Introduction to Teleoperation

or

"It's like remote control... only better!"

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5 April 2016

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But first…

Some house keeping

Calendar at a glance

Week	Dates	Lecture	Reviews	Demos	Assessment submissions
1	2/3 – 6/3	Introduction			
2	7/3 – 11/3	Principles of Mechatronic Systems design			Problem analysis
3	14/3 – 18/3	Professional Engineering Topics			
4	22/3 – 25/3	Your soldering is (probably) terrible	Progress review 1		
Break	28/3 – 1/4				
5	4/4 – 8/4	Introduction to Teleoperation			
6	11/4 – 15/4				
7	18/4 – 22/4		Progress seminar	25% demo	
8	25/4 – 29/4	Switch to Q and A sessions			
9	2/5 – 6/5			50% demo	
10	9/5 – 13/5		Progress review		
11	16/5 – 20/5			75% demo	Preliminary report
12	23/5 – 27/5				
13	30/5 – 3/6	Closing lecture		Final testing	Final report and reflection

You are here

Lecture nominations

- Only two people nominated topics
  - Lots of folks tried to vote after the Friday deadline – yes, I noticed!
  - Still, one obvious clear winner: teleoperation
  - But I'll cover material on communications, too
- If you want to nominate a topic, feel free to do so – next week will probably be Q&A

FAQ Roundup

- **None as yet**
  - All quiet on the Eastern front.

Back to business…

Teleoperation – tally ho!

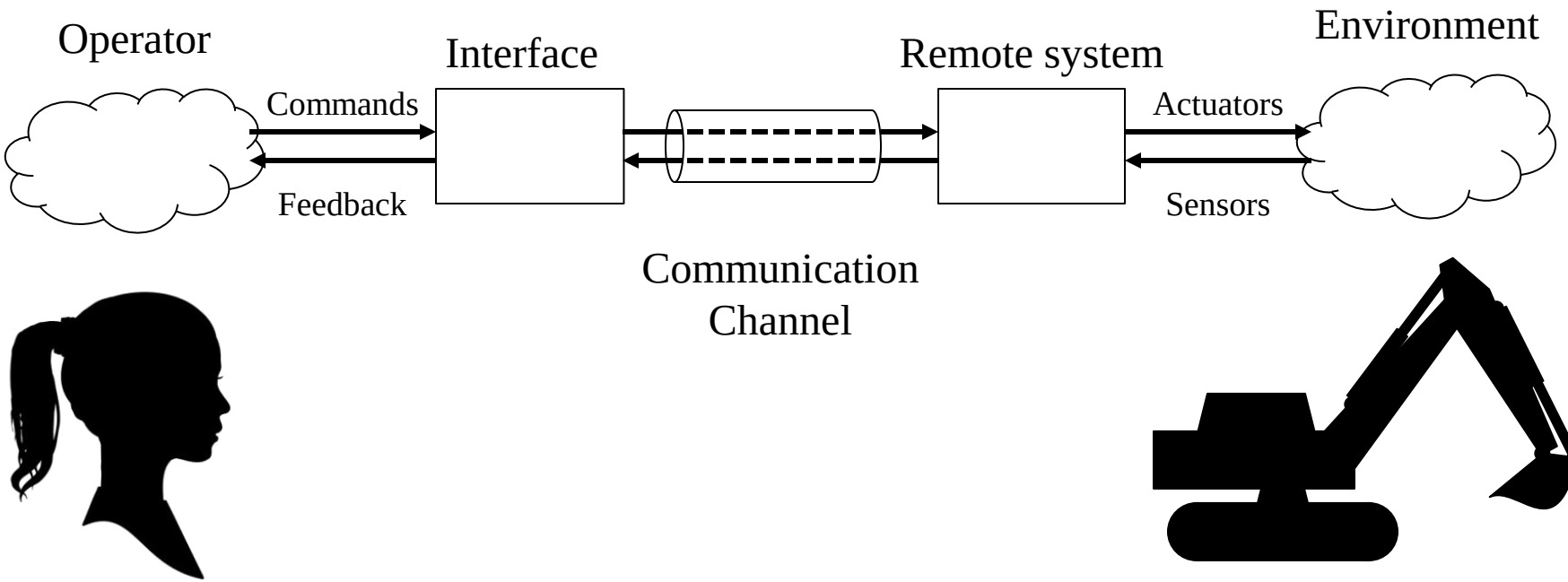
Teleoperation

- *Tele*- from Ancient Greek τῆλε meaning "at a distance"
- *Operation* from the Latin *operātiō* meaning "to work", etymologically related to *opus*

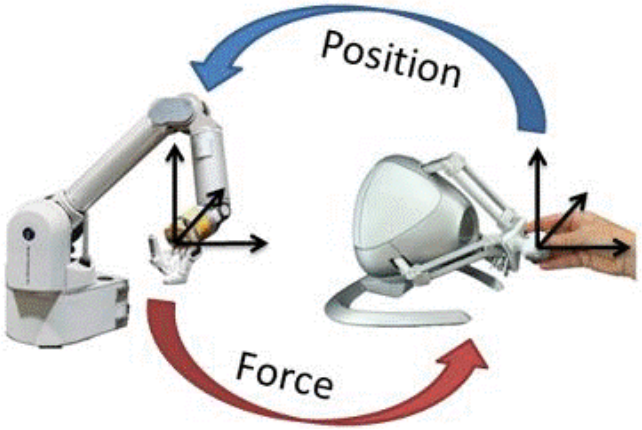
Literally: To work at a distance

What's involved

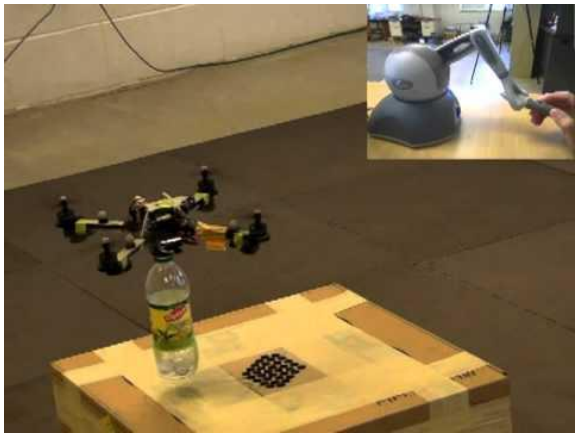
- Let's do that systems thing!



