Simplified Automated Material Handling System:

MAGNEBOTS

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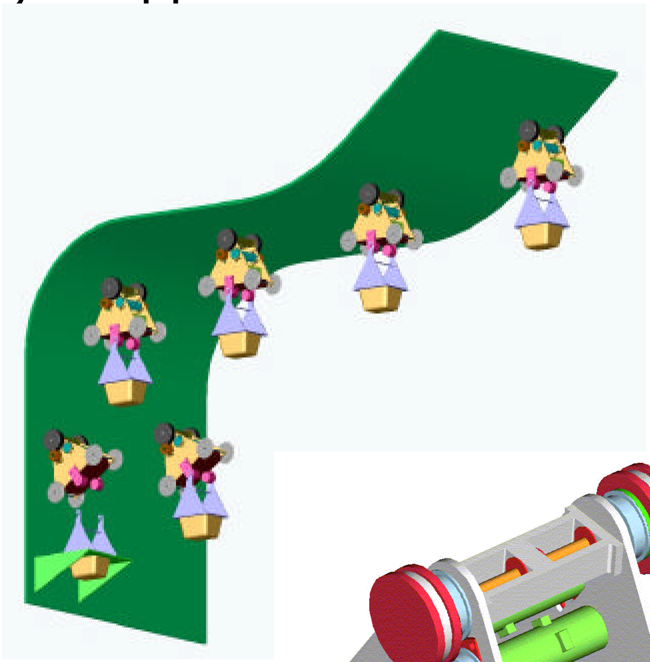
http://pergatory.mit.edu/magnebots

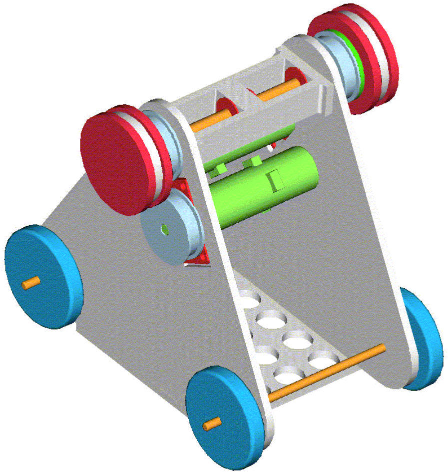
MAGNEBOTS Concept

GOAL: Develop a low-cost, high-performance automated material transportation system for a variety of applications

FUNCTIONAL REQUIREMENTS:

- Simple design
- High speed, quality motion.
- Flexible layout
- Expandable and integrable
- Standard hardware and software interfaces
- Small footprint
- Operational safety





STRATEGY: Use small triangular battery-powered vehicles attached to a trackless steel pathway surface by magnetic wheels.

Outline

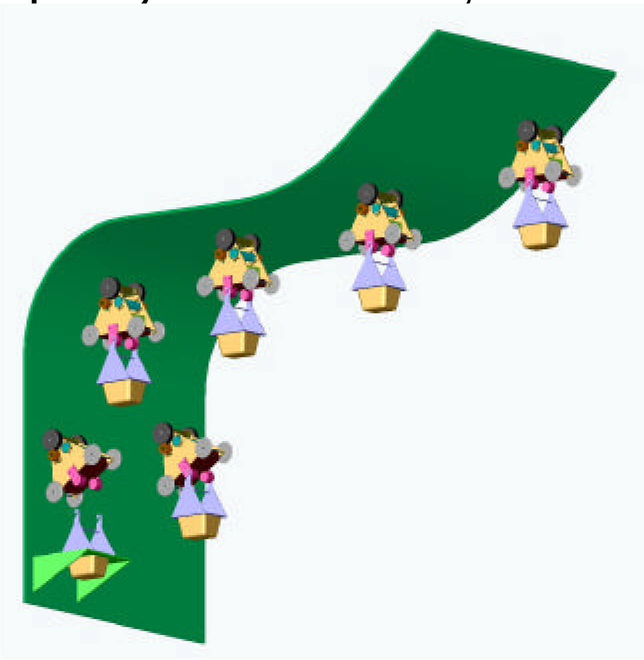
- Background
- System concept
- Magnebot vehicle:
  - Mechanical design
  - Control algorithm + sensor system
  - Communications hardware
- Prototypes
- Conclusions

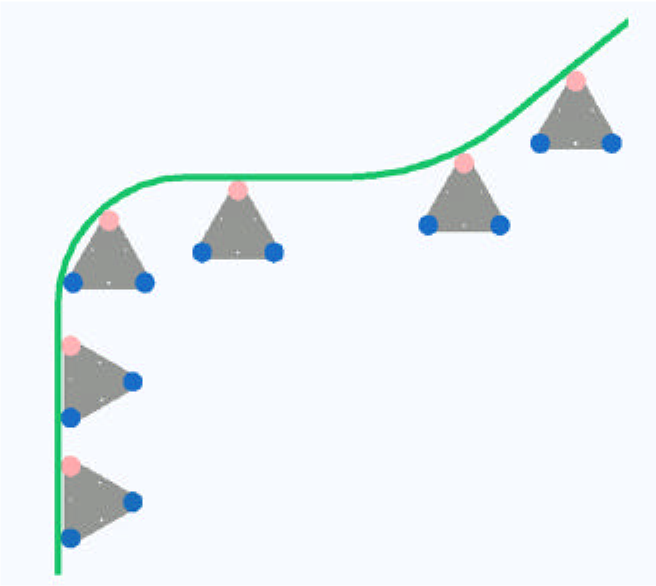
Automated Material Handling Needs

- Factory Automation
- Cleanroom Automation
- Warehouse Automation
- Hospital Automation
- Office/Home Automation

Magnebots: Salient Features

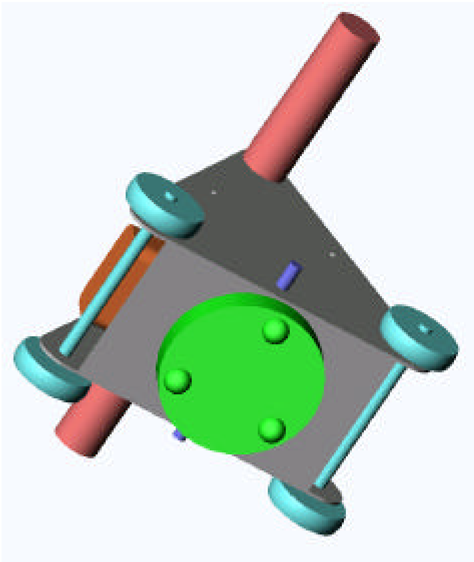
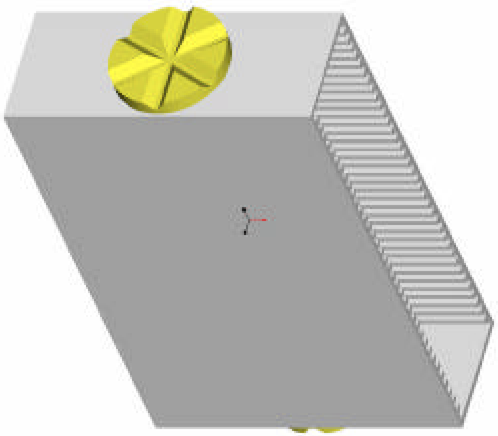
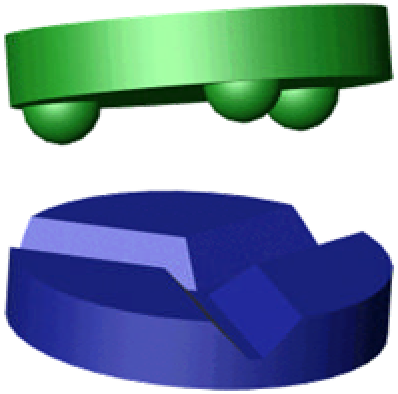
- **Trackless design:**
  - Zero footprint vs. floor-based AGV or overhead monorail systems.
  - No need for complex track-switching modules or storage systems.
  - Thin metal sheets can be bent into any shape.
  - Pathway sections and vehicles and can be added and removed anywhere, anytime.
  - Simplicity = lower cost, increased transportation speed.





