Mining Ventilation Control

Dr. Emmanuel WITRANT

Lessons Handout

Lesson	Topics
1	**Mining Ventilation Fundamentals** *Airflows in mines; Pollutants; Design and sizing of the ventilation process; Mathematical modeling for control from the 60s to the 90s.*
2	**Some feedback control principles** *Control system design; Modeling dynamics in the time and frequency domains; Models for control; The feedback principle; Stability and controllability; The robustness versus performance dilemna.*
3	**Model of mine ventilation network system** *Fundamentals of Physical modeling; Model of the network system using Kirchhoff's laws; Dynamic models of the network; Simulation softwares.*
4	**Air flow modeling in deep wells** *The basic equations of fluid dynamics; From Euler equations to lumped models; Fans, rooms and pollutant sources; Volume-averaging and estimation of the transport coefficients; Time-delay approximation.*
5	**Extraction rooms air quality model** *Aerogas dynamics of chamber-like mine workings; Fluid statics: buoyancy force; Stratified flows and forced plumes; Constrained shape of the pollutants profile; Peripheral dynamics induced by fans and tarpauline tubes.*
6	**Principals control strategies to mining ventilation** *Control of the ventilation network; Nonlinear control of the flow network in coal mines; Distributed dynamics control in deep wells: fast MPC and time-delay compensation; Hybrid control of the extraction rooms.*
7	**Application of wireless sensors to mining ventilation** *Background on wireless sensing, c and advanced services; Communication architecture; Models and algorithms; Advanced network architectures and services; Case study on localisation services.*

Universidad Pedagogica y Tecnologica de Colombia
Sogamoso, April 2013.

Mining Ventilation Control

Outline

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Universidad Pedagógica y Tecnológica de Colombia,
Sogamoso, April 4, 2013

Outline
E. Witrant

An international framework - special thanks to:

Sweden ABB: A.J. Isaksson, M. Strand
- Boliden
- KTH: K.H. Johansson, C. Fischione

Italy U of L'Aquila: A. D'Innocenzo, M.D. Di Benedetto, F. Santucci, E. Serra, S. Tennina and U. Tiberi

France LSS: S. Olaru, G. Sandou, S. Niculescu
- GIPSA-lab: N. Marchand, M. Alamir, F. Castillo

India IIT Dehli: M. Khare, S. Chinthala

USA U California at San Diego: M. Krstić

Colombia UPTC: J.M. Salamanca

+ on flow systems

France LGGE: P. Martinerie
- Renault: V. Talon

Switzerland CERN: B. Bradu, P. Gayet

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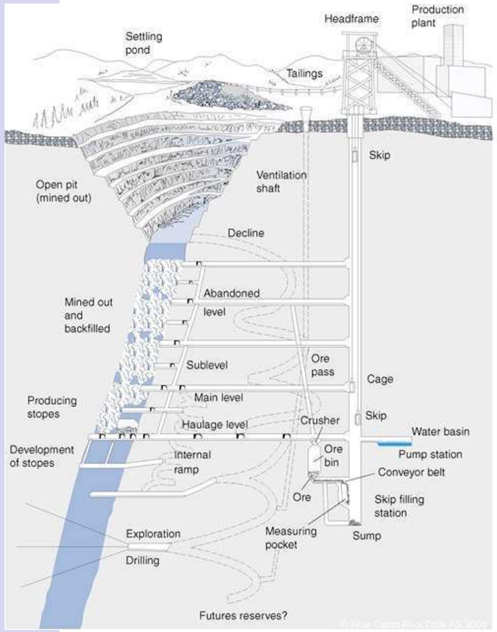
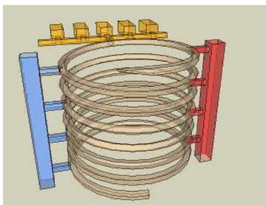
Mining



Components:

- Blasting and drilling
- Transport: trucks or hoist
- Ore crushing
- Ventilation: 50% of energy consumption
- Mining = 4% (US) - 6% (South Africa) of industrial electrical consumption



Outline
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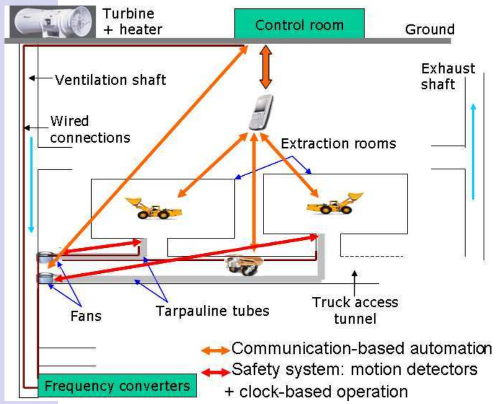
Mining ventilation control

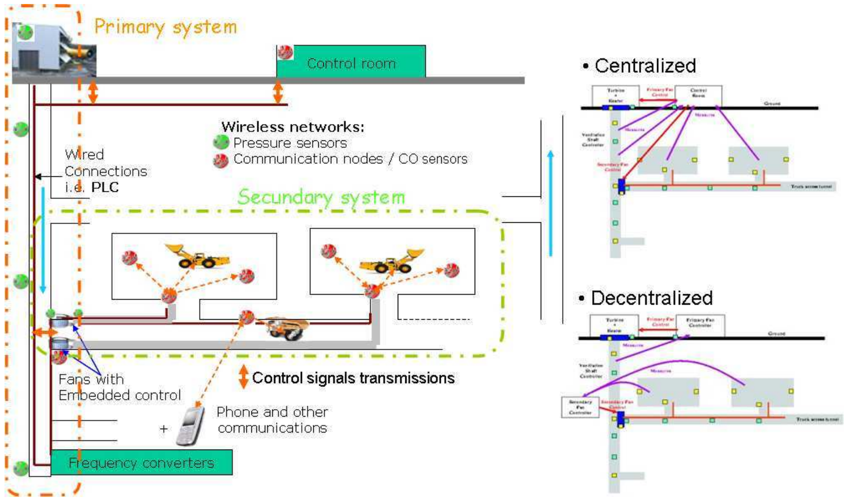
Actual automation in Sweden



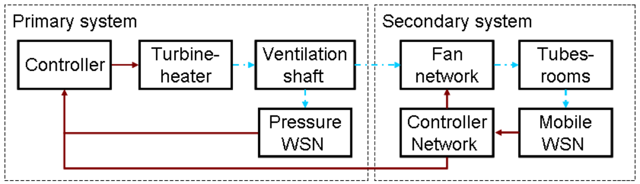
- Ventilation control = worst case ventilation design
- i.e. tunnels diameter / fans power depending on number of trucks
- Operation at max power when extracting the ore
- No continuous air quality monitoring (scheduled), no Wireless Sensor Network (WSN)

Visit at Garpenberg mine (operated by Boliden®), Sweden

Potential wireless control architecture



Control architecture



- Objectives:
  - Control air quality (O_2, NO_x and CO) in extraction rooms
    - turbine and heater provide airflow pressure to fans
    - fans ensure air quality in extraction rooms
  - Safety through wireless networking for personal communication and localization
- Automation/design constraints:
  - Physical interconnections, actuators limitations and networking capabilities
  - Sensing capabilities: chemical, pressure and temperature

Course goal

Provide technical skills and research insights for mining ventilation control.