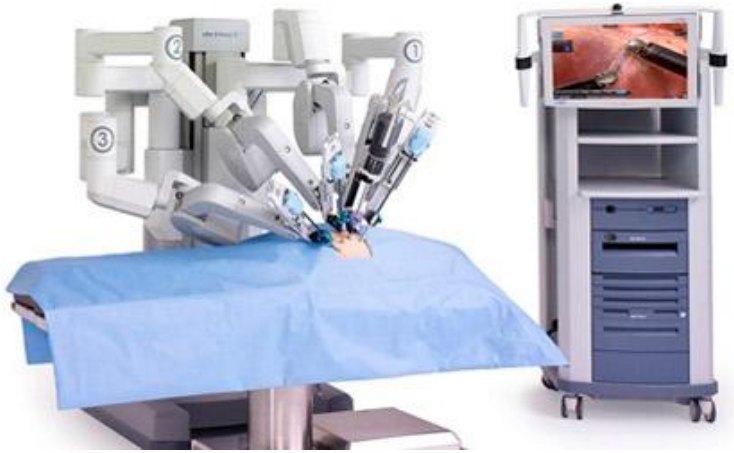
Some examples



WAM and Novint Falcon



Asctech Hummingbird and Phantom



Da Vinci surgical robot

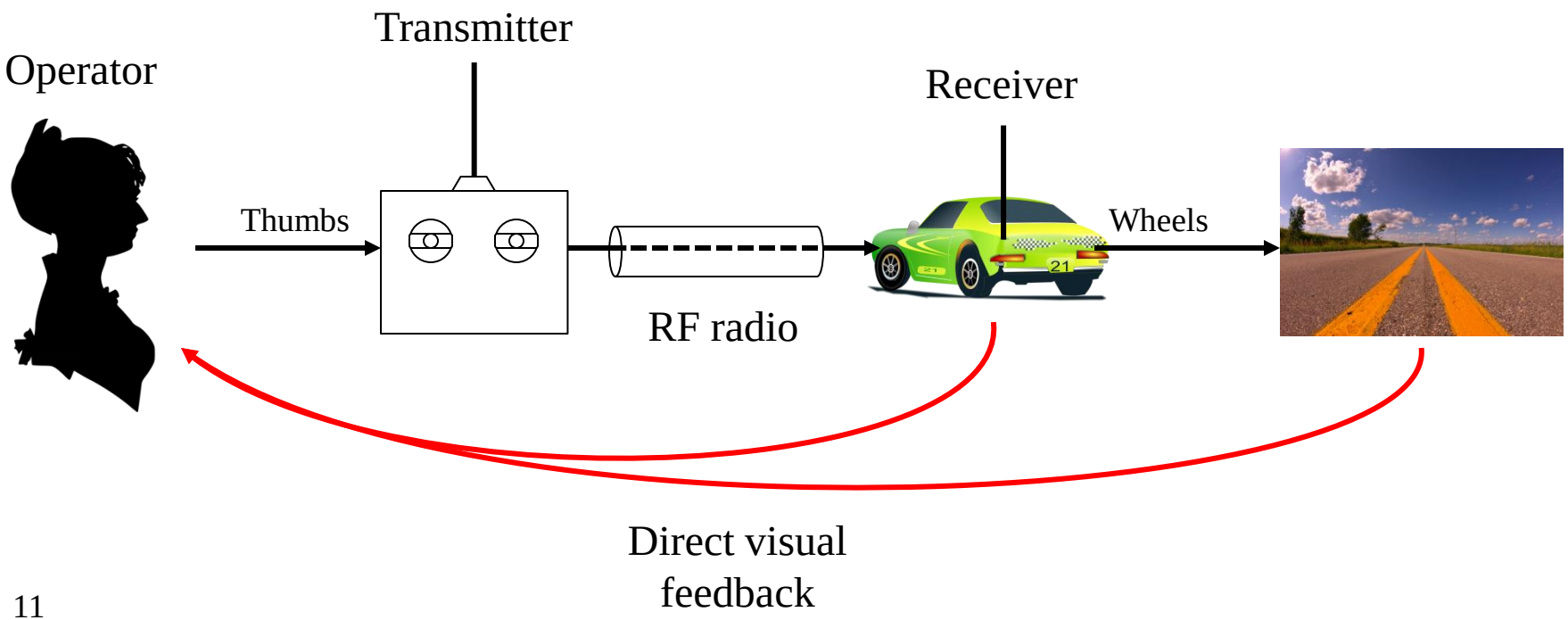
Operation models

Two possible operation models:

- Unilateral
  - Homologous to open-loop control
- Bilateral
  - *"Now with 100% more lateral"*
  - Conveys the sensation of interaction to the user
  - Homologous to feedback control

