Surface Based Wireless Power Transmission and Bidirectional Communication for Autonomous Robot Swarms

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Overview

- The Swarm Power Problem
- Related Power Distribution Approaches
- Other Wireless Power Systems
- Proposed Power Surface Design
- Proposed Power Surface Characterization
- Conclusions

The Problem

Powering a Swarm of Robots

- Different activity levels = different power consumption
- Primary cell batteries are environmentally unfriendly
- How to maintain rechargeable batteries?

Solution: Get rid of batteries. Provide continuous wireless power to the swarm from its operating surface.

Image Credit: Axelrod, Georgia Tech

Image Credit: Caprari, EPFL Switzerland

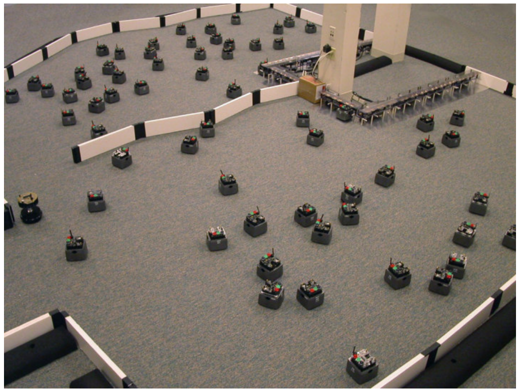


Image Credit: McLurkin, MIT

Potential Solutions

- Onboard Power:
  - Batteries
    - Exchange Behaviors
    - Docking Behaviors
  - Alternative Sources
    - Hydrocarbon Fuels
    - Fuel Cells
    - Biomass Fuels

- Offboard Power
  - Tethers
  - Solar, Fields, Kinetic

Image Credit: Roomba from iRobot.com

Image Credit: Caprari, EPFL Switzerland

Proposed Solution

Wireless, battery-less power

(Robots are RFID tags with wheels & sensors)

Ampere's Law (coil):

$$H(x) = \frac{I \cdot N_t \cdot r^2}{2\sqrt{(r^2 + x^2)^3}}$$

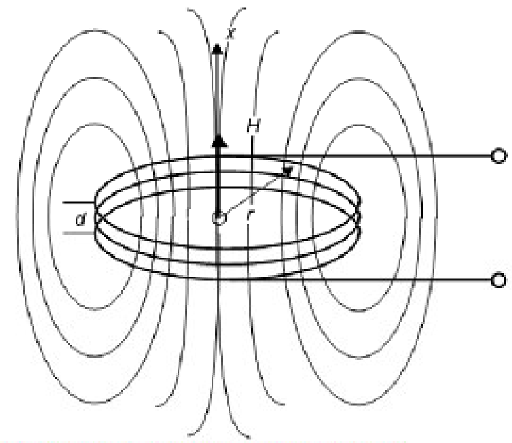


Image Credit: Finkenzeller, "RFID Handbook"

Faraday's Law:

$$E = \mu_0 H \omega N_p A_p$$

Related Work

Other Inductive Wireless Power Systems

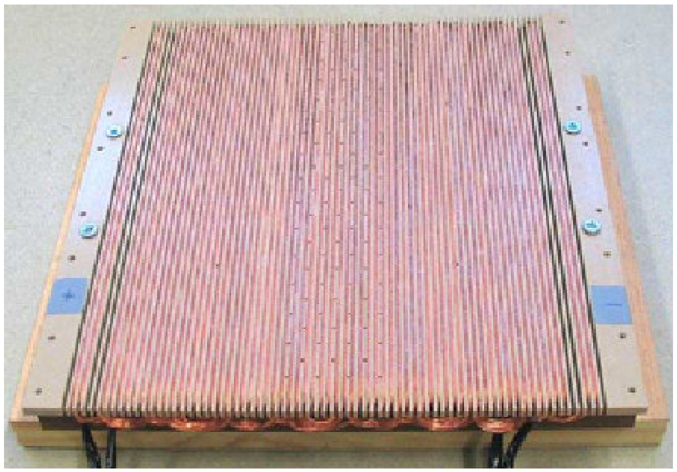


Image Credit: Gao, Fraunhofer IBMT

Multiple magnetic induction coils
- Mechanically complex
- Complex control scheme
- Can provide localization info
- Not easily tile-able

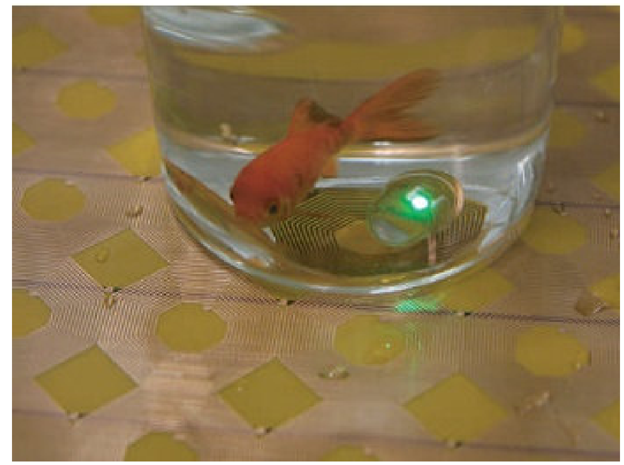
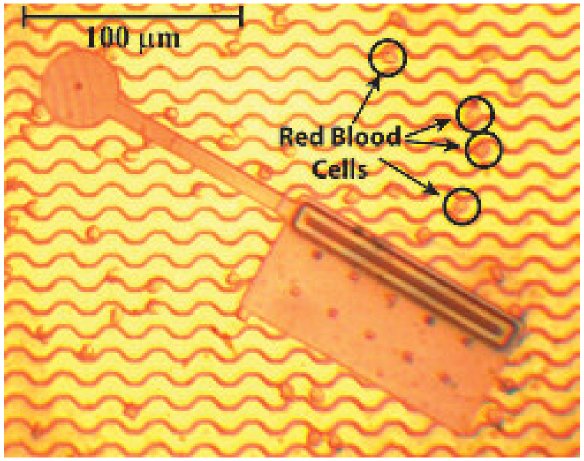


