Networked Robot Swarms
Ready or Not?

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PerCom 2019, Kyoto, Japan

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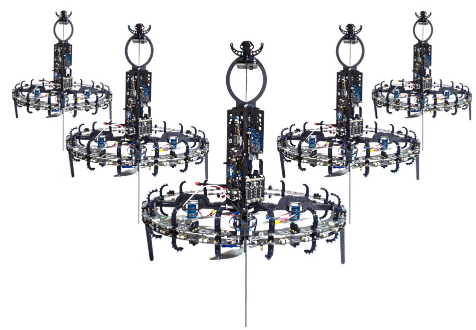
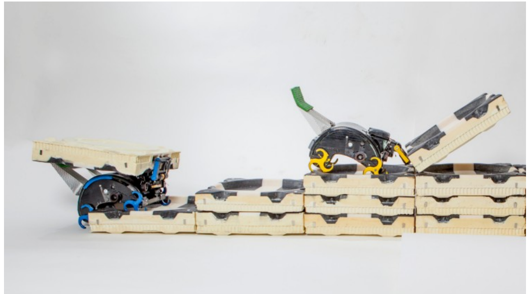
Robot Swarms – Already Here

- We're building networked swarms of robotic agents
- This could take us a number of directions…



Eye Bot - EPFL

Swarmfarm.com



Harvard - Termes

- But to <u>swarm</u>, need communication & more… how?
  - Let's follow some history on the communications…

Early Challenges in Communications

- Move information faster than people
- Approaches
  - Put messages on faster beasts
  - Use light (e.g., smoke signals)
  - Use sound (e.g., drum signals)
  - Use water (e.g., hydraulic telegraph)
- Most of these have limited distances
  - And depend on the environment
  - And are not always highly practical
  - So this didn't really last

Hydraulic Telegraph of Aeneas
4th Century BC, Greece

A 1938 UK design connected the endpoints (not deployed)

The Chappe Telegraph

- France and beyond, ~1792 - 1852
  - Semaphores – 500 mph and 2-3msgs/min
  - ‘Routers’ every 10-15miles / forming a **network**
  - Dependent on human operators
- Benefits
  - Message could reach <u>large distances</u> fairly quickly
  - Difficult to forge messages (w/out insider)
- Impediments and challenges:
  - Good weather (visibility/daylight) required
  - Easy to intercept; “supported” steganography (!)
  - Not so mobile/tiny; expensive to run
- Replaced by electrical/galvanic telegraph in 1852

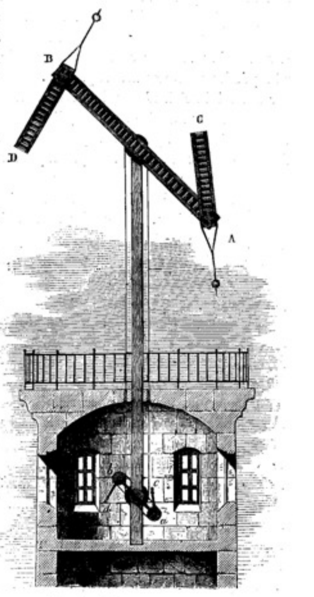
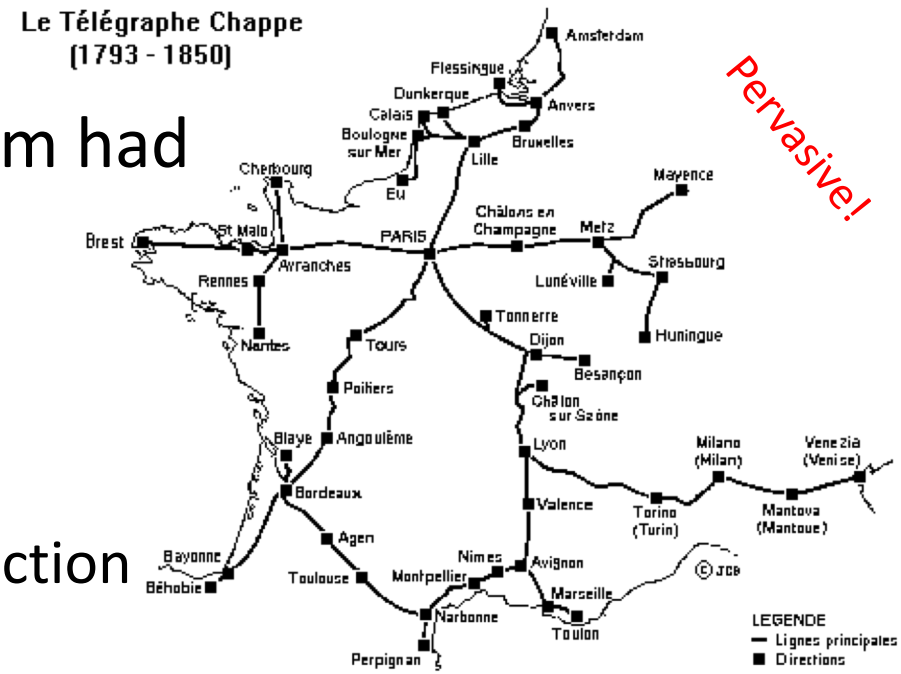