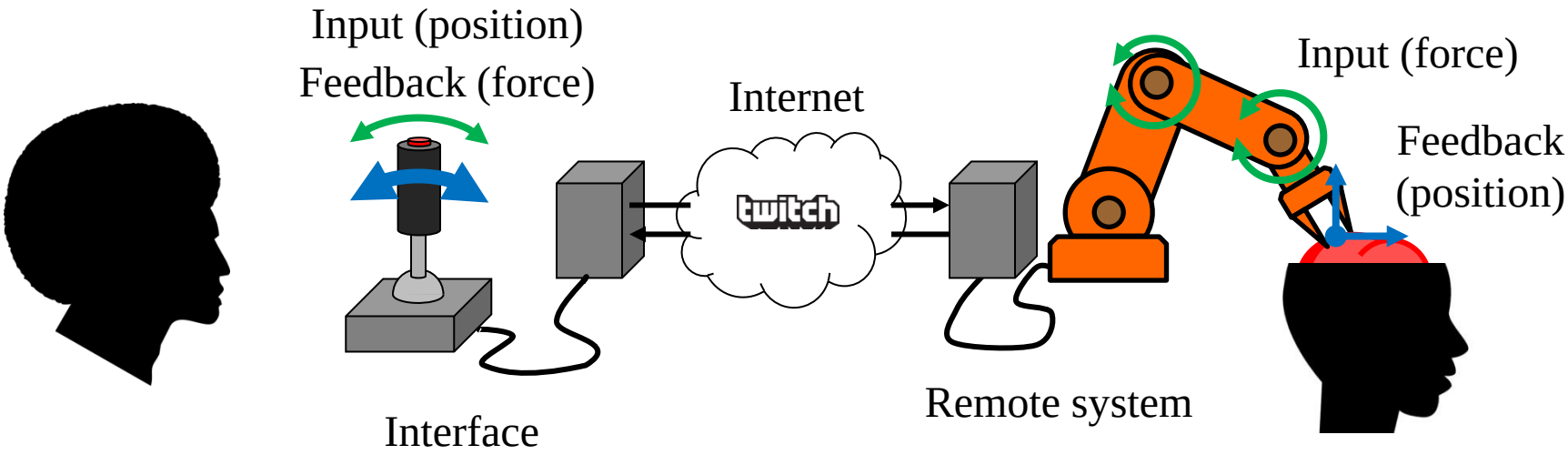
Unilateral model

- Simplest example (eg. RC car)
  - User demands an input, assumes the remote system reflects the desired action perfectly



Bilateral model

- Dynamic coupling (eg. haptic feedback)
  - User sends command, output reflected to user



Doesn't have to be just position – could be force, velocity, integrated values, pressure, temperature, etc.

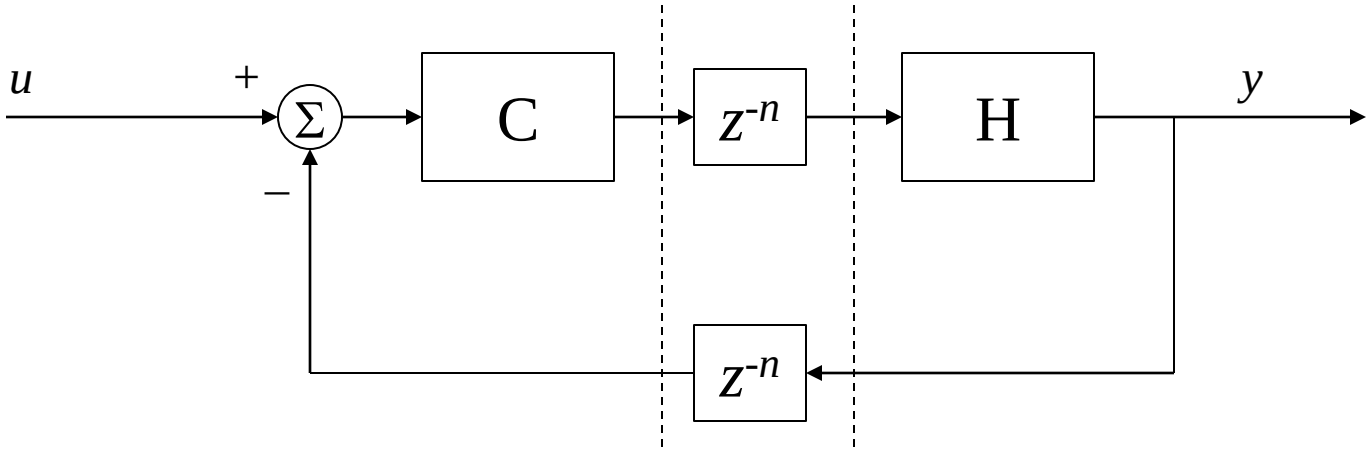
So what makes this hard?

- Subtle analytical challenges
  - System stability under large (variable!) delays
  - Whole-system stability of coupled dynamics

- Prosaic information engineering problems
  - Visual feedback challenges
  - Bandwidth limitations
  - Human-machine interface, etc

Control with delays

- Can treat some systems just like a highly delayed classical system:



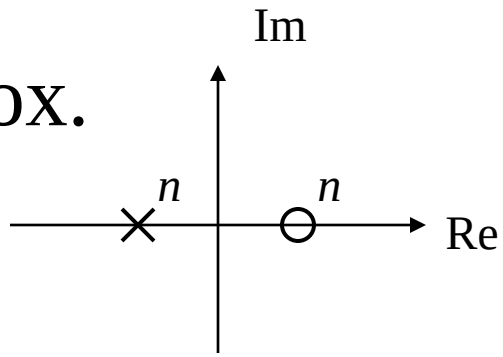
Channel
delayed by *n*

Control with delays

- Continuous – consider Padé approx.

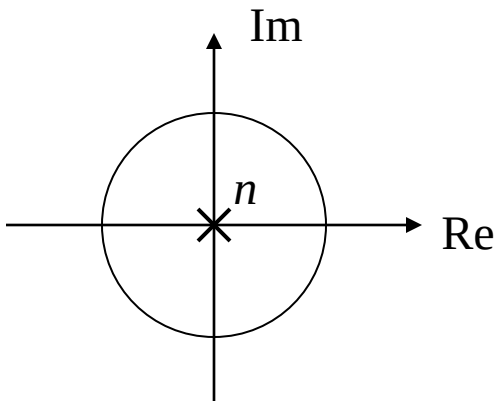
$$\exp\{-sT\} = \frac{\exp\{-sT/2\}}{\exp\{sT/2\}} \approx \frac{1 - sT/2}{1 + sT/2},$$

(1st order approximation)