Image Credit: Sekitani et al, University of Tokyo

Multiple magnetic induction coils
- Mechanically complex
- MEMS and organic FETs
- Complex control scheme
- Can provide localization info
- Tile-able

Related Work

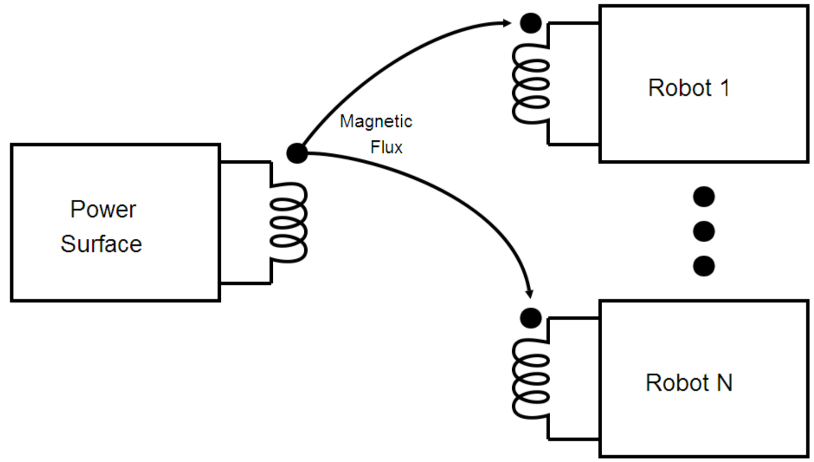
Nano-robots powered by fields



NIST Image Credit: Craig McGray

- Surface fields cause actuation of nano-actuator
- No logic or memory in the robot
- Better considered "distributed actuator"

System Design



- 112KHz operating frequency
- Single resonant transmitter coil in power surface
- Non-resonant receiving coil on each robot
- Magnetic flux coupling between transmitting and receiving coils
- Surface to robot coupling virtually unaffected by number of robots
- Mechanically and electrically simple
- Supports bidirectional communication
- Does not support localization

Resonance Considered

Advantage of Resonant Coils:

- High Q increases circulating current in transmitting coil for given drive voltage- yields higher induced voltage in robot

$$H(x) = \frac{I \cdot N_t \cdot r^2}{2\sqrt{(r^2 + x^2)^3}} \qquad E = \mu_0 H \omega N_p A_p$$

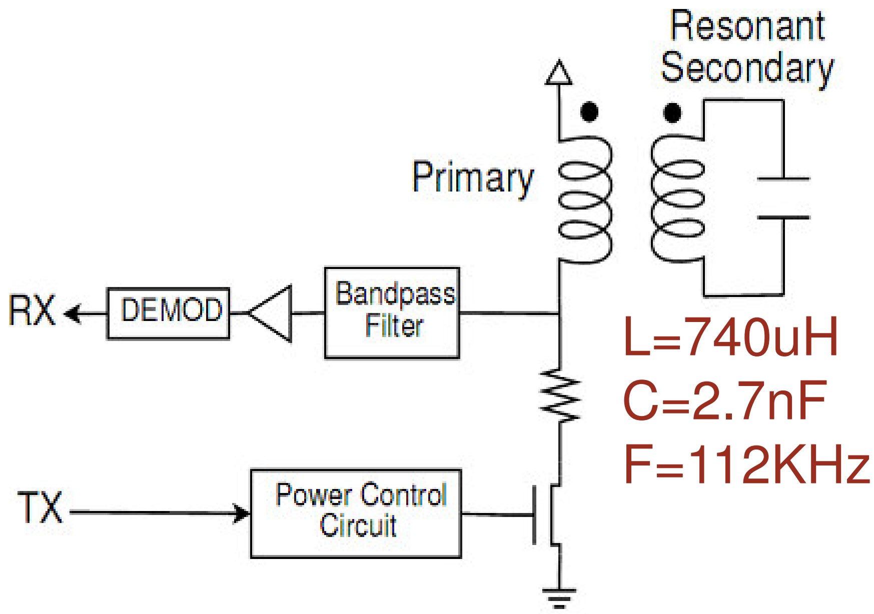
Disadvantages of Resonant Coils:

- High Q coils present manufacturing problems
- Coupled resonant coils interact and de-tune each other
- High Q resonances limit available bandwidth for communication