Main topics:

- Mining ventilation automation principles and design
- Mathematical modeling of the mine flow network, of aerodynamics in ducts and of the ore extraction rooms
- Principles of feedback control and advanced strategies of feedback design dedicated to mine ventilation control

Class overview

Les.	Topic
1	**Mining Ventilation Fundamentals (2h)** *Airflows in mines; Pollutants; Design and sizing of the ventilation process; Mathematical modeling for control from the 60s to the 90s*
2	**Some feedback control principles (4h)** *Control system design; Time and frequency domains; Models for control; The feedback principle; Stability and controllability; Robustness vs. performance.*
3	**Model of mine ventilation network system (3h)** *Fundamentals of Physical modeling; Model of the network system using Kirchhoff's laws; Non-minimal and minimal models of the network; Simulation softwares.*
4	**Air flow modeling in deep wells (2h)** *Fluid dynamics; From Euler to lumped models; Fans, rooms and pollutant sources; Volume-averaging and estimation of the transport coeff.; Time-delay approx.*
5	**Extraction rooms air quality model (2h)** *Gas dynamics in rooms; Fluid statics and buoyancy; Stratified flows and forced plumes; Constrained shape of the pollutants profile; Peripheral dynamics.*

Les.	Topic
6	**Principals control strategies to mining ventilation (1h30)** *For the ventilation network; for deep wells: fast MPC and time-delay compensation; Hybrid control of the extraction rooms.*
7	**Application of wireless sensors to mining ventilation (30 mn)** *Background on wireless sensing, c and advanced services; Communication architecture; Models and algorithms; Advanced network architectures and services; Case study on localisation services*

Reference textbooks

- Hartman HL, Mutmansky JM, Ramani RV, Wang YJ. Mine Ventilation and Air Conditioning (3rd edn). Wiley: New York, 1997.
- Anderson, J.: Fundamentals of Aerodynamics, McGraw-Hill Companies, 1991.
- C. Hirsch, Numerical Computation of Internal & External Flows: the Fundamentals of Computational Fluid Dynamics, 2nd ed. Butterworth-Heinemann (Elsevier), 2007.
- S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control: Analysis and Design*, 2^{nd} Ed., Wiley, 2007.
  http://www.nt.ntnu.no/users/skoge/book/ps/book1-3.pdf
- K.J. Åström and B. Wittenmark, *Computer-Controlled Systems: Theory and Design*, 3^{rd} Ed., Prentice Hall, 1997.
- H. Khalil, Nonlinear systems, Prentice-Hall, 2002

Class website

- Go to:

  http://physique-eea.ujf-grenoble.fr/intra/Formations/M2/EEATS/PSPI/UEs/courses_CoMVC.php

  or Google "MiSCIT" then go to "Courses", "Advanced control theory" and "Mine Ventilation Control"
- at the bottom of the page, click "Restricted access area" and enter with:
  - login: MineVentCont
  - password: sogamoso

UFR de Physique

Mining Ventilation Control

Lesson 1: Mining Ventilation Fundamentals

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Universidad Pedagógica y Tecnológica de Colombia,
Sogamoso, April 1, 2013

Mining Ventilation Fundamentals
E. Witrant
Airflows in mines
Historical perspectives
Control processes
Engineering controls principles
Pollutants
Diesel Aerosols and Gases in Underground Mines
Diesel Particulate Matter
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Head losses and mine heads
Head gradients
In mine openings
Head losses
Air power
Mathematical modeling for control
Conclusions

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Airflows in mines [Hartman et al. 1997]

Environmental control of the mine atmosphere

- Artificial atmosphere needed to sustain miners: need to be controlled!
- Most versatile control tool in mining engineering
- Mining ventilation = fluid dynamics applied to airflows in openings and tunnels
- Need to define amount and direction of air throughout the mine: limits in quantity, quality and temperature-humidity
- Essential for safety, as well as worker productivity and job satisfaction