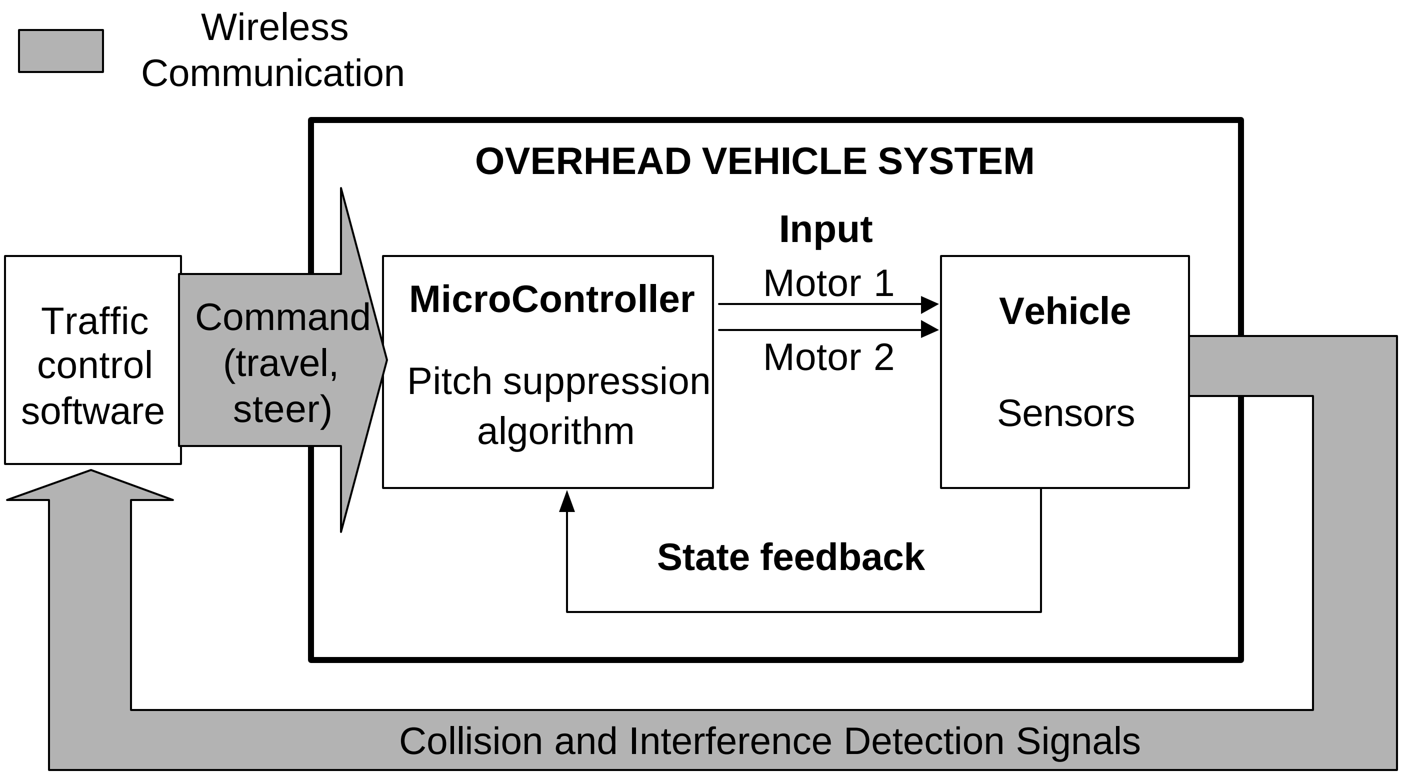
Salient Features

- **Cordless vehicles:**
  - Each suspended by two wheels with permanent magnets.
  - Differential control of DC drive motors.
  - On-board control algorithm suppresses pendulum-like swing motion.
- **Standard Interfaces:**
  - Self-engaging/disengaging payload coupling.
  - Wireless TCP/IP communications among vehicles and other clients.

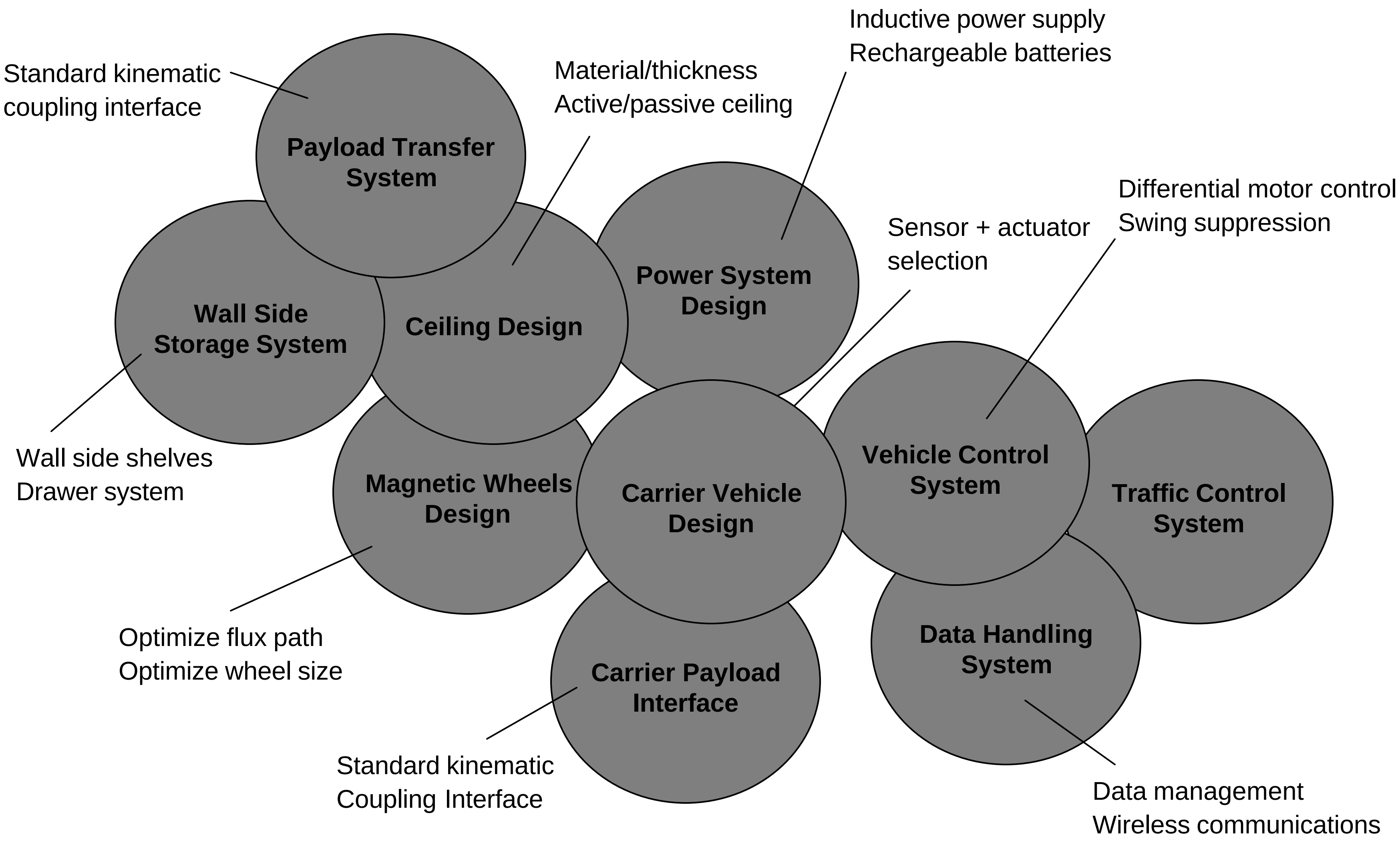




Salient Features

- **Local control with centralized command:**
  - Position tracking dead-reckoning between references
  - Centralized collision prediction/avoidance



Design Strategy: Modules



Magnebot Vehicle Design

Chassis:

- Closed structure: stiff and lightweight
- Monolithic pillow block ensures good bearing alignment.