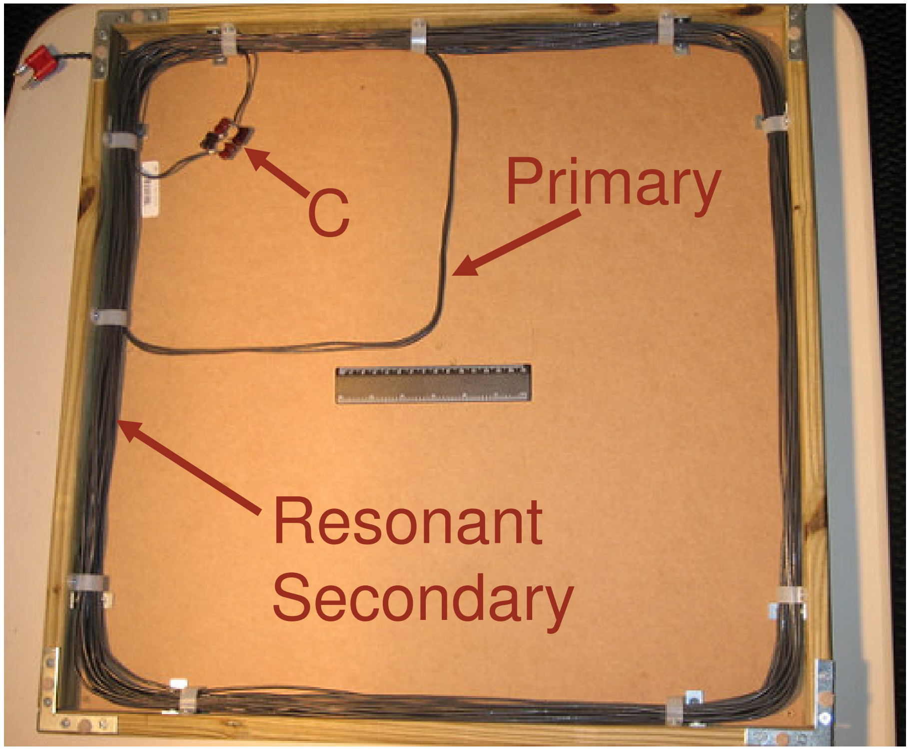
Tradeoff:

- Use resonant transmitting coil under surface
- Robots use non-resonant receiving coils
- Robots interact with surface resonance, but not each other

Power Surface Design

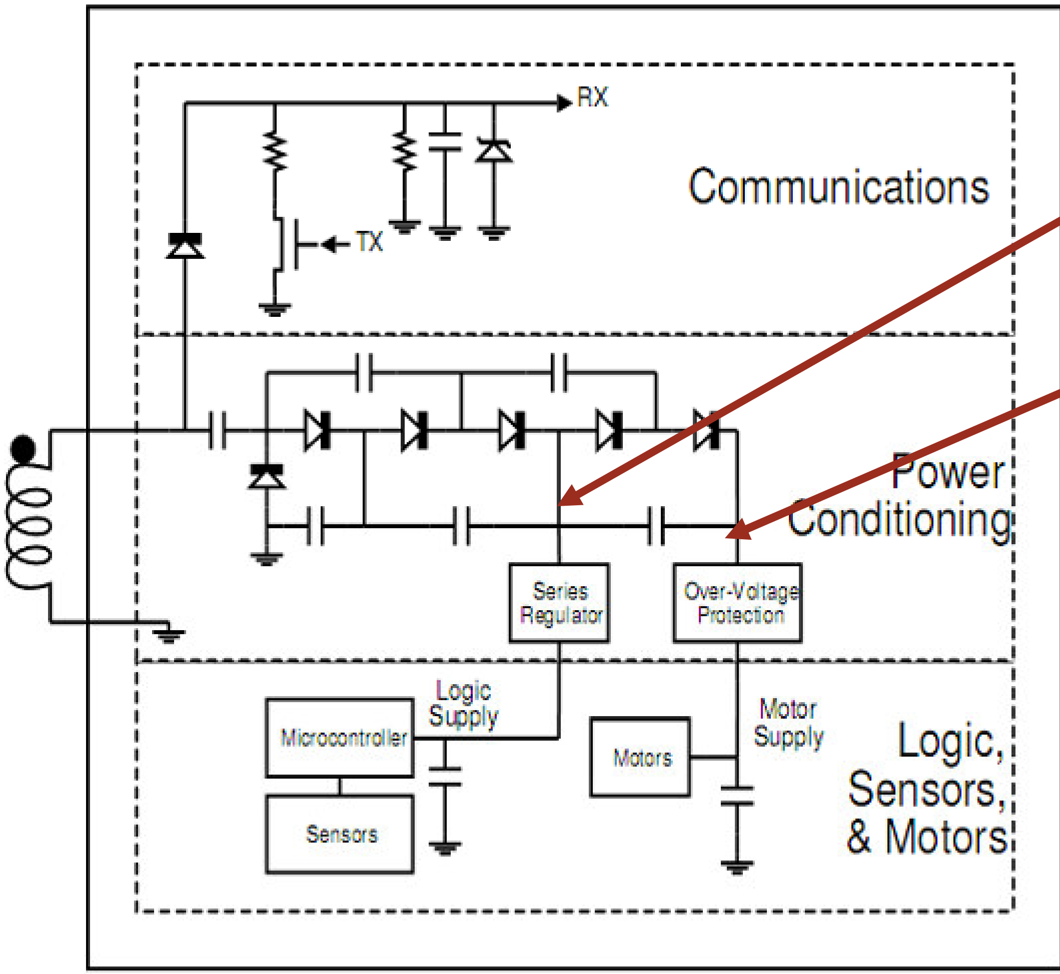


Schematic



Underside of Prototype
(0.6m x 0.6m)