- Discrete – add delays directly

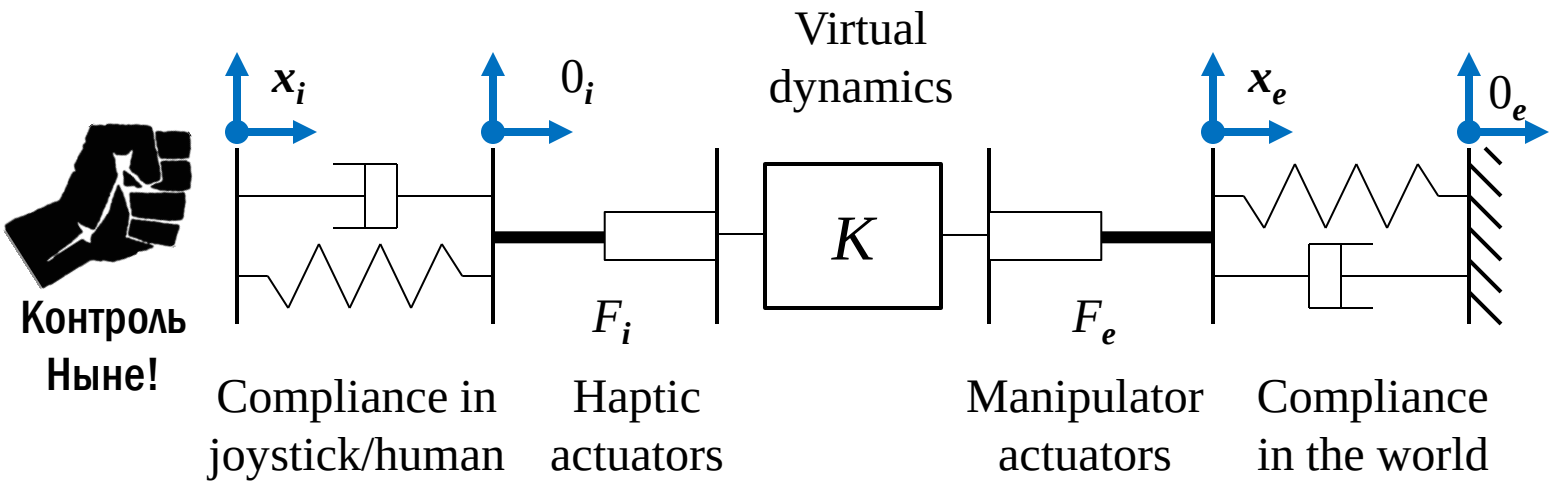
$$\exp\{n\} = z^{-n}$$



Feed-forward control is practically mandatory for regulating these systems

Haptic control schemas

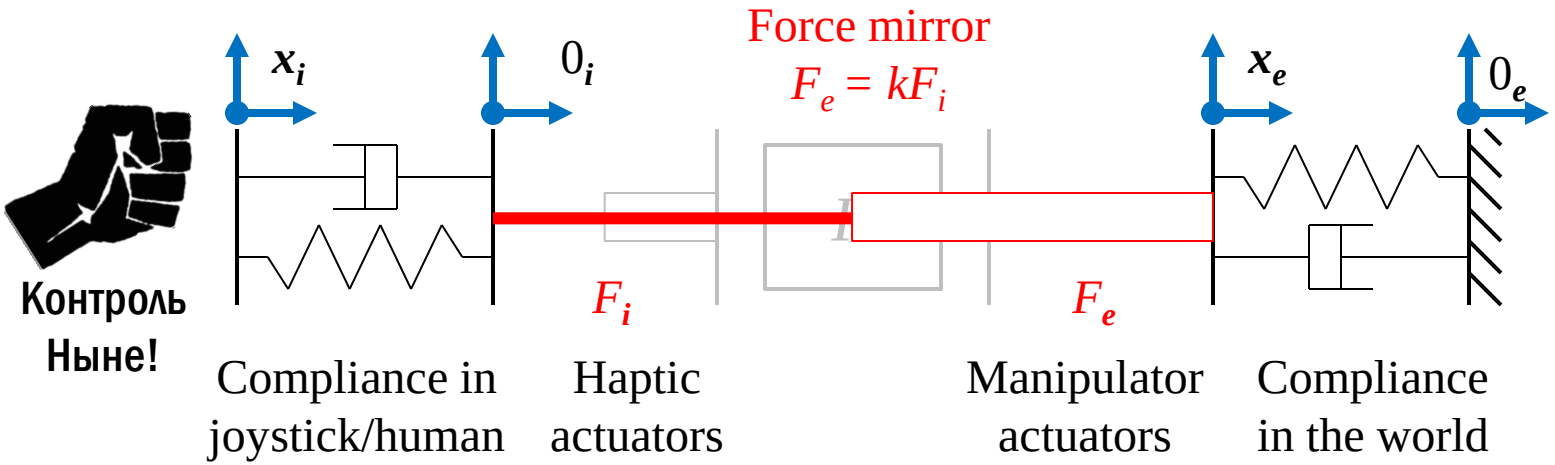
- Plurality of processes for peeling panthers



General system concept

Haptic control schemas

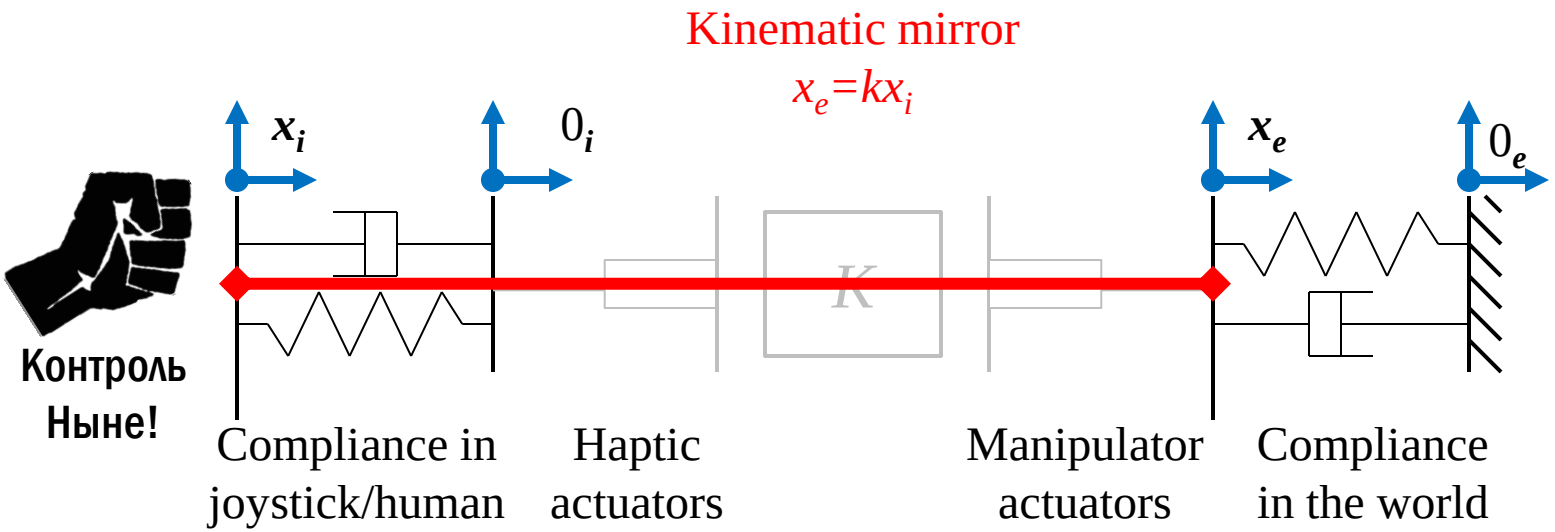
- Plurality of processes for peeling panthers