Fig. 19. — Télégraphe de Chappe.

Chappe Telegraph (architecturally)

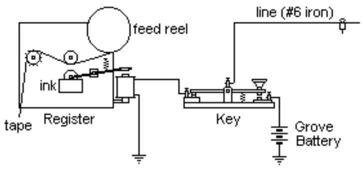


Pervasive!

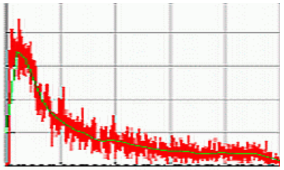
- Architecturally, this system had
  - Source coding
  - Control signals
  - Synchronization
  - Flow control
  - Error correction and detection
    - Selective ACK/repeat
- Some of these ideas appeared > 100 years earlier:
  - Robert Hooke, “On Showing a Way How to Communicate One's Mind at Great Distances”, May 1684

Used the recently-invented telescope…

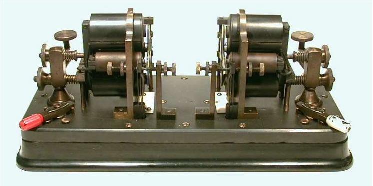
Electrical Telegraphy (1840+)



Typical Morse (Vail) Telegraph Station (1860s)

signal

distance

- Use electricity to send messages on wires
- Basic components available by early 1800s
  - Volta's voltaic cell, galvanometer, and e-magnet
  - But the effect of electricity degraded significantly with distance
  - Joseph Henry solved this by 1830 but Morse didn't know (yet)
- Benefits
  - Cost reduction of perhaps 30x versus optical telegraphs
  - No weather or daylight or direct LoS issues; 24/7 operation
  - Low latency – (replaced pony express in US by Oct 1861)
  - Enormous scale; a form of TDMA (Baudot) / msg switching
- Impediments:
  - Multiple wires in common conduit with degrading insulation
  - Confusion and suspicion
  - Repeaters



Note: famous patent case 1854 – Morse v O'Reilly

Telegraphy and Security

- Messages encoded at first for compression (save ¥)
- Codes for privacy/compression of telegrams
  - Use of codes differed significantly among countries
    - And many were business-specific (see talks by S. Bellovin)
  - In 1864, founding of ITU, standardized & allowed codes
  - In the US, earlier (1845) due to so much commercial use
- And…concern about the low latency *as a threat*
  - Routine information could now be sensitive
  - (e.g., ship departure records out before ship departs)