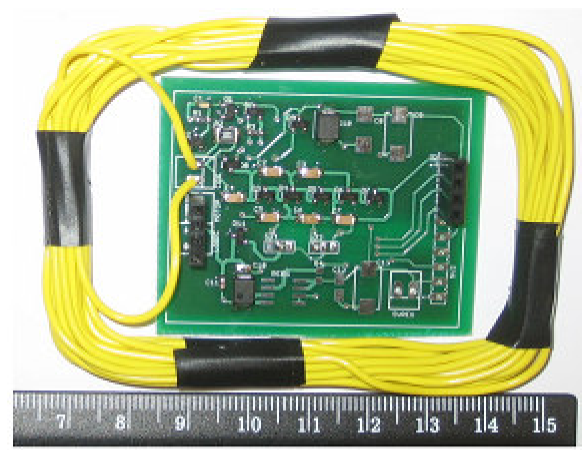
Robot Power Design



Schematic

Logic Power
High Priority

Motor Power
Lower Priority



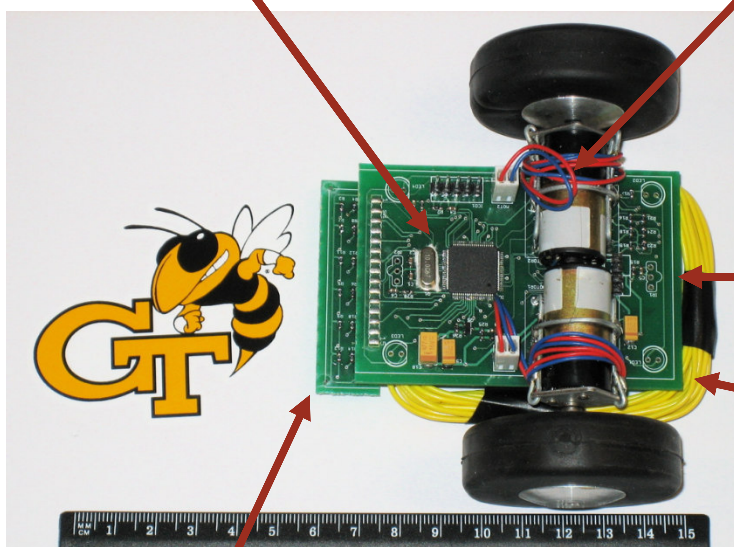
Communications &
Power Conditioning
Board

Robot Prototype

Line-Following Application

PIC microcontroller

ESCAP
DC gearmotors



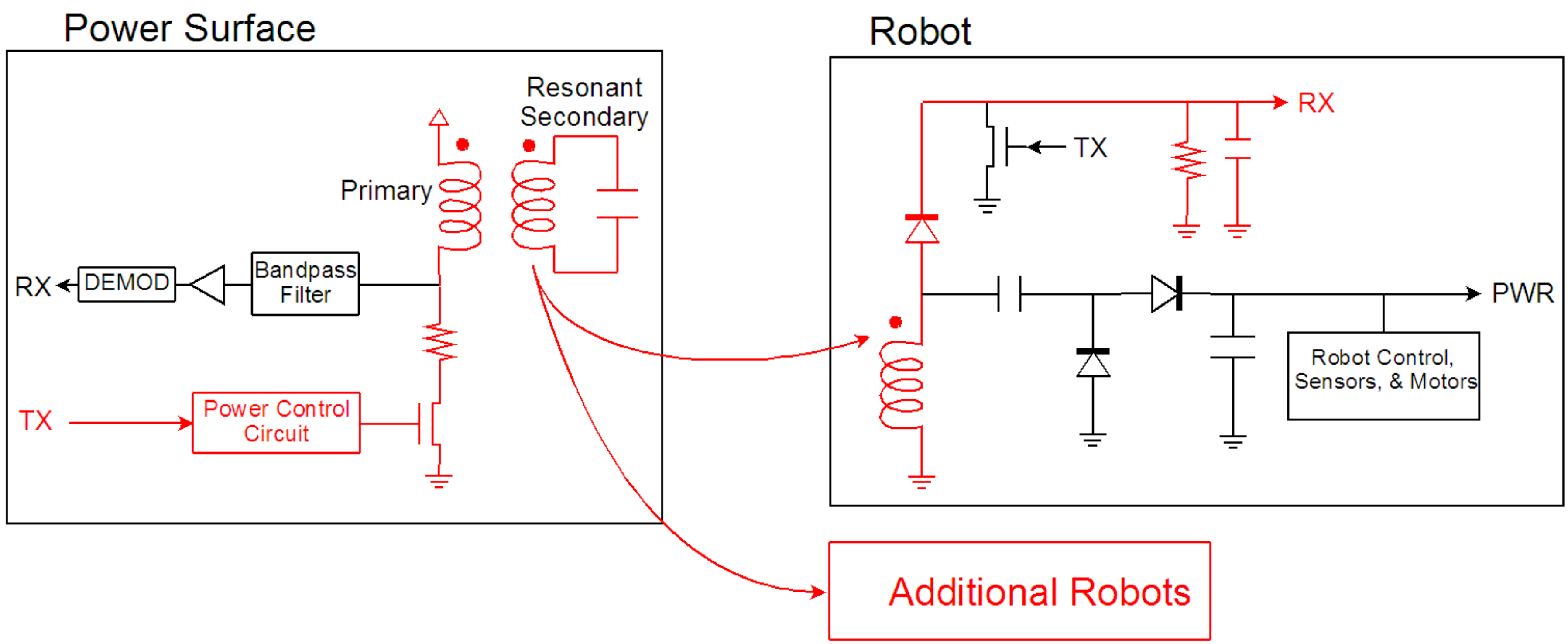
IR Comm.