Motors:

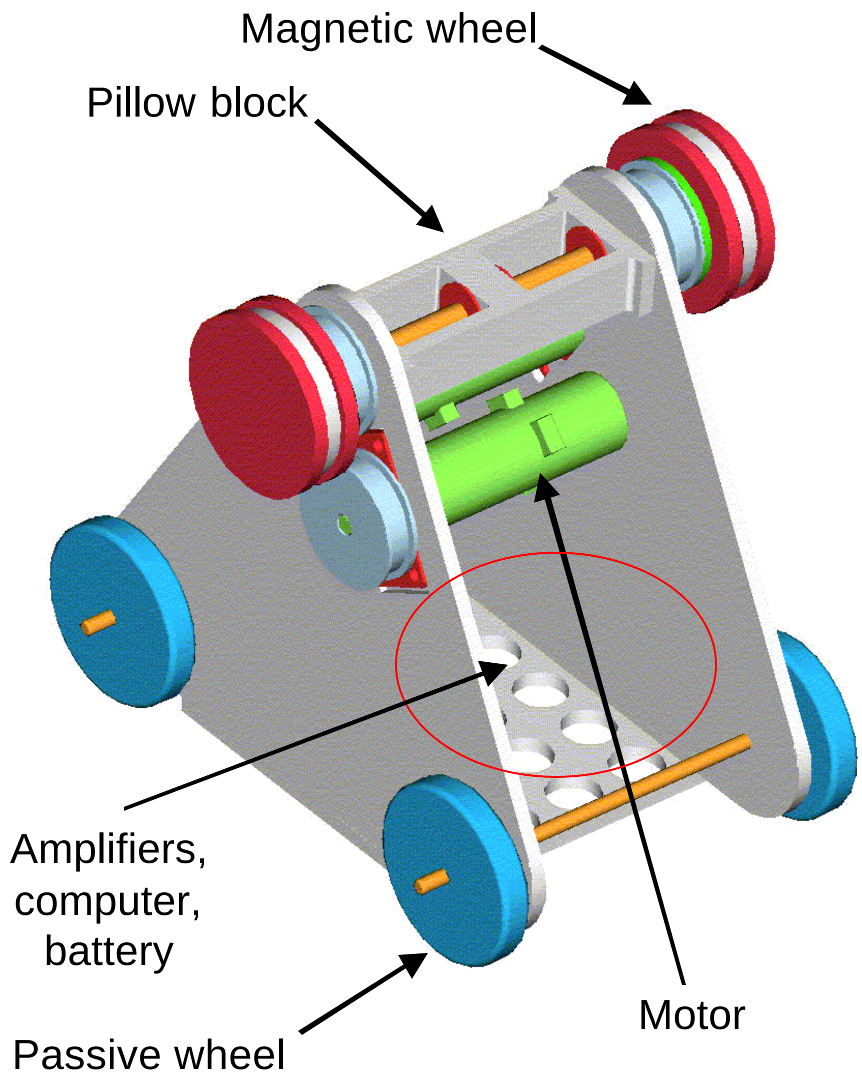
- Mount directly to side plates
- Require high torque output and stall torque
- Low RPM

Amplifiers:

- Compact + lightweight
- Operate at low voltage (< 25 V)

Passive wheels:

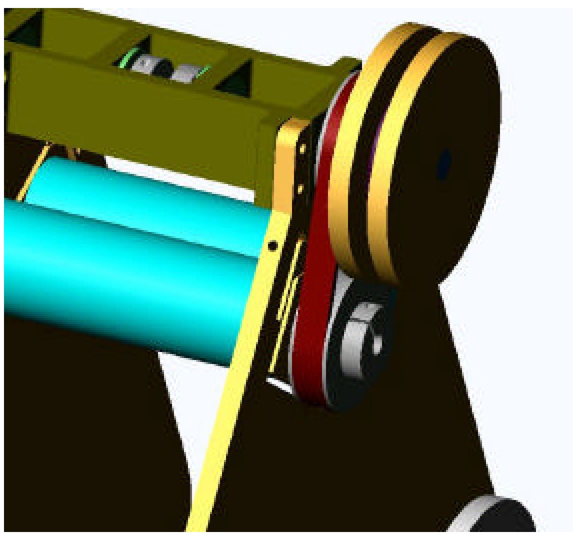
- Delrin w/rubber coating



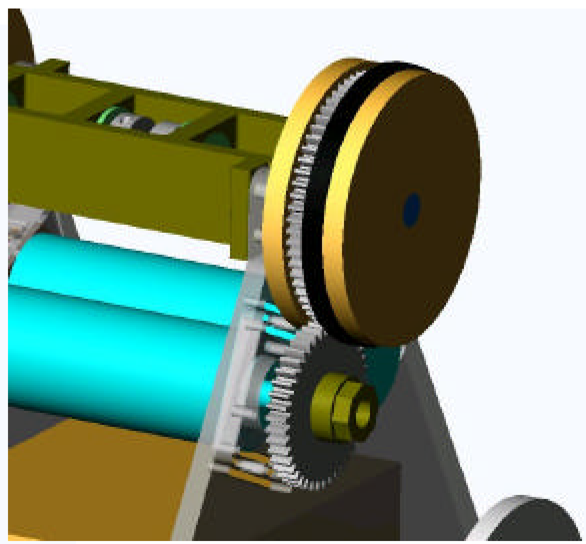
Drive Coupling

Chassis design accommodates various drive couplings:

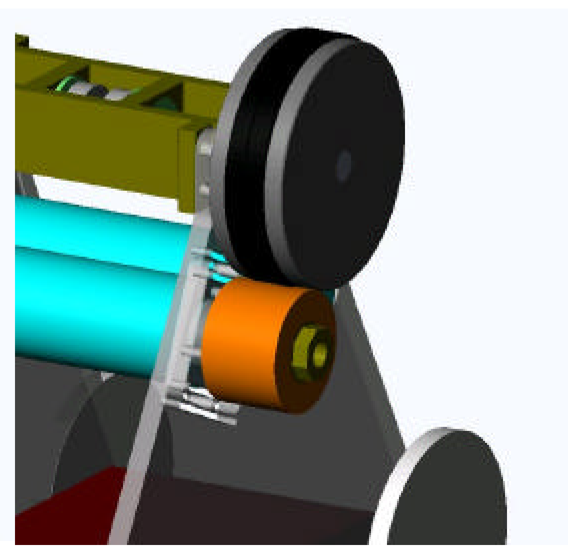
- ~3:1 additional transmission reduction
- 0.5g acceleration demands approximately 1.5 N-m per motor
- Friction drive features:
  - Self-preloading (between steel roller and magnetic drive wheel)
  - Flexural motor mounts cut directly into side plates



Belt drive
$<1^{o}$ backlash



Gear drive
$<1^{o}$ backlash

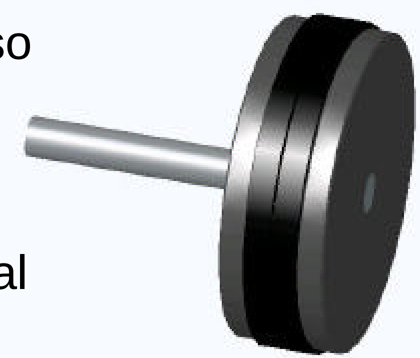


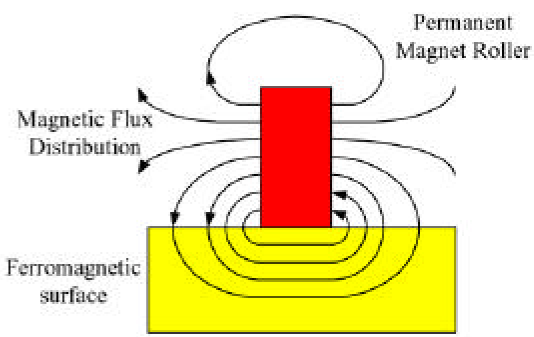
Friction drive
0^{o} backlash

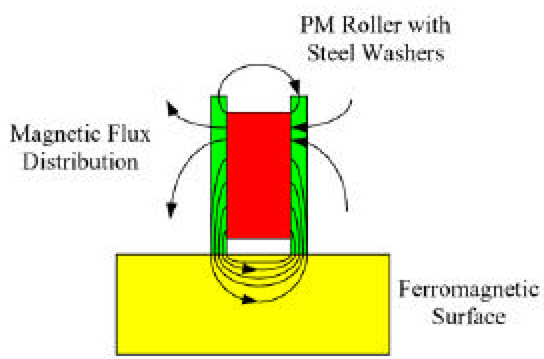
Magnetic Wheels

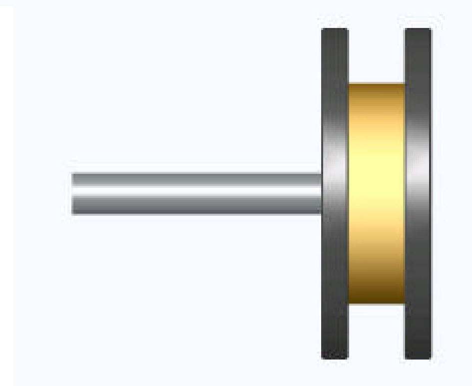
Permanent magnet mounted between steel washers:

- Long history of similar usage for robots to inspect pipelines.
- Washers (low reluctance) focus the magnetic flux, increasing the attractive force.
- Limiting condition is preventing slip while climbing walls, so add rubber disks over magnets to increase friction coefficient.
- Neodymium-Iron-Boron magnets.
- Press-fit shaft through magnet and washers, then turn final pass to ensure concentricity.
- > 40 lb normal force per wheel; ~30% sacrifice when rubber is added.