Electric Wireless Communication

- Maxwell predicted existence of electromagnetic waves in 1873; Hertz demonstrated this carries into space by 1886 [he died in 1894, age 36]
- Loomis (dentist in USA) first demonstrated "wireless telegraphy" in 1886 with kites [controversial]
- Marconi demonstrated radio in 1895, across English Channel (1899), across Atlantic (1902)
- Secret (FH) comms system – 1941 patent of Hedy Lamarr and George Antheil (USPTO#2292387)

Photo: Jamie/Creative Commons

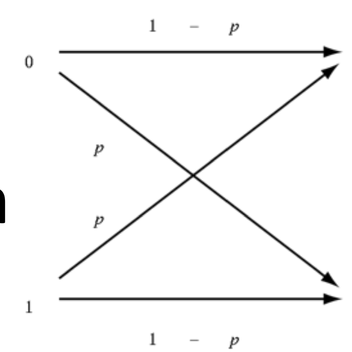
The Telex Network

- Started in 30s, popular in post-WWII
- Special network for delivering messages among teleprinters – binary voltages ; not the phone network
- First standardized worldwide network of its kind
  - 50 baud (~66 wpm)

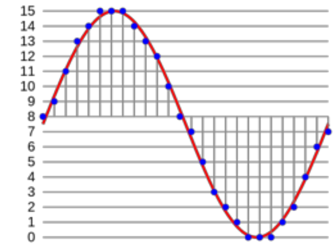
- Transitioned to phone lines and modems
  - Ultimately replaced by FAX in 1980s (pictures!)
  - But still today a hobby for some (“telex over radio”)
- Automated message switching (“InfoMaster”)
  - With machine-generated ACKs (unlike G2 FAX!)

Understanding Channel Errors

- A formal mathematical understanding of communication channel impairments was lacking…
- Claude Shannon (1948)
  - Modeling of noise in an errant [bit changing] channel
  - A theory of information and entropy measure
  - Coining of the term ‘binary digit’ (bit)
- Really defined the limits of communication
  - And appropriate performance measures
  - Greatly affected thinking on cryptography



The Digital PSTN



- Using ‘bits’ a possibility of ‘error-free’ long distance transmission became possible (Paper: “Philosophy of PCM”)
- Phone network evolution to digital core
  - Transition in the 1960s (tech: fiber optics, transistors)
  - Addressed problem of cumulative degradation in analog
  - Repeaters could re-construct the signal perfectly
    - Assuming sufficient S/N ratio, *reduces* noise
- Electronic switching replaces electromechanical
- ‘Last mile’ remained analog (still is in many places)

So Where Are We Now?

- Faster/farther – drums to optics to digital
- Scale – p2p links to global telephone network
- Reliability/resiliency – acknowledgements, retransmission, digital repeaters, coding
- Wireless – from signals to voice to coded, jam-resistant communications to commercial AM and later FM
- Security – mostly codebooks and codewords, and the beginnings of 'phone phreaking'

- So its about the 60s now.
  - What about the Internet and robots?