Coil

IR line sensor array

Communication

Surface-to-Robot

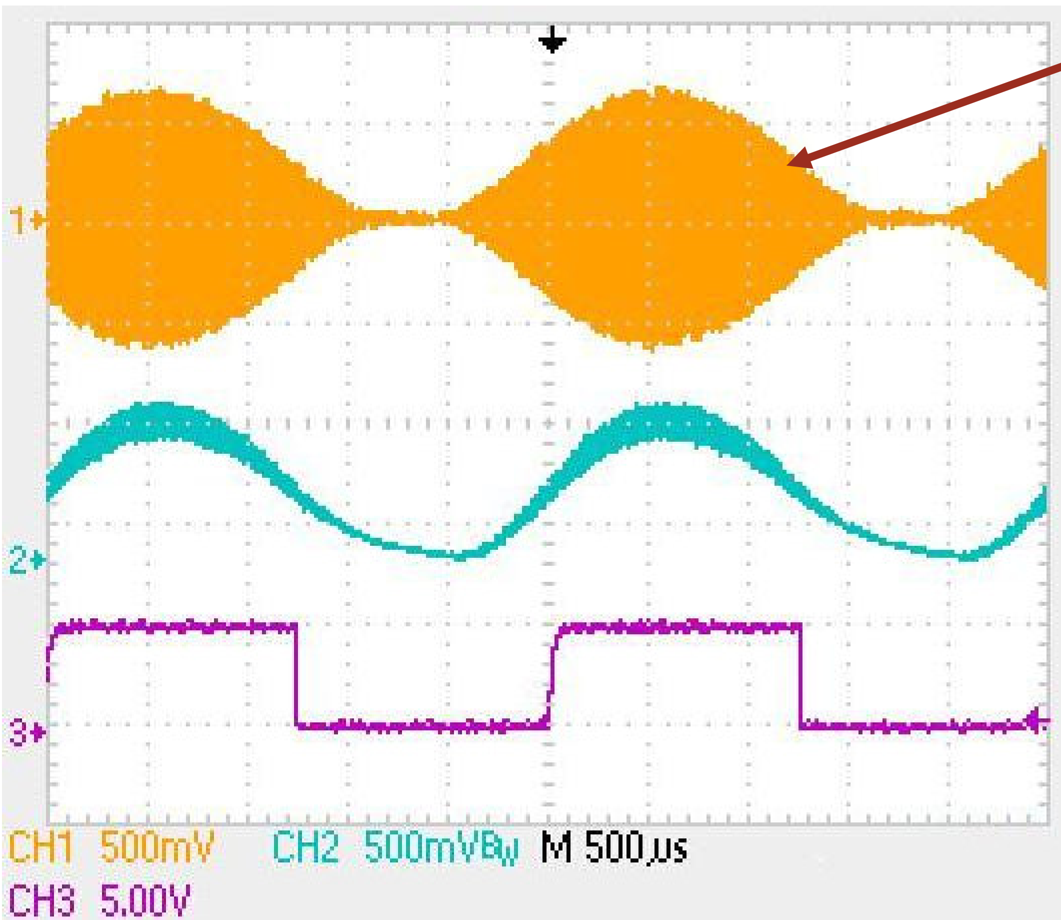


- 100% AM modulation
- Data rate 800bps, limited by coil Q of 125

Communication

Surface-to-Robot at 800 bps

Coil resonance limits rise time / data rate



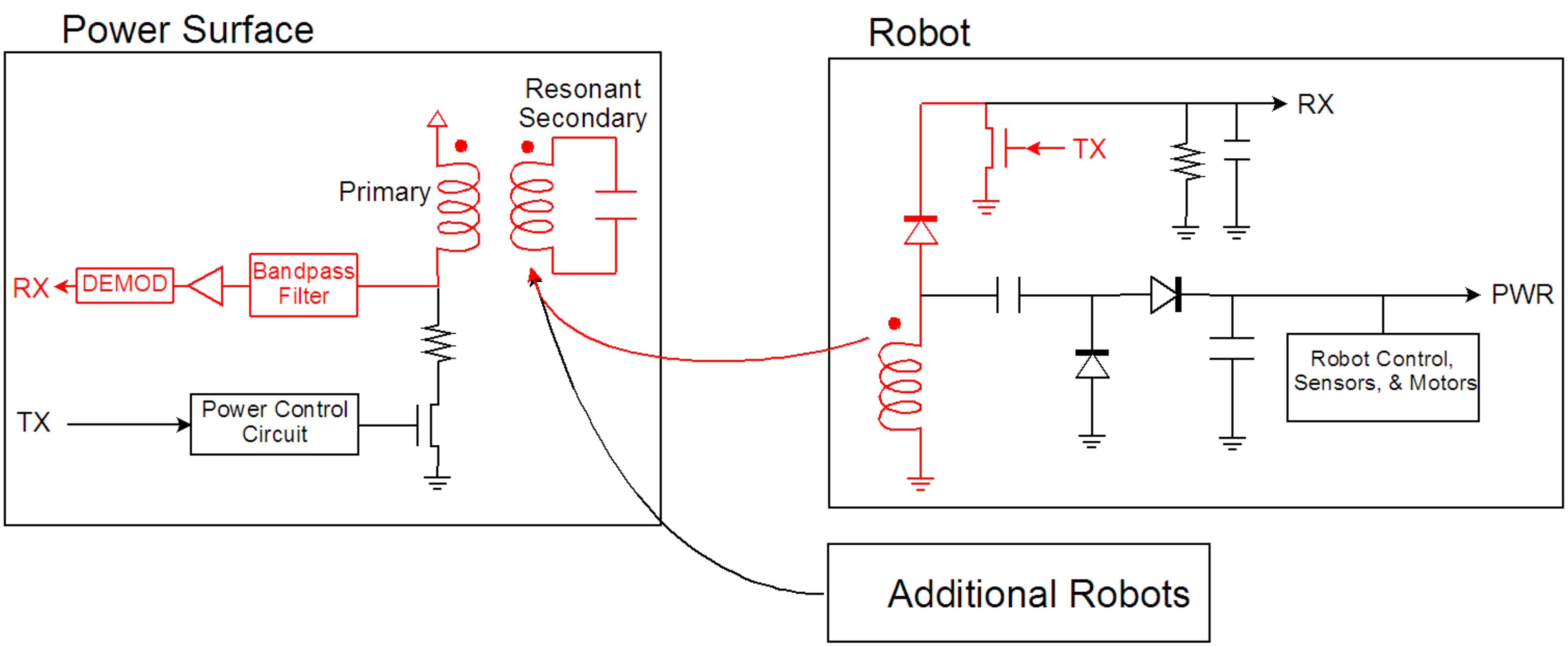
Surface Field Amplitude-Modulated

Robot Filtered RX