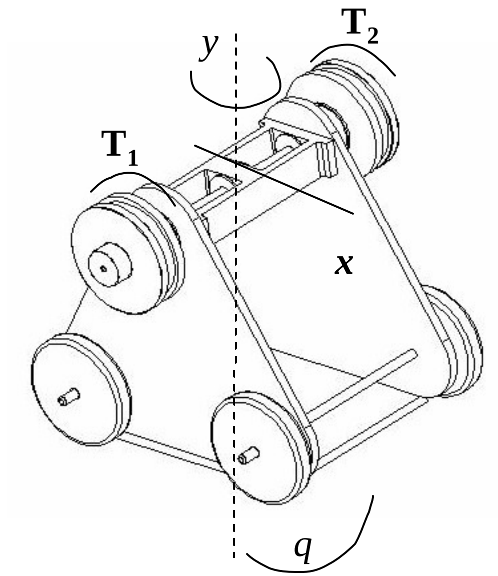




Control Strategy

Maintain zero pitch angle while tracking forward velocity and steer velocity commands:

- System states:
  - $x, \dot{x}$
  - $q, \dot{q}$
  - $y, \dot{y}$



- Control inputs
  - Motor torques: T_1, T_2
- Many control schemes possible:
  - Full-state feedback
  - State-space (LQR)
  - Loop-within-loop
- Friction compensation

$$T_{drive} = \frac{T_1 + T_2}{2}, \quad T_{yaw} = \frac{T_1 - T_2}{2}$$

$$\frac{q}{T_{drive}} = \frac{-a}{s^2 + {k_2}^2}$$

$$\frac{X}{T_{drive}} = \frac{b(s^2 + {k_1}^2)}{s^2(s^2 + {k_2}^2)}$$

$$\frac{y}{T_{yaw}} = \frac{c}{s^2}$$

Sensor System

Accelerometers:

- Analog Devices ADXL202AE MEMS accelerometer
- Mounted as close to vehicle pivot as possible.
- Senses gravitational acceleration plus dynamic acceleration, e.g.:

$$V = V_{set} + C_{sens}(\ddot{x}\cos(q) - g\sin(q))$$

Rate gyros:

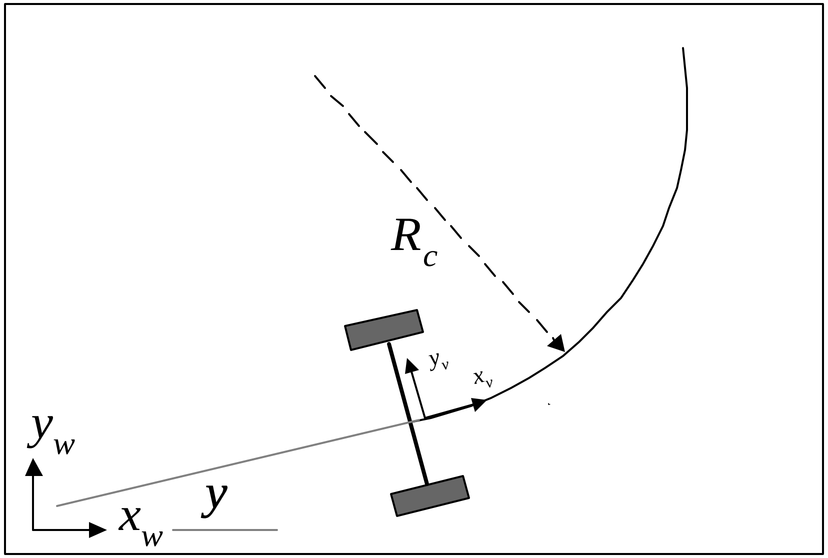
- Gyration MicroGyro 100 2-axis rotation rate sensor.

Low pass filter on accelerometer + high-pass filter on integrated gyro signal = low-drift pitch estimate.

Sensor System

Optical encoders:

- Quadrature decoding = 4000 counts per revolution of motor input shaft.
- Use derivative to estimate forward velocity and steer velocity (better than integrating gyro yaw rate)
- Dead-reckoning of forward position in world coordinates:



$$\begin{bmatrix} dx \\ dy \end{bmatrix}_V = \begin{bmatrix} R_c \sin(dy) \\ R_c\left(1-\cos(dy)\right) \end{bmatrix}$$

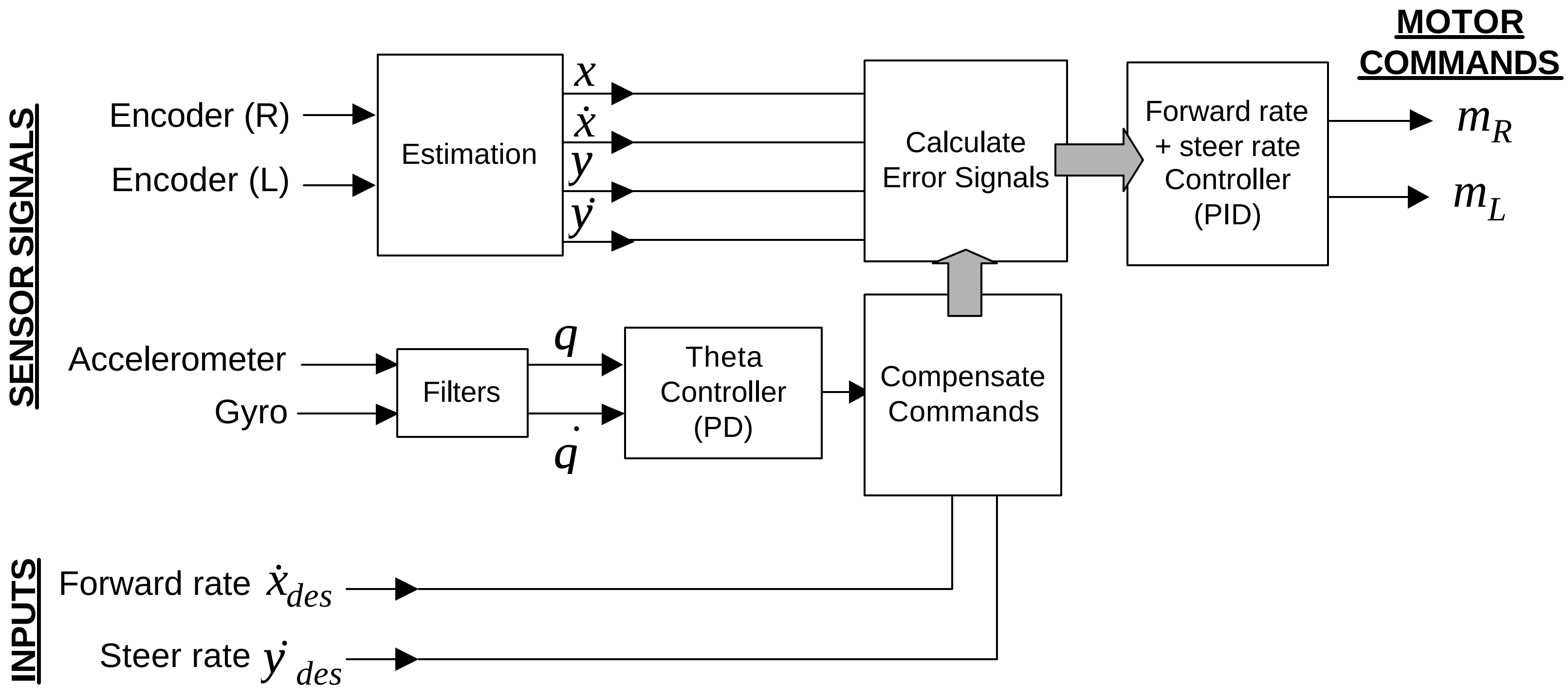
$$R_c = \frac{W}{2}\left\{\frac{dq_1 + dq_2}{dq_1 - dq_2}\right\}$$