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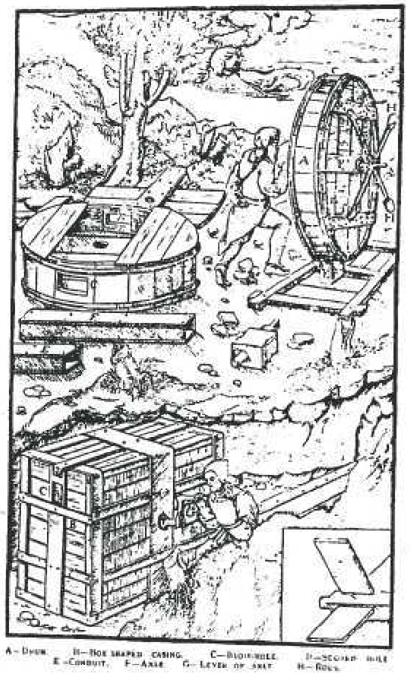
Historical perspectives

- Paleolithic: miners exposed to oxygen defficiency, toxic gases, harmful dusts and debilitating heat
- 1st millenium BCE: air through multiple openings and circuits + fire-induced currents
- Middle Ages: ventilation = mining art, involving “ventilation machines”: deflectors, bellows, fans
- depth constraint = high rock pressure and temperature + deterioration of atmosphere ⇒ ventilation became the most important branch of deep mining

E.g. Agricola 1556: deflectors, bellows and fans



Control processes for total air conditioning

1. Quality control - purifying air and removing contaminants such as:
   - gases - vapors and gaseous matter + radiation
   - dusts - particulate matter
2. Quantity control - regulating the magnitude and direction of air flow through:
   - ventilation (primary)
   - auxiliary or face ventilation
   - local exhaust
3. Temperature-humidity control - controlling latent and sensible heat by
   - cooling
   - heating
   - humidification
   - dehumidification

Engineering controls principles

1. prevention or avoidance
2. removal or elimination
3. suppression or absorption
4. containment or isolation
5. dilution or reduction

+ Medical/legal control principles
Distinction between comfort (for humans) and product (for plants) air conditioning.

Pollutants [Bugarski et al., 2011]

Diesel Aerosols and Gases in Underground Mines

- Diesel engines = major source of submicron aerosols, CO, CO2, NOX, SO2 and hydrocarbons (HC) in underground coal and metal/nonmetal mines.

⇒ Challenge to control workers' exposure and need to establish a comprehensive program based on a multifaceted and integrated approach:
- Curtail emissions of the diesel particulate matter (DPM) and toxic gases at the source;
- Control pollutants after they are released in the underground mine environment;
- Use administrative controls to reduce exposures of underground miners to pollutants.

Diesel Aerosols and Gases in Underground Mines (2)

- Involve key departments of mining companies: health and safety, engine/vehicle/exhaust aftertreatment maintenance, mine ventilation, and production, + those responsible for acquiring vehicles, engines, exhaust aftertreatment systems, fuel, and lubricating oil.

⇒ A program coordinator is crucial to the success of diesel control programs

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Diesel Aerosols and Gases in Underground Mines (3)

- Such program should be dynamic and based on information gathered through surveillance:
  - of parameters for planning, execution, and coordination of the program (e.g., size of the diesel-powered fleet, role of diesel-powered equipment in the mining process, type of engine emissions, contribution of diesel-powered equipment to exposure of underground miners to DPM and criteria gases, quality of diesel fuel and lubricating oil, and ventilation supply and demand)
  - identify and quantify the extent of the problem, identify and evaluate potential solutions, and identify and establish a hierarchy of potential solutions

⇒ Key role of Information Technologies and System Analysis!

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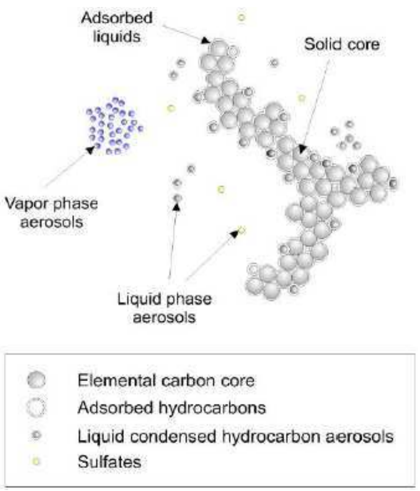
Diesel Particulate Matter (DPM)

- DPM ≐ any material being emitted from a diesel engine that can be collected on a filter through cooled and diluted exhaust.