Robot RX Data

Communication

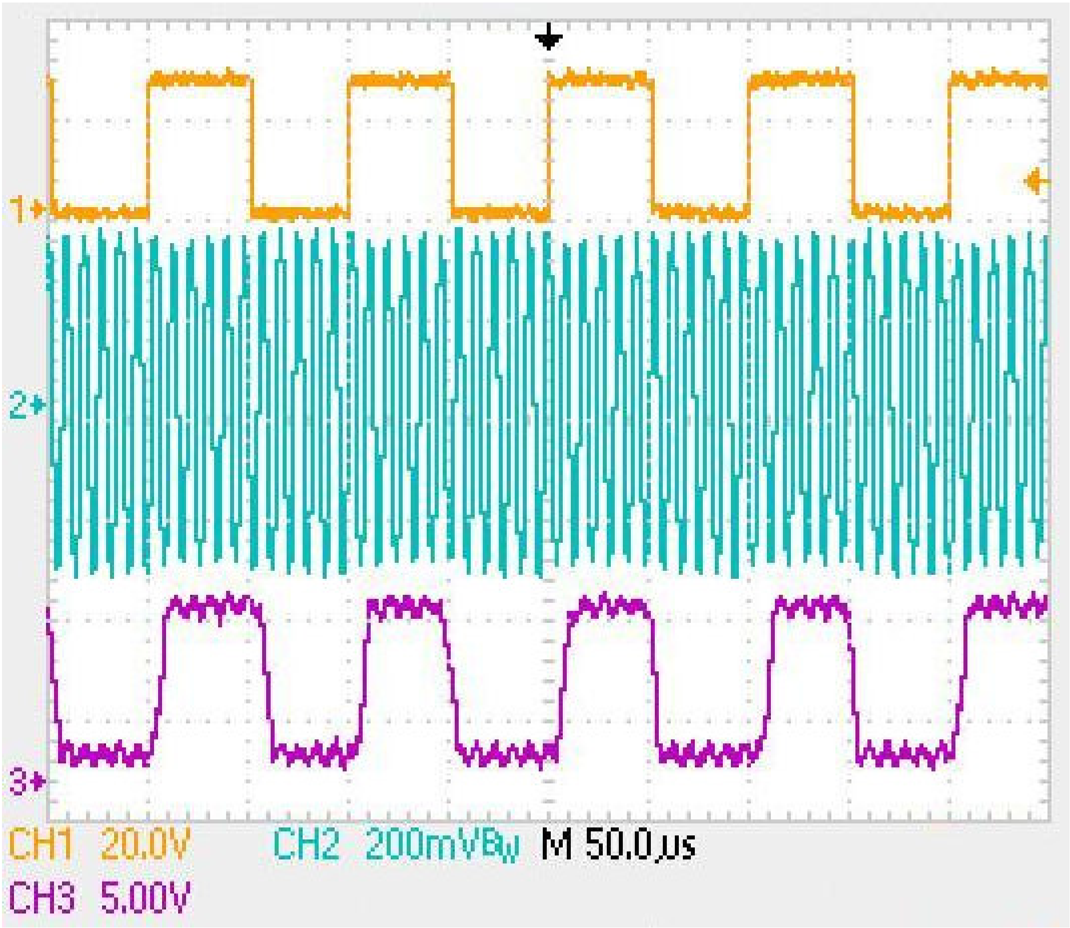
Robot-to-Surface



- Load modulation by FET switch
- Data rate 20Kbps, 1% modulation depth

Communication

Robot-to-Surface at 20 kbps



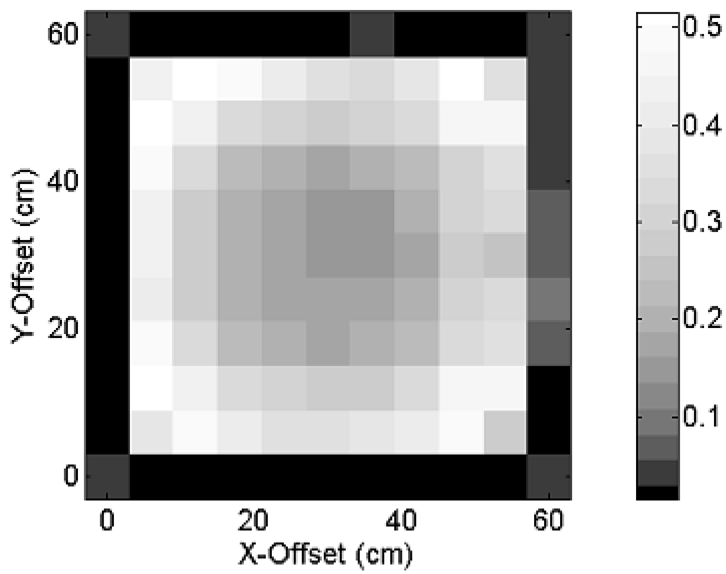
Robot TX Data

Surface DEMOD input

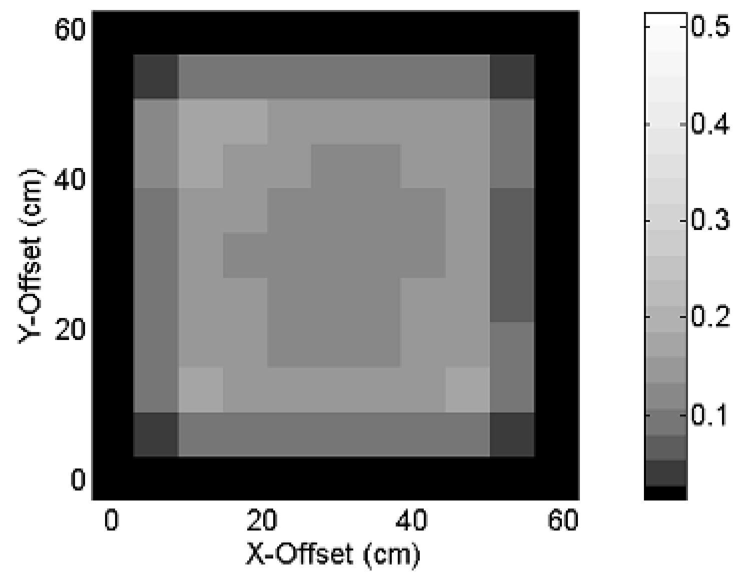
Surface DEMOD output

