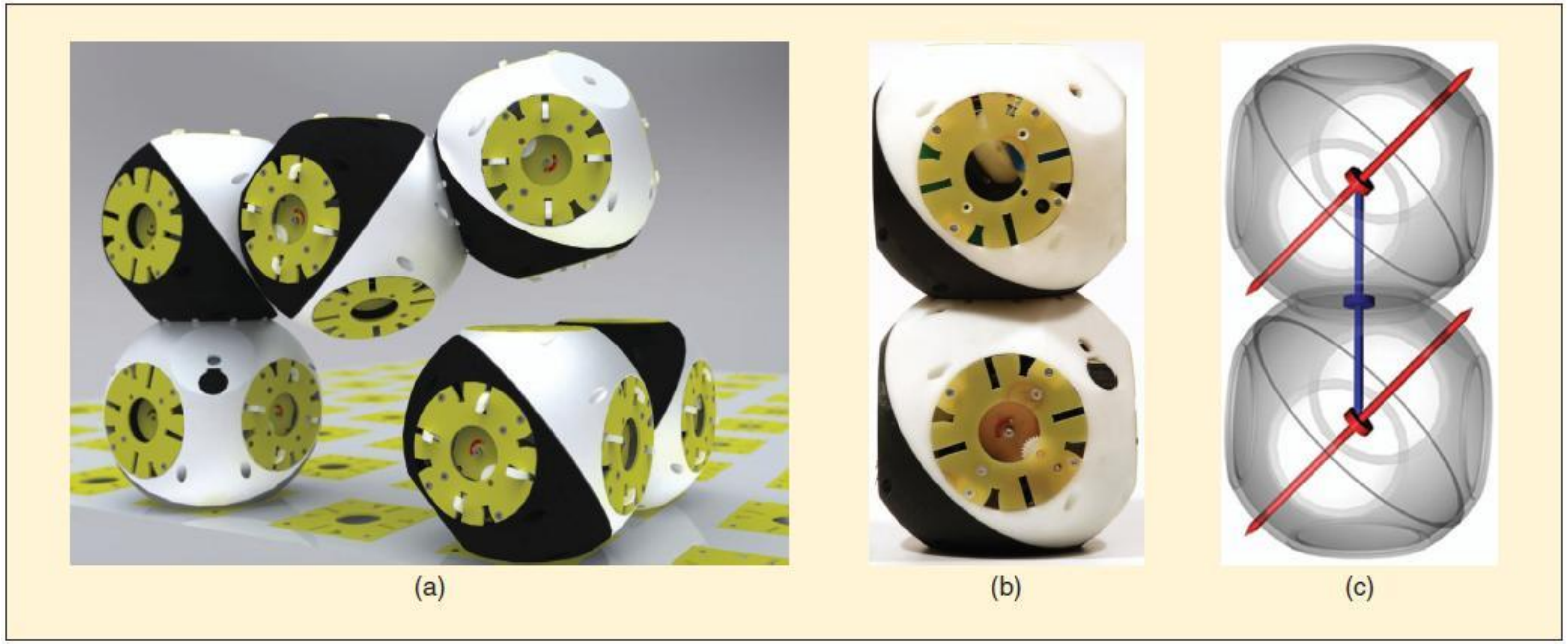

FIGURE 1 (a) Rendered visualization of one Roombots *metamodule* on the left and a *single* Roombots module on the right. Rectangular connector plates (yellow/green) are embedded in the floor. (b) Roombots module (real picture). (c) Three DOF per Roombots module: red axes are outer DOF, the blue DOF is rotating the two sphere-like parts of a Roombots module against each other. The ability to freely swivel the two outer joints against each other distinguishes a single Roombots module from plugging two Molecube [28] modules together. This loosely follows the concept of adding a center joint in Superbot [30], compared to M-TRAN II [31].

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