- Includes four byproducts of diesel combustion: elemental carbon (EC), organic carbon (OC), ash, and sulfuric compounds
- Combine to form DPM aerosols →
- In general, 1 oom < other respirable dust aerosols in underground mines ($< 1\mu m$)

⇒ Not removed by gravitational settling and deposited in the human respiratory tract!



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DPM: Elemental Carbon (EC)

- Combustion = mixture of fuel (hydrocarbon, C_xH_y) vs. intake air:

$$C_xH_y + (x + y/2 + 2)O_2 + N_2 \rightarrow xCO_2 + \frac{y}{2}H_2O + 2NO$$

  Lean (efficient) or rich (lack O_2)
- If hot enough in rich regions, fuel burns without O_2, creating charred remains, or solid carbon soot ≐ EC
- Emitted from the engine exhaust as solid particulate matter, forming the core of a typical diesel-particle agglomerate
- Driven by temp, residence time and availability of oxidants
- Reduced:
  - at the source by increasing the surface area contact of fuel and air → in-cylinder controls
  - by capturing these particles within the exhaust system using diesel particulate filters

DPM: Organic Carbon (OC)

- Forms when hydrocarbons (in fuel and lubricating oil) are consumed but not fully oxidized during the combustion process. Sources =
  - fuel in overly lean regions (not enough fuel)
  - fuel that is post-injected into the chamber too late
  - lubrication oil that is scraped from cylinder walls or introduced into the combustion chamber from other sources
- Temperatures may be high enough to vaporize the C_xH_y, but not to convert them into CO_2 and H_2O.
- Partially composed of volatile material; react and change in both composition and phase during emission.
- Controlled:
  - at the source by reducing oil consumption, improving fuel and oil formulations, and improving fuel injection design and timing
  - at the exhaust by diesel oxidation catalysts (DOCs)

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DPM: Ash

- Come from additives (detergents, dispersants, etc.) in fuel and lubricating oil composed of metallic elements. When consumed, they form inorganic solids = ash
- Cannot oxidize in secondary reactions with aftertreatment devices and may accumulate within the exhaust system and cause maintenance issues over time.
- Reduction accomplished by reducing the metallic fraction of the fuel and oil, and by lowering the amount of oil consumed during the combustion process.

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DPM: Sulfuric Compounds

- Form when sulfur in the fuel and lubrication oil oxidizes during the combustion process
- Gaseous emission that can damage or deactivate expensive exhaust catalysts
- React with other compounds in the exhaust and form solid sulfates, contributing to overall DPM emissions
- Controlled by the transition toward ultralow sulfur diesel fuels (ULSDF) and low-sulfur content lubricants (e.g., CJ-4 oil, the newest API class)

Total Carbon (TC) and EC:TC Ratio

- TC = EC + OC: sum of the Elemental C and Organic C fractions of DPM.
- EC:TC Ratio: fraction of EC in TC.
- Depends on engine operating conditions, engine type, fuel type, and a number of other parameters

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Gases: Nitrogen Oxides (NO and NO_2)

- $N_2 + O_2 + HC \rightarrow$ gaseous NO_x emissions, or oxides of nitrogen (NO and NO_2)
- Rate of formation exponentially related to the temperature of combustion $\rightarrow$ in-cylinder controls to lower the peak temperatures = exhaust gas recirculation (EGR) control
- Secondary control through aftertreatment:
  - such as lean NO_x catalysts (LNCs)
  - selective catalyst reduction (SCR)
- NO_x/DPM tradeoff: lowering NO_x emissions through in-cylinder techniques typically results in an increase in DPM, and conversely