Power Density

Measured Power (Watts) into simulated robot load (80 Ω) at various heights above surface



0 cm (on surface)

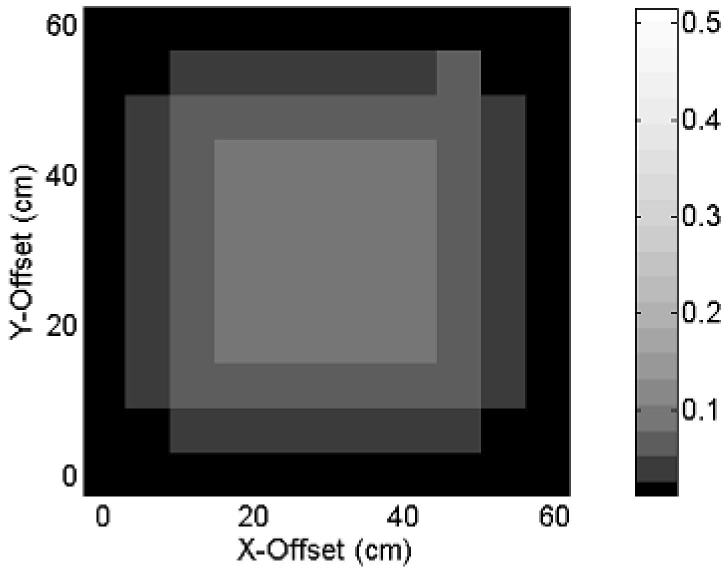


5 cm above surface

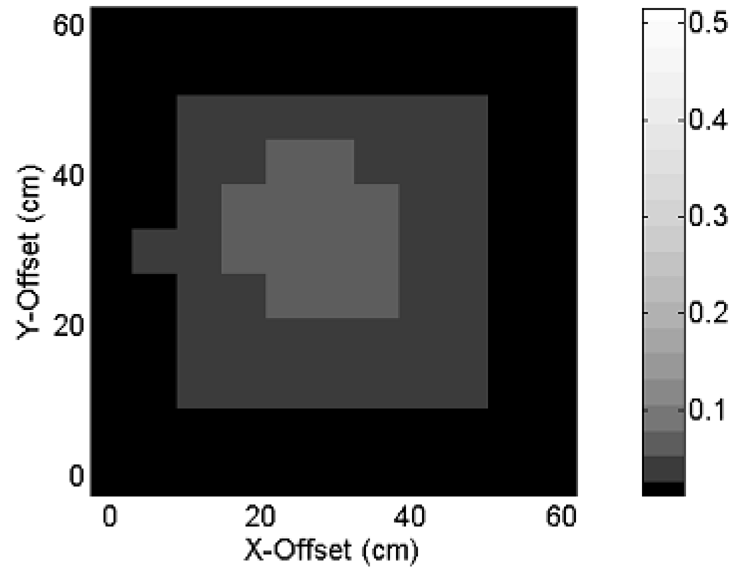
└> 4.1mW/cm^2 average

Power Density

Measured Power (Watts) into simulated robot load (80 Ω) at various heights above surface