$$dy = \frac{R_w\left(dq_1 + dq_2\right)}{W}$$

Control Algorithm

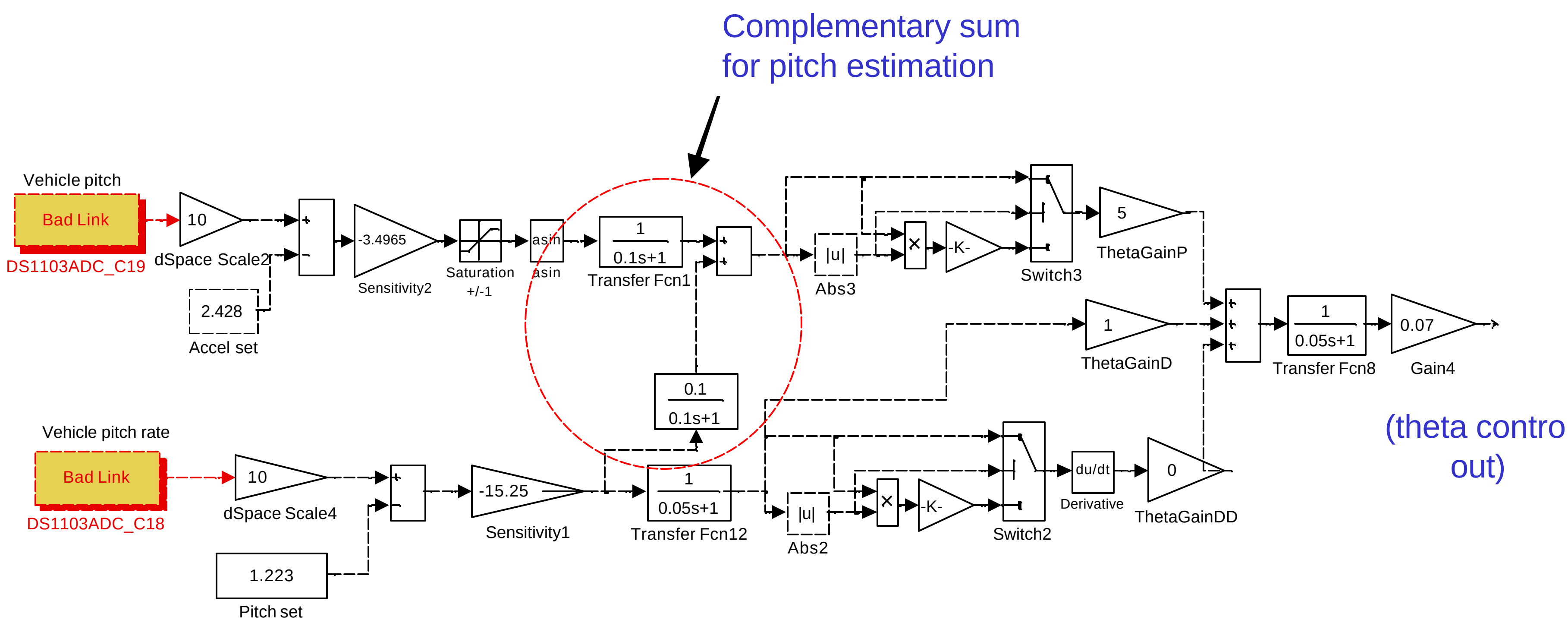
Decoupled control of pitch and forward motion:

- Compensate forward velocity and steer velocity commands with PD control of theta error signal.
- PID control of resulting forward velocity error and steer velocity errors.

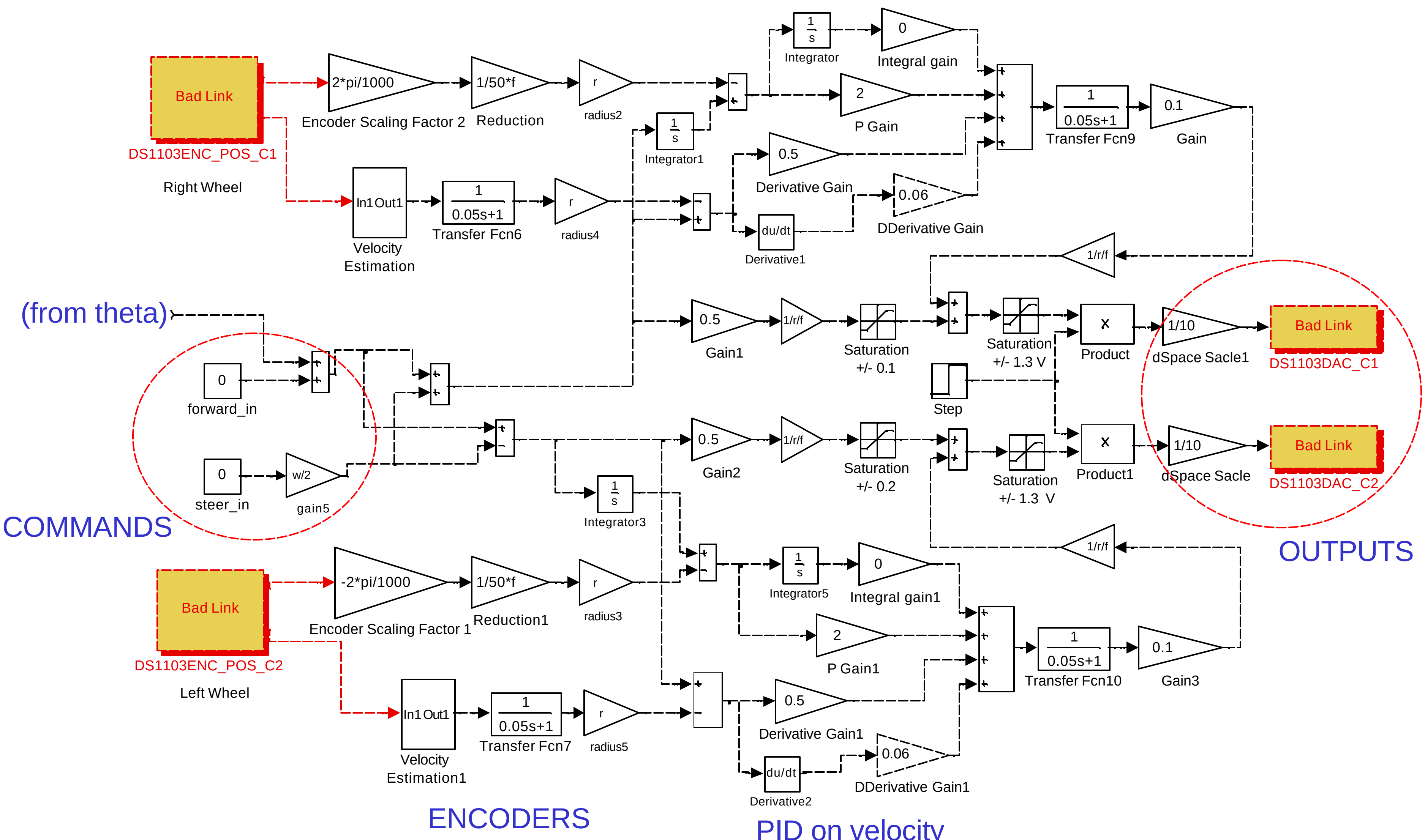


- Position control scheme (outer loop – server?) TBD.