"Force in, force out"
Positions decoupled

Haptic control schemas

- Plurality of processes for peeling panthers

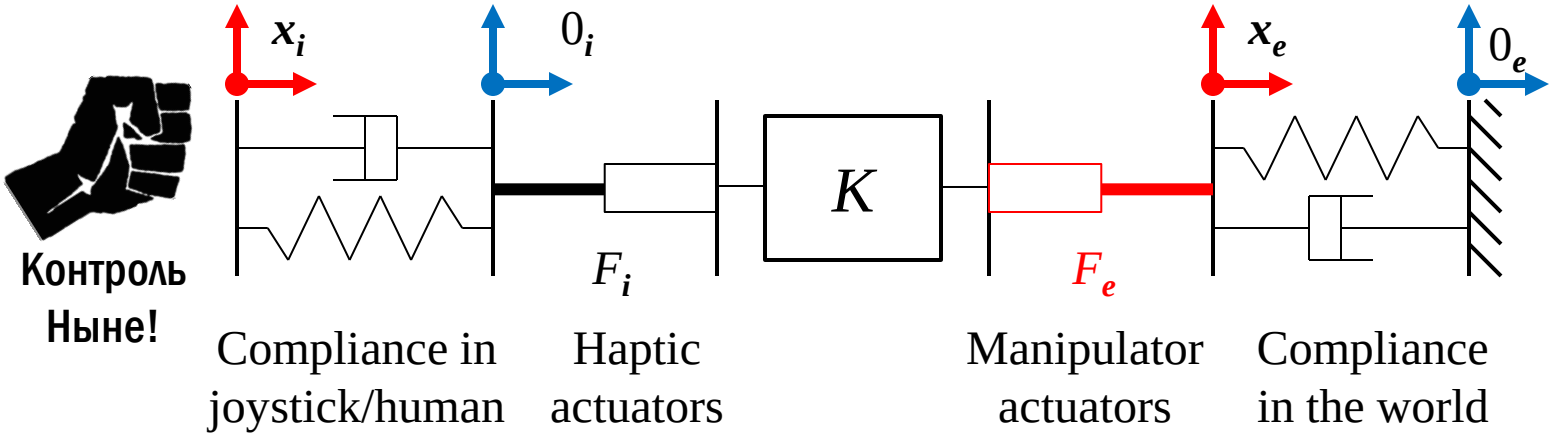


"Position in, position out"
Forces may be arbitrarily large

Haptic control schemas

- Plurality of processes for peeling panthers

Impedence control

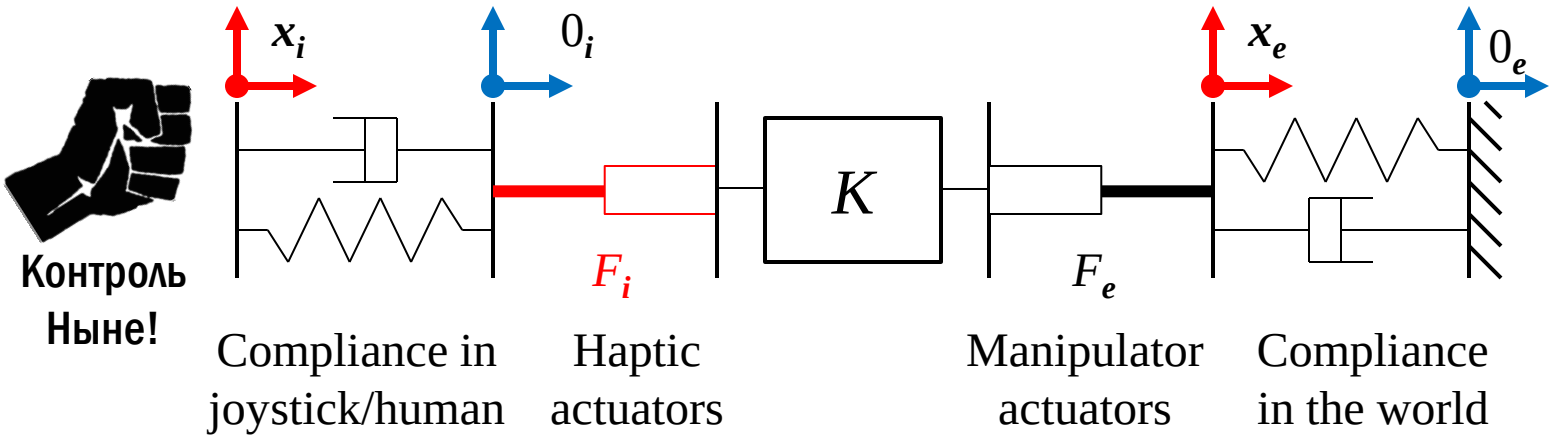


"Position in, force out"
User observes reflected stiffness

Haptic control schemas

- Plurality of processes for peeling panthers

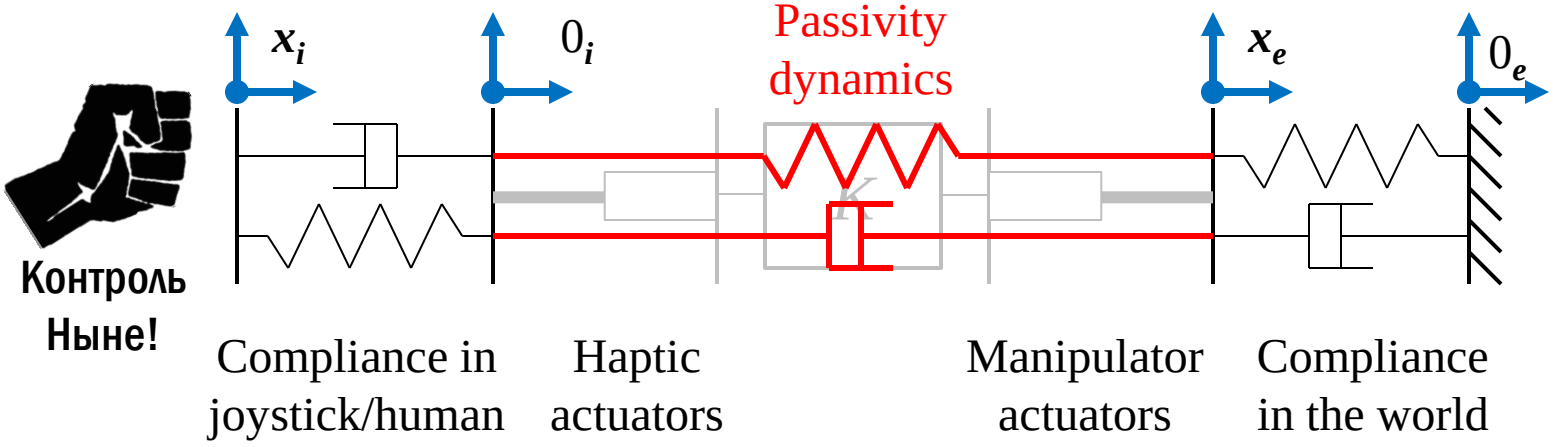
Admittance control



"Force in, position out"
User observes reflected inertia

Haptic control schemas

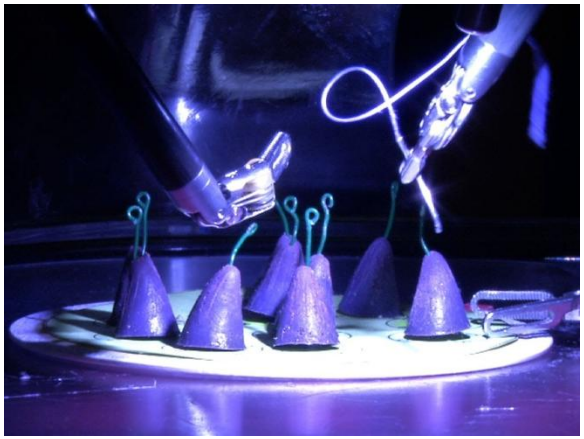
- Plurality of processes for peeling panthers



"Energy in, energy out, minus a bit"
Simulated resistive elements

Subtle stuff

- You can get really clever with this stuff
  - Change *k* for force to get force amplification
  - Change *k* for position to get motion scaling
- The Da Vinci surgical robot low-pass filters its position control to remove shake from the surgeon's hand
  - Also try "Lazy Nezumi" for Photoshop…



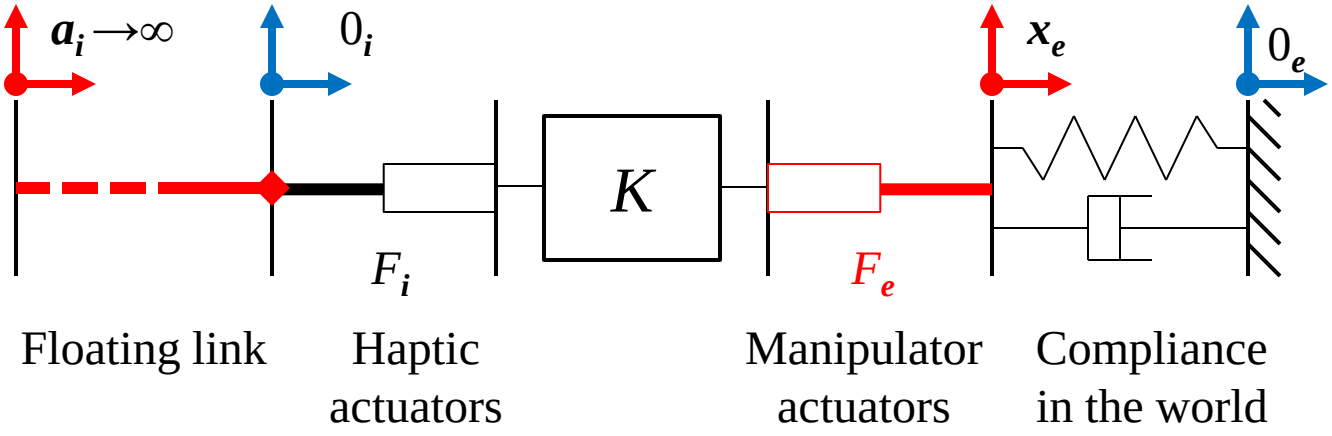
Whole system stability

- All these linear haptic control schemes can be analysed with the control theory you know and love!
  - You *do* love control theory, right?
- It's very easy to build a system that is stable with a hand in the loop, but unstable when the operator lets go (exciting to watch!)
  - Plz don't built systems like this

Whole system stability

- For example… let go of an impedance controller, what happens?

Impedence control



Control input will be driven to the limits of its operating range

Prosaic engineering problems

- Perspective, field of view
  - Can you see what you're doing? Enough of it?
  - From the right angle?
  - Lots of difficult teleoperation problems can be solved just by moving the camera…
- Depth perception
  - Is your task inherently 3D?
  - Do you need true stereoscopy? Will multiple views do? How about vision plus depth map?

Prosaic engineering problems

- Information focus, operator workload
  - How much stuff do you need to monitor all at once? Do you need a HUD? A stick shaker?
  - How do you know when it's working right?
- What is the most natural way of controlling your application?
  - Haptic glove vs 3D stylus for manipulator arm
  - Joystick vs Google maps for drones

Prosaic engineering problems

- Bandwidth limitations
  - What is the response time of your system?
  - Is there enough bandwidth for fine control?
  - How often do you get images back? How often do you *need* images back?
- Comms channel is unreliable
  - How do you handle lost packets for a dynamically-coupled haptic system?
  - How do you manage grossly variable response times? What if packets get out of order??