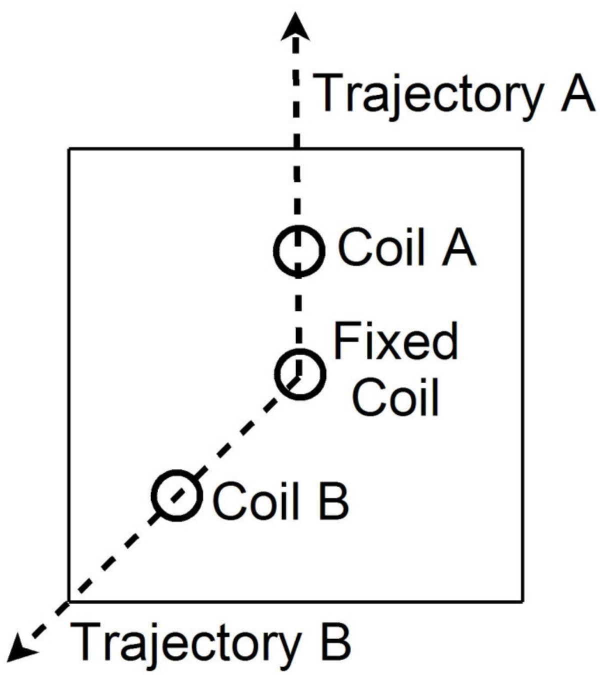
10 cm above surface

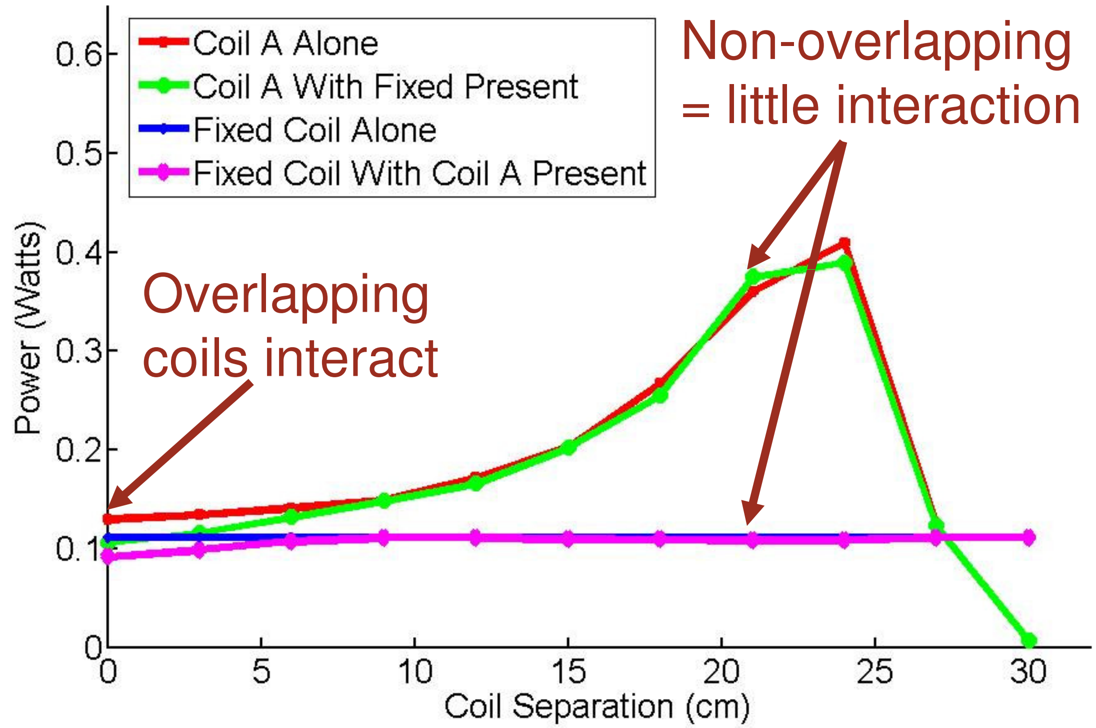


15 cm above surface

Robot-Robot Interaction

Non-Resonant Coils on Robots

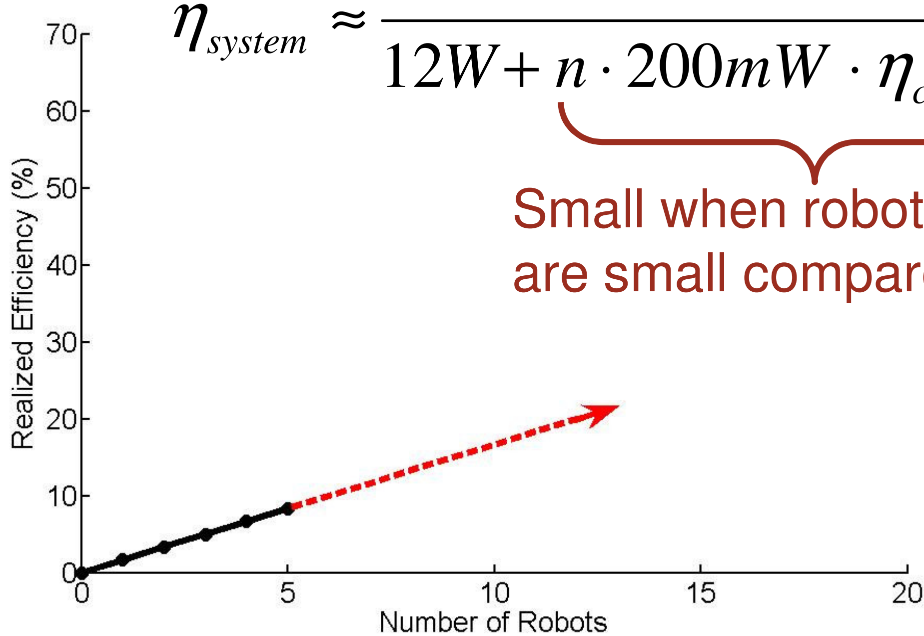




Virtually no interaction between robot coils until they're atop each other

System Efficiency

$$\eta_{system} \approx \frac{n \cdot 200mW}{12W + \underbrace{n \cdot 200mW \cdot \eta_{coupling}}_{\text{Small when robot coils are small compared to surface}}}$$



- Surface quiescent draw is 12W
  to overcome losses in transmitting coil.
- Each robot recovers ~200mW
- Efficiency increases with # of robots

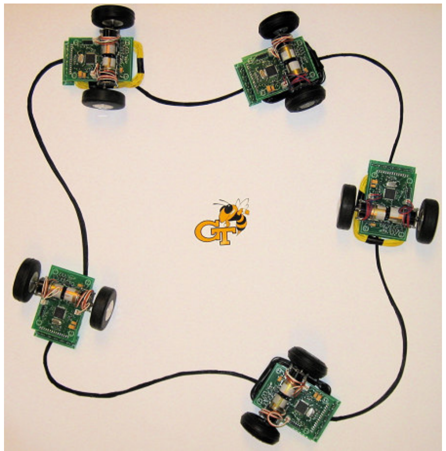
Summary

Benefits:

- Simple, Low Cost Construction
- Persistent Power to Large Number of Robots
- Bidirectional Communication
- Enabling Technology for Swarm Research

Future Work:

- Characterize Efficiency with Larger Number of Robots
- Improve Communication Bandwidth
- Develop Tiling Scheme
- Web Community for Interested Researchers



Questions?

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