Block Diagram: *Sensors + Swing*



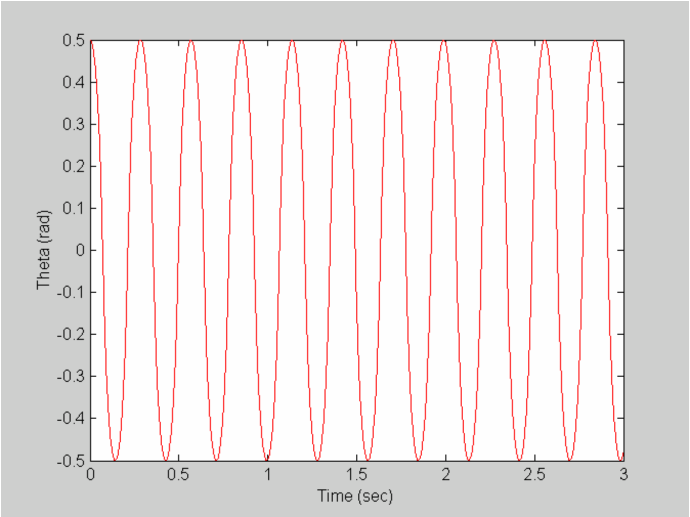
Block Diagram: *Forward Control*

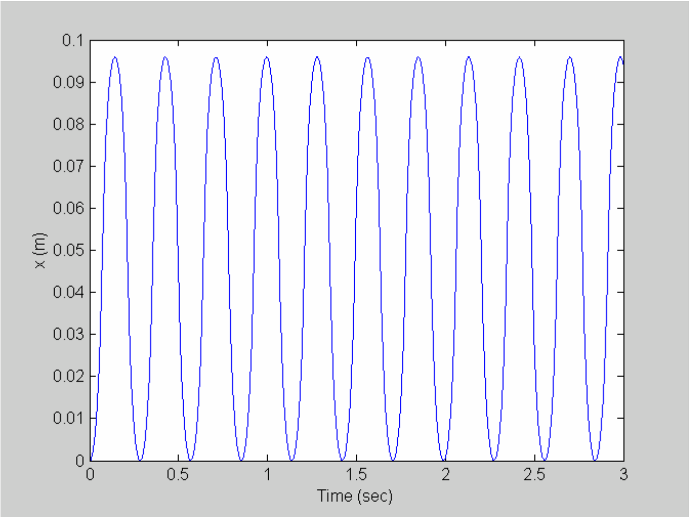


Simulations

Control

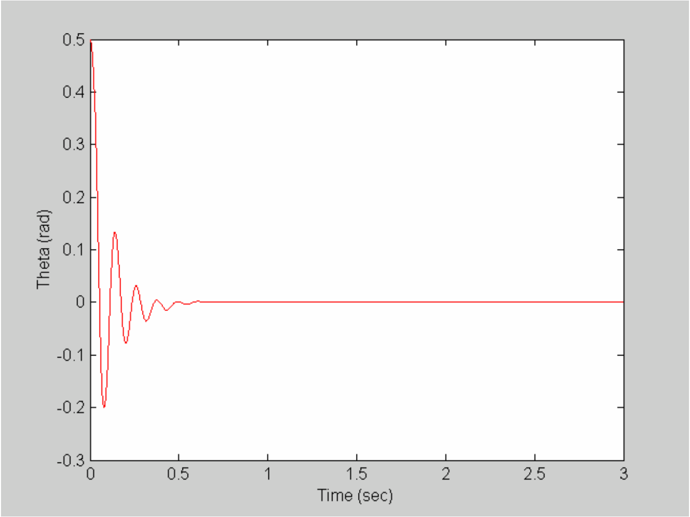
OFF

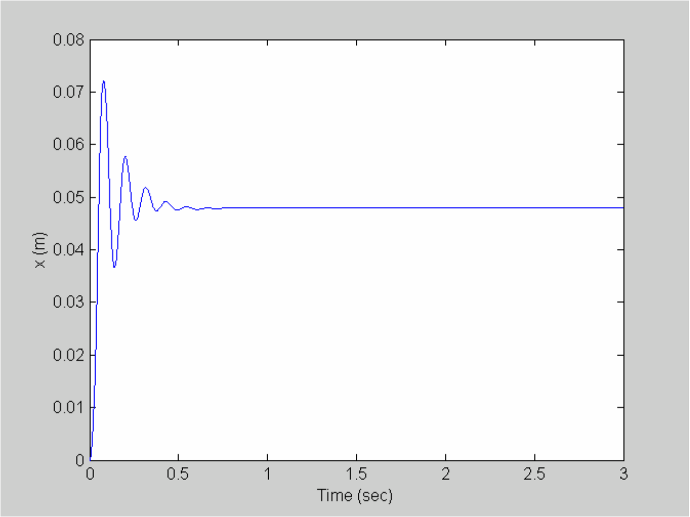




Control

ON



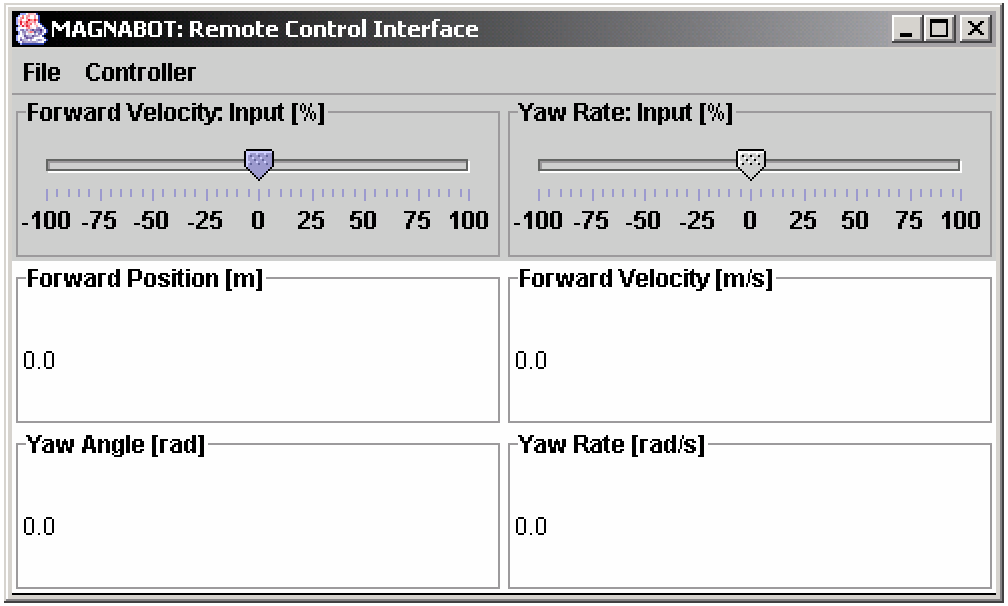


Swing (*q*)

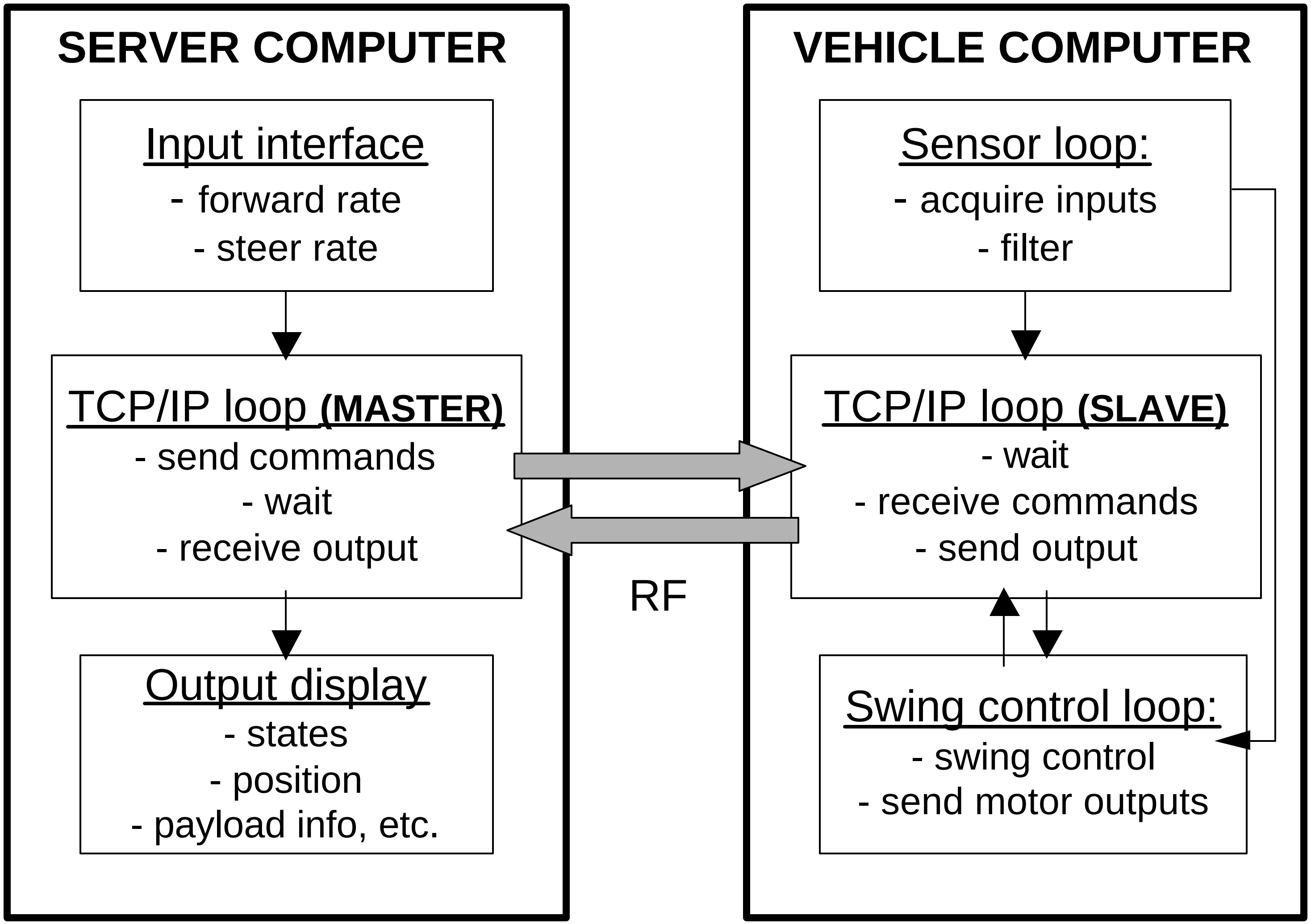
Forward (*x*)

Computation Strategy

- Vehicle is a roving network object with unique (IP) address.
- Inner and outer loops: Swing control runs from on-board controller, taking command signals from off-line computer.
- Takes standard I/O commands via TCP/IP .
- Scalable + extensible: Can add large numbers of vehicles, and use existing network infrastructure (e.g. 802.11b).
- Java interface to send commands (x rate, y rate) and read state feedback.