Steve Wozniak

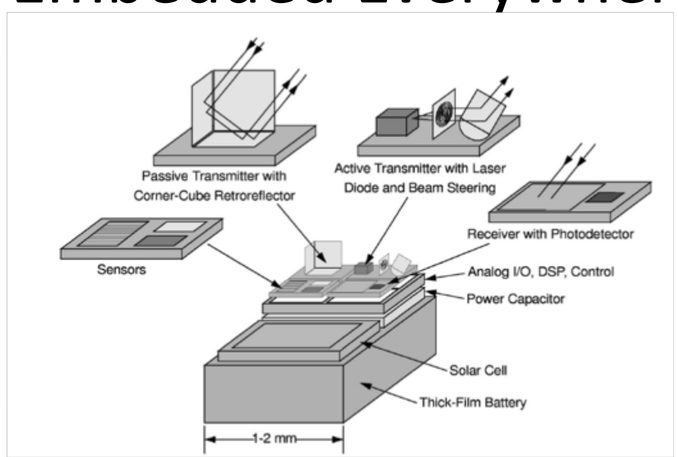
Early M2M and Packet Networks

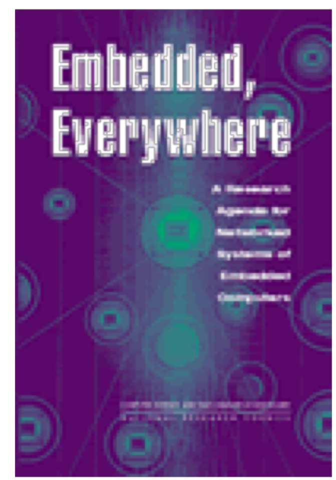
- The ARPANET – sharing resources using a network
  - An experiment in packet switching to provide resilience
  - Dynamic routing, statistical multiplexing (queues)
- X.25 and Minitel (1978 to 2012)
  - Packet switching supporting virtual circuits
  - Resiliency through re-routing; fixed window
  - Minitel – successful French personal services (e.g., social)

- The Internet – a ”concat”-ed network (“catenet”)
  - Short-term store and forward, packet format, gateways
  - Datagram service (no per-connection state) -> M2M!

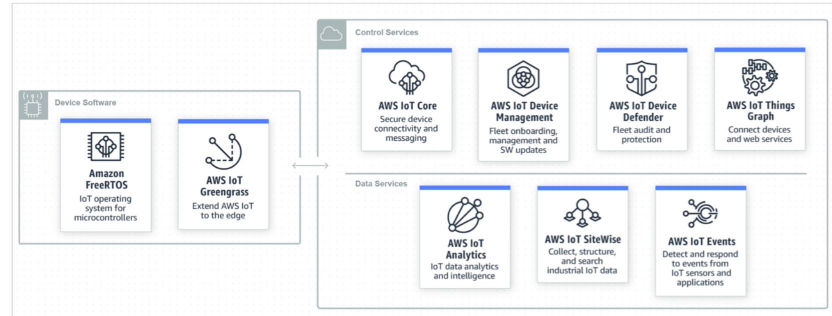
Tiny Pervasive Communication

- Early 2000’s brought interest in wireless sensor networks: “smart dust” and “motes” (later WSNs)
  - Focused on limited computing, power, and range
  - Clever inter-mote protocols and implementations
  - Progenitor of today’s IoT (Internet of Things)
- E.g., 2001 NAP “Embedded Everywhere”





Cloud-Managed IoT



AWS IoT Core

- Cloud frameworks to coordinate small devices
  - ‘Function as a Service’ (serverless) model includes them
- Networking features
  - Local low-latency reactions (e.g., industrial)
  - Toleration of disconnected operation
  - Edge processing before cloud upload (e.g., in MEC[?])
  - Security and privacy of the data
    - Some data maybe never goes to the cloud
- Assumes better hardware than we did in 2001…
  - Basically, a Raspberry Pi+ (ARM, x86, 1GHz, Linux)

What about those Robot Swarms?

- We shall require a combination of:
  - Power, communications, computation
  - Sensors, actuators, algorithms
- Desired behavior is semi-autonomous swarming
  - Semi-autonomous: limited human engagement
  - Swarming: self-adapting group behaviors
- Also human-robot interactions
  - With various degrees of proximity

Kirgami-skin robot (Harvard)

Batteries & Energy Harvesting

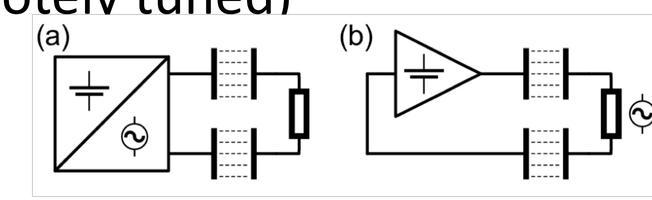
- Rectenna (1960s) – energy harvesting antennas
  - Modern version (2015+, GaTech) – <u>optical</u> using Carbon nanotubes
- Triboelectric nanogenerators (TENG e.g., clothing)
- Battery configurations (today driven by mobile & EVs)
  - Gold nanowire (MnO_2 on wires in a gel, UCI)
  - Laser produced supercapacitors [using graphene]
  - Urine/water-powered fuel cell (Gates foundation)
  - Solid state Li-Ion (Toyota)
- Other battery chemistries
  - Dual carbon (Power Japan Plus)
  - Sand-anode Li-Ion (UCR)
  - Na-Ion battery
  - Graphene batteries / balls (Samsung)