Wireless networks and comms

Hey, while we're on the topic of communications channels…

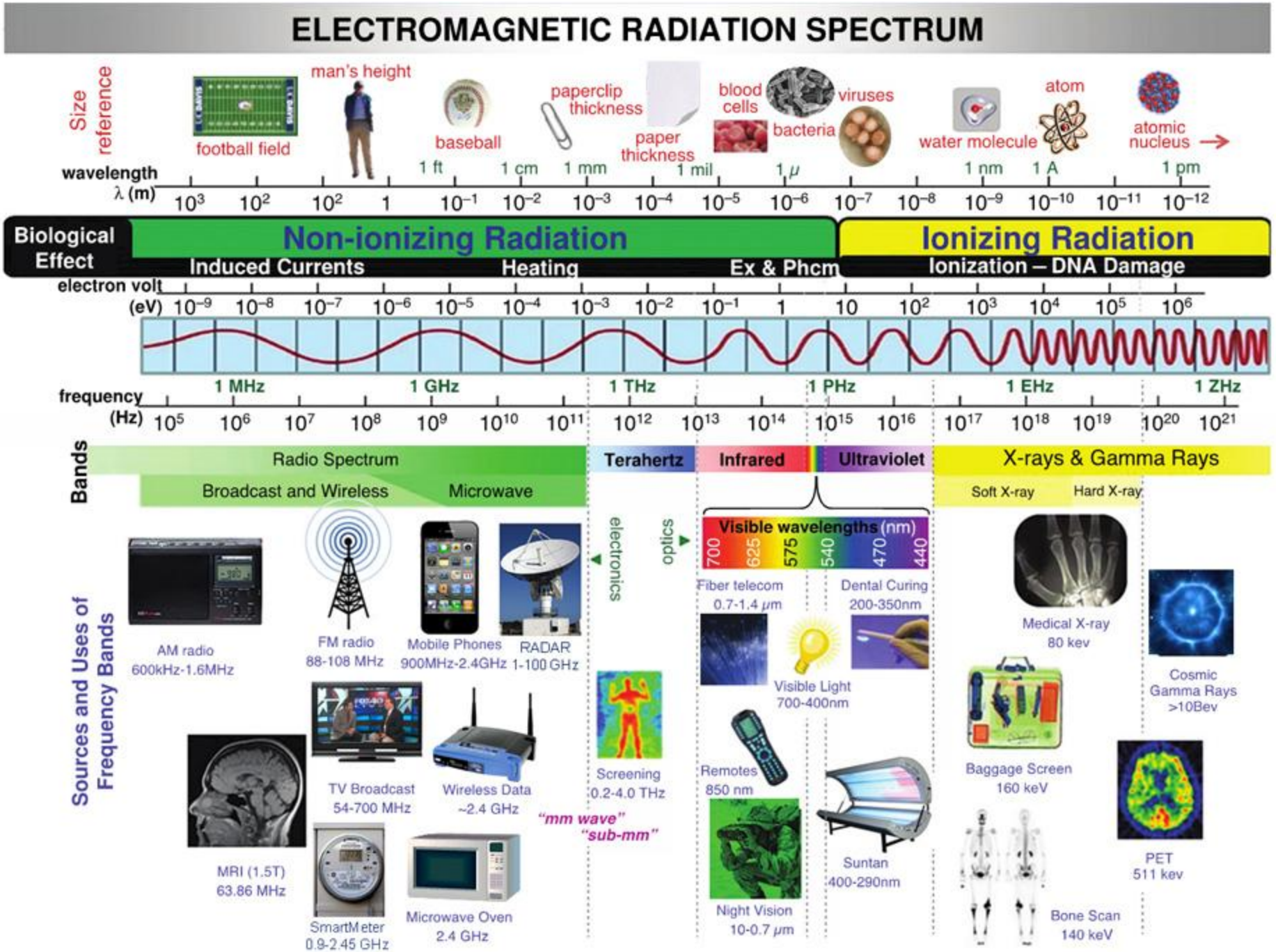
The other lecture request was for networks and communications

Meditations on wireless comms

- Wireless communications is fascinating, and you can practically get a whole degree on just it alone.

- For mechatronics engineers, it boils down to "Which radio module should I buy?"

Every discussion of RF starts with the electromagnetic spectrum



[Scientific American]

Quick comments the radio spectrum

- Radio spectrum is extremely valuable
  - You don't get much to play with
- "Open" spectrum is predominantly concentrated in the ISM bands
  - ISM: Industrial, Scientific and Medical
- Fortunately, most of the RF compliance work has been done for you

Frequency, data rate and power

- The higher your radio frequency, the faster you can transfer data
  - But also the more difficult filtering becomes, thus shorter range
- Transmitting more power gets you higher above the noise floor and thus greater range
  - But you also cause more interference

The ISM bands*

Frequency range		Bandwidth	Center frequency	Availability
6.765 MHz	6.795 MHz	30 kHz	6.780 MHz	Subject to local acceptance
13.553 MHz	13.567 MHz	14 kHz	13.560 MHz	Worldwide
26.957 MHz	27.283 MHz	326 kHz	27.120 MHz	Worldwide
40.660 MHz	40.700 MHz	40 kHz	40.680 MHz	Worldwide
433.050 MHz	434.790 MHz	1.74 MHz	433.920 MHz	Region 1
902.000 MHz	928.000 MHz	26 MHz	915.000 MHz	Region 2
2.400 GHz	**2.500 GHz**	**100 MHz**	**2.450 GHz**	**Worldwide**
5.725 GHz	5.875 GHz	150 MHz	5.800 GHz	Worldwide
24.000 GHz	24.250 GHz	250 MHz	24.125 GHz	Worldwide
61.000 GHz	61.500 GHz	500 MHz	61.250 GHz	Subject to local acceptance
122.000 GHz	123.000 GHz	1 GHz	122.500 GHz	Subject to local acceptance
244.000 GHz	246.000 GHz	2 GHz	245.000 GHz	Subject to local acceptance

[~~wikipedia~~ “Radio Regulations”, Internationla Telecommunications Union-R 2012]