Software Structure



Computer Hardware

Z-world BL2100 SmartCat board with 22.1 MHz Rabbit processor

RJ-45 connection to bottom side

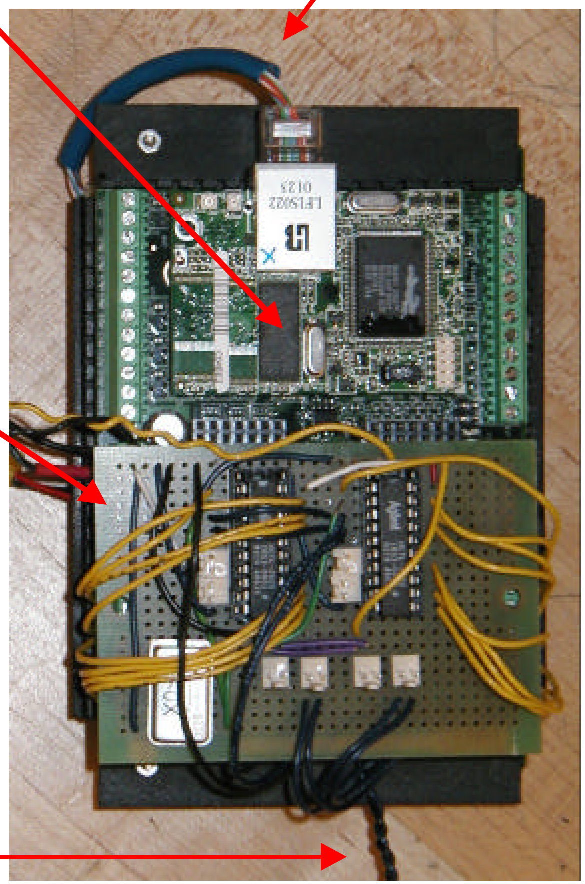
Lucent 802.11b wired-wireless Ethernet converter

Sensor interface board:

- HCTL-2020 quadrature decoder IC's

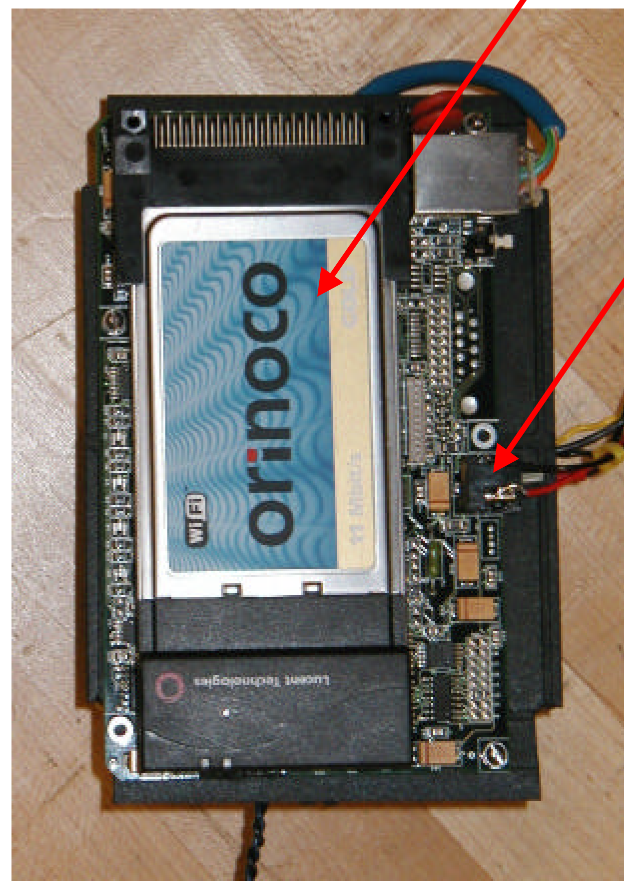
- Sockets for sensor inputs and sensor power delivery

Outputs to amplifiers



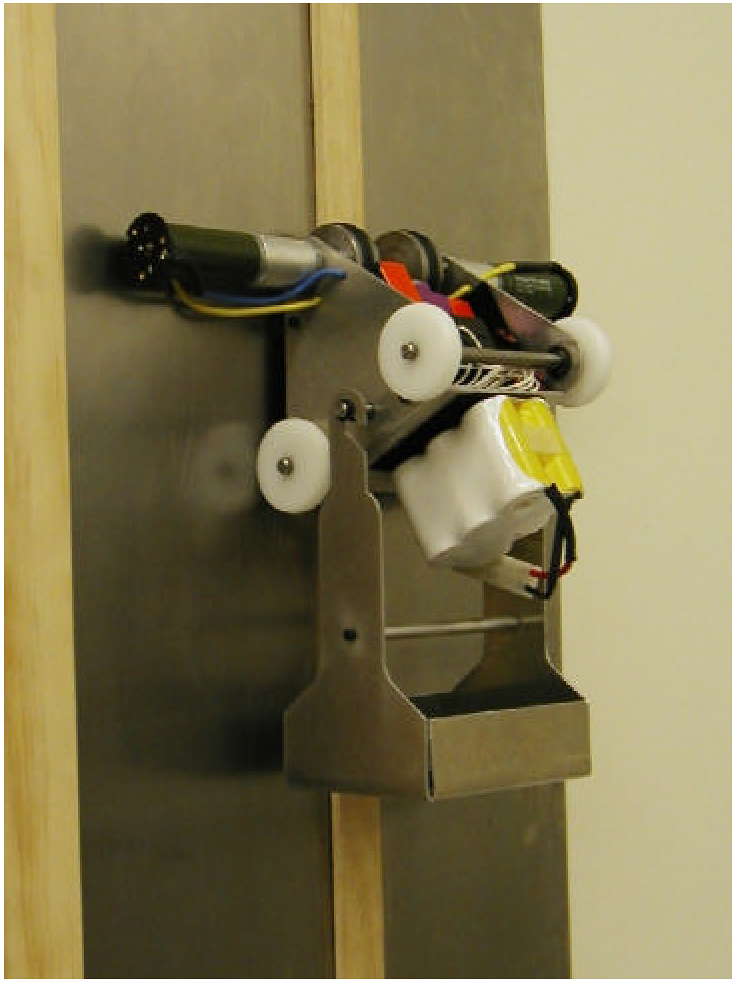
(Top)

Adapted for battery power



(Bottom)

First Prototypes

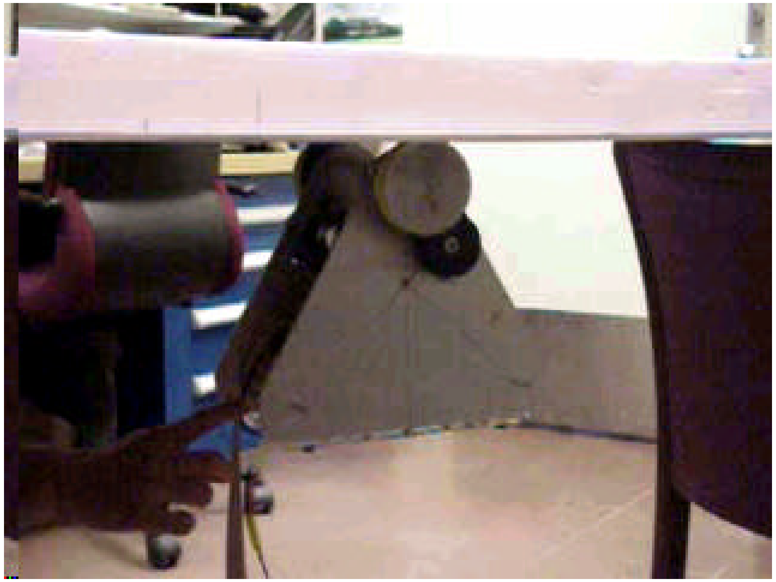


Ceiling Installation

Second Prototype: Swing Control

- Timing belt drive (rigid motor mounts)
- Theta estimation by integrating gyro signal
- Tether to D-Space processor board (controller in Simulink)