Ji et al, Rectanna, 2014

Wireless Power

Wardenclyffe Tower
Nikola Tesla 1901-2

- Demonstrated systems tend to use directional microwaves (only high frequencies propagate well)
  - WPT (wireless power xfer)- patented by Tesla (1914)
  - Inductive coupling (magnetic field)
  - Capacitive coupling (electric field)
  - Optimality when source-load are conjugates
- Current R&D: parity-time 'on site' symmetric systems
  - Based on non-Hermitian Hamiltonian quantum mechanics (of increased interest starting mid-2000s) [in non-linear circuit]
  - Couples circuit back to source (not remotely tuned)
  - Avoids tuning controls at load



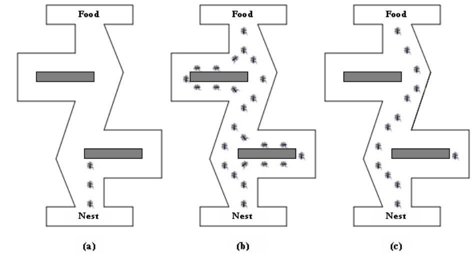
Communications

- Direct Links – radios (RF), optics (laser), acoustic
- Environment modification – stigmergy
  - E.g. RFID tags in pre-configured environment
- Protocols
  - Time & transmission synchronization
  - Reliable delivery, disruption tolerance
  - Routing, coding, controlled flooding
  - Flow / Congestion control

Processing and Programming

- Significant capability in integrated SoCs
  - ARM, Arduino, PIC, Atmel, Qualcomm, …
- Low-power circuits
  - GaTech recent mixed-signal ASIC for low power control
- Programming : top down and/or bottom up
  - Conventional languages (C/C++, Python, etc)
    - URBI (UObject component arch), and ROS (Robot OS)
  - Domain specific languages (e.g., Buzz, Meld)
    - Virtual stigmergy and neighbor messages in Buzz
    - Based on logic-type programming (P2) in Meld

Swarm Intelligence



Science and Academic Publishing 2012

- Emergent colony behavior from limited individuals
  - Biofilms (bacteria), fish schools, bird flocks, ants/bees/termites, locusts, primates
- Tasks: path planning, nest construction, task allocation, collective defense/attack
- Algorithms: Particle Swarm Optimization (PSO)
  - Others: ant colony (ACO), glowworm swarm (GSO), artificial bee colony (ABC), cuckoo search (CSA)
- Desired properties: simple, scalable, decentralized, local, parallel, (energy conserving)

Human-Robot Interactions

- Example from fire fighting (Naghsh et al 2008)
  - Human: supervisor, operator, mechanic, peer, bystander
  - Issues: poor viz, toxic gases, structural integrity, limited information, flashovers, intermittent comms (metals), limited time, stress
- Remote (base station) and local (e.g., tactile)
- Single and multi-operator with gestures
  - Leader election, followed by flocking
- Direct Brain-Computer Interface
  - DARPA BCI Chip

The Myo – now discontinued

Observations

- Swarms of robots are already here
  - They're just a new 'user' of communications
- Comms challenges focused on connecting humans; now it also includes M2M, but many similar issues
  - Next were about latency and secrecy
  - Then about scale and availability
- Swarms require multiple technologies: power, comms, computing, algorithms, sensors/actuatos
  - These are mostly here today
- So what are you worried about?

Thanks

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