* “ISM” is a great name for a garage rock band

A brief survey of radio standards

Module	Frequency	Typ. range	Typ. data rate	Typical application
FM	433/434 MHz 868 MHz 900/915 MHz	100 m 100 m 20 m	4.8 kbit/s 9.6 kbit/s 115.2 kbit/s	Garage door opener Wireless POTS phone
Zigbee	868 MHz 915 MHz 2.4 GHz	70 m 70 m 70 m	40 kbit/s 45 kbit/s 250 kbit/s	Wireless sensor networks
Nordic	2.4 GHz	50 m	1 Mbit/s	Wireless sensor networks
Bluetooth	2.4 GHz	10-100 m	0.7 – 2 Mbit/s	Laptop/cellphone peripheral
Wi-Fi	2.4 GHz	30 m	11 Mbit/s+	Mobile network
0G 1G 2G 3G 4G	Various 150 Mhz 0.9 – 1.8 GHz 0.4 – 3 GHz 1.7 – 1.8 GHz	80 km 40 km+ 35 km 30 km 5 km	9.6 kbit/s 14.4 kbit/s 144 kbit/s 2 Mbit/s 100 Mbit/s?	Cellular telephony and data

Pros, cons of comms systems

FM:	Very cheap, lousy transfer rate
Bluetooth:	Good speed, limited range
Zigbee:	Mesh networking, limited speed
Wi-Fi:	Great speed, lots of overhead
Cellular:	Wide reach, very expensive
Satellite:	Global reach, crazy expensive
Pigeon:	High bandwidth, unreliable

THE ELECTROMAGNETIC SPECTRUM

THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.

ABSORPTION SPECTRA:

HYDROGEN:

HELIUM:

DEPENDS®:

TAMPAX®:

RED ORANGE YELLOW GREEN BLUE VIOLET OCTARINE

700nm 450nm

VISIBLE LIGHT

OTHER WAVES:

SLINKY WAVES

SOUND WAVES

20 KHz AUDIBLE SOUND 20 Hz

THAT HIGH-PITCHED NOISE IN EMPTY ROOMS

THE WAVE

SHOUTING CAR DEALERSHIP COMMERCIALS

CIA (SECRET)

HAM RADIO

KOSHER RADIO

CELL PHONE CANCER RAYS

99.3 "THE FOX"

101.5 "THE BADGER"

106.3 "THE FRIGHTENED SQUIRREL"

SPACE RAYS CONTROLLING STEVE BALLMER

ALIENS

GRAVITY

SETI

24/7 NPR PLEDGE DRIVES

AM (US)

VHF UHF FHF

WIFI

BRAIN WAVES

SULAWESI

SUPERMAN'S HEAT VISION

JACK BLACK'S HEAT VISION

SUNLIGHT

MAIN DEATH STAR LASER

CENSORED UNDER PATRIOT ACT

POTATO

BLOGORAYS

MAIL-ORDER X-RAY GLASSES

SINISTER GOOGLE PROJECTS

POWER & TELEPHONE	RADIO & TV	MICROWAVES	TOASTERS	IR	VISIBLE LIGHT	UV	VISIBLE DARK	MILLER LIGHT	X-RAYS	GAMMA/COSMIC RAYS

λ (m) 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}

100Mm 10Mm 1Mm 100km 10km 1km 100m 10m 1m 10cm 10cm 1mm 100μm 10μm 1μm 100nm 10nm 1nm 100pm 10pm 1pm 100fm

f (Hz) 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22}

1Hz 10Hz 100Hz 1KHz 10KHz 100KHz 1MHz 10MHz 100MHz 1GHz 10GHz 100GHz 1THz 10THz 100THz OTHER ENTERTAINING GREEK PREFIXES LIKE PETA- AND EXA- AND ZAPPA-

Q (Gal² Colonels) 17 117 17 17 42 Φ $e^{\pi}-\pi$ −2 540^{50} 12 11^{2}

[xkcd.com]

Wired communication

Just to touch on wired comms:

- Tethered (obviously)
- Much higher data rates and lower noise
- Can be susceptible to RF, especially over longer runs (led is effectively an antenna)
  - Shielded cable and twisted-pair mostly solve this
- Gets very expensive for especially long range installations… eg. across the Atlantic

Wired communication

UART	*Everywhere*, limited speed and range
SPI/I2C	Good speed but very short ranges
RS485	Like UARTs with long-range twisted-pair, ok speed, requires transceivers
CAN	Extreme reliability, but complicated software overheads and slowish
USB	Very fast, flexible, huge overheads
Ethernet	High speed but clunky, big overheads
Fibre-optic	You’re not using fibre-optics

Sure, but…

Ok, Paul, that's really cool and all,
but really what we really wanted you to
tell us was how to solve the problem.

Obviously.

Cool bruh

No worries.

Here are some useful thoughts

And now…

Gratuitous project tips!

Simple simple simple

Robust robust robust

Test test test

(and test again)

Gratuitous project tips!

- Some things engineers *never* try to build if they can buy, copy or otherwise avoid it:
  - Power supplies
  - Motor drivers
  - Analog amplifiers
  - Inertial Measurement Units
  - Sensor fusion and estimation algorithms
  - Vision processing libraries

Gratuitous project tips

- You almost certainly don't need silky smooth video.
  - Why waste all your processor cycles just passing data around? Don't pipe data through a micro unless it's completely unavoidable.
- Oh yeah, and Arduino will come back to haunt you in the end… trust me on this.
  - Yes, you can use Arduino – but I won't respect you in the morning…

Gratuitous project tips

- Nobody is thinking about manipulation nearly enough; nobody has a good solution
  - Grabbing the LEGO figures is the hardest part of this course – ***disregard it at your peril!***
- Why the glob are you wasting your time looking at QR codes for, if you haven't even gotten the basics working yet?
  - Seriously, this will ruin you.

Gratuitous project tips

- Are you sure your wireless communication scheme will work?
  - I mean, really really sure?
  - Like… have you tested it?
  - In a sealed box coated in metal foil?
  - For reals?
  - Well… ok then…

Gratuitous project tips

That's all for now!

But maybe more later…

Request for comment

What feedback do you have
on the course thus far?

How can we make the course better?

What skills do you wish you had?
(or want to improve?)

Questions

Tune-in next time for…

Q&A 1

or

"Questions and Answers: Let's put them together and see if they match!"

Fun fact: Leonardo Da Vinci made a robot knight that could walk and move its arms and head, and a robot lion that could walk, shake its head and roar.