Controller OFF



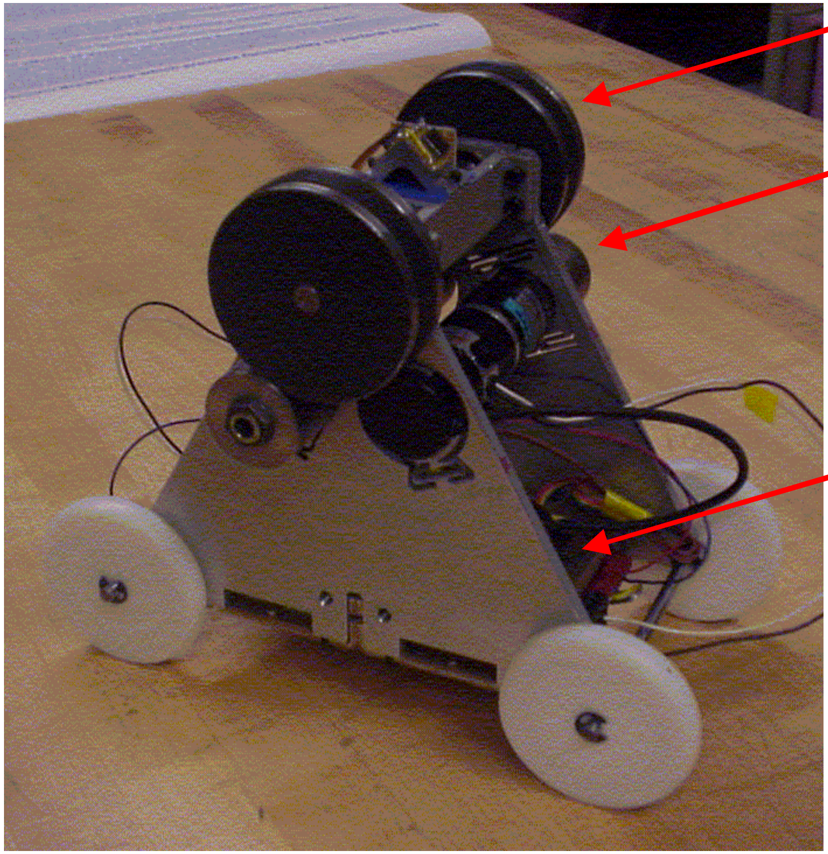
Controller ON

Second Prototype: Forward Motion

Controller ON

Third Prototype

- Friction drive with compliant motor mounts
- Rubber rings between wheel washers:
  - 24lb traction to driving roller
  - 40lb traction to pathway surface.
- Accelerometer mounted near wheel pivot
- Command via Ethernet to Rabbit board
- Pin-locking payload interface (not shown)



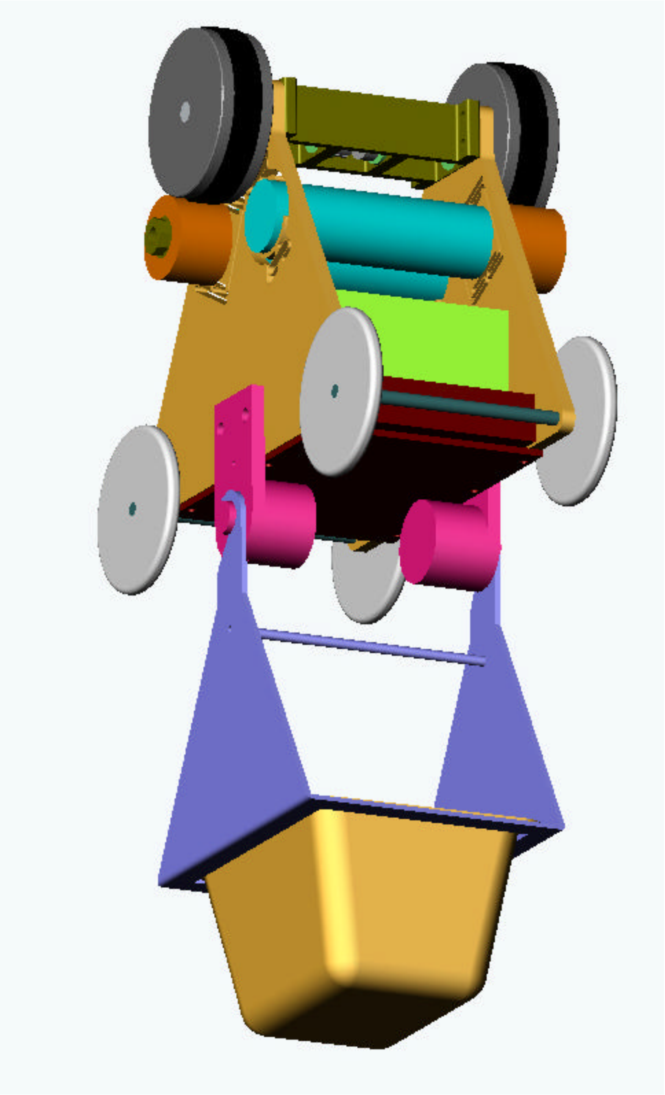
3” dia. wheels w/1.5” dia. magnets

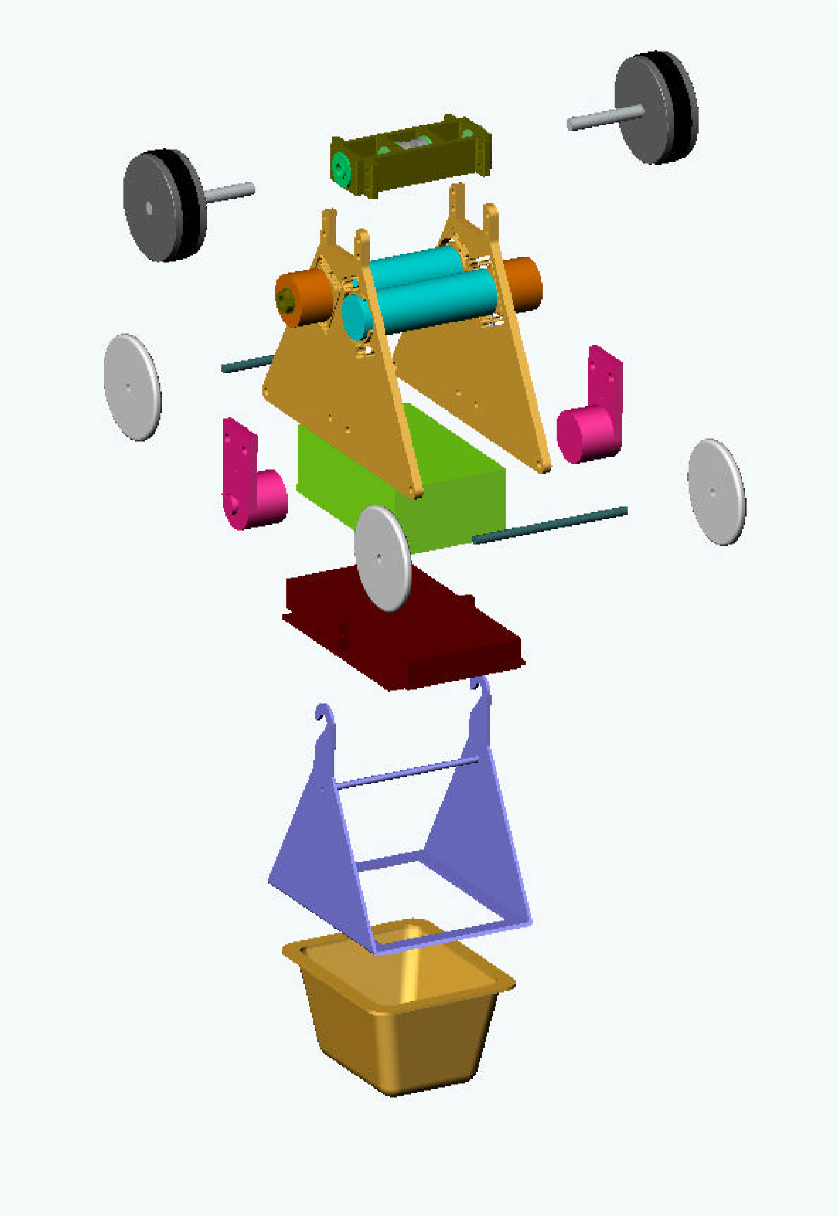
HD Systems RH-8
- 50:1 harmonic drive gearbox
- 100 RPM
- 24V supply

Copley Controls DC servo amplifiers

Ultralife lithium polymer battery pack
- 7 cells in series

Model with Payload Carrier





Conclusions

- Magnebots is a simple, yet versatile concept for an overhead vehicle system with a wide variety of applications: factories, hospitals, etc.
- Triangular vehicle body enables navigation of smooth transitions between ceiling and wall panels.
- Straightforward extension to inverted (balancing) operation as a toy; simplification possible for overhead positioning of lights (homes!) and other equipment.
- Robust mechanical hardware, performance enhancement by controls, vehicle coordination by wireless communication = synergistic integration in the true spirit of mechatronics.

Acknowledgements

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