Gases: Carbon Monoxide (CO)

- Results from a non-ideal combustion: incomplete oxidation of carbon in the fuel to carbon dioxide, most often from a lack of available oxygen or low gas temperatures.
- Typically minimal but extremely high toxicity motivated stringent regulation
- Reduced by improving the overall combustion efficiency by limiting any fuel-rich conditions within the cylinder and using diesel oxidation catalysts (DOCs) within the exhaust system ($CO \rightarrow CO_2$ in secondary reactions)

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Gases: Gas-Phase Hydrocarbons (HC)

- Typically referred to as volatile (VOC) and semivolatile organic compounds (SVOC): complex mixture of many chemical species, e.g. highly toxic polycyclic aromatic hydrocarbons (PAHs)
- Control of gas-phase OC emissions at the source is the same as nongaseous OC control
- DOCs within the exhaust system are often used as a secondary control

Gases: Sulfur Dioxide (SO_2)

- Forms when sulfur in the fuel and lubrication oil oxidizes
- Can damage or deactivate expensive exhaust catalysts in contemporary diesel engines
- Controlled by the transition toward ultralow sulfur diesel fuels (ULSDF) and low-sulfur content lubricants (CJ-4 oil)

Mining Ventilation Fundamentals
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Emission Sources [Avanti 2011]

Table 1.3-3: Emission Data for the Main Equipment Powered by Diesel Engines

Area	Equipment Name	Model	Location		Power	Emission Factor (g/HP-h)						Emission Rate (g/s)					
			UTM (mE)	UTM (mN)	(HP)	PM10	PM2.5	NOx	SO2	co	CO2	PM10	PM2.5	NOx	SO2	co	CO2
Pit	Haul truck	Cat 793D	473650	6142040	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Pit	Haul truck	Cat 793D	473000	6142090	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Pit	Haul truck	Cat 793D	473533	6141956	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Pit	Haul truck	Cat 793D	473110	6141622	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Pit	Haul truck	Cat 793D	473270	6141378	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Pit	Hammer drill	Sandvik QXR 920	473580	6141667	540	0.6345	0.6028	6.3053	0.0049	0.0024	0.1461	0.0952	0.0904	0.9458	0.0007	0.0004	0.0219
Pit	Hydraulic shovel	Komatsu PC5500	473530	6141620	2520	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1607	0.1527	3.6176	0.0034	0.0017	0.1023
Total in pit												1.0011	0.9510	21.3379	0.0201	0.0098	0.5984
Surface	Haul truck	Cat 793D	474395	6143100	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Surface	Haul truck	Cat 793D	475000	6143430	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Surface	Haul truck	Cat 793D	474222	6142222	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Surface	Haul truck	Cat 793D	474440	6142308	2337	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.1490	0.1416	3.3549	0.0032	0.0016	0.0948
Surface	Track dozer	Cat D10T	474000	6143575	433	0.2330	0.2214	4.1758	0.0049	0.0024	0.1461	0.0280	0.0266	0.5023	0.0006	0.0003	0.0176
Surface	Track dozer	Cat D10T	475533	6143626	433	0.2330	0.2214	4.1758	0.0049	0.0024	0.1461	0.0280	0.0266	0.5023	0.0006	0.0003	0.0176
Surface	Grader	Cat 16M	473578	6142578	297	0.2523	0.2397	3.8293	0.0049	0.0024	0.1461	0.0208	0.0198	0.3159	0.0004	0.0002	0.0121
Surface	Grader	Cat 16M	473489	6143466	297	0.2523	0.2397	3.8293	0.0049	0.0024	0.1461	0.0208	0.0198	0.3159	0.0004	0.0002	0.0121
Surface	Wheel dozer	Cat RTD 834G	474923	6142484	525	0.2330	0.2214	4.1758	0.0049	0.0024	0.1461	0.0340	0.0323	0.6090	0.0007	0.0004	0.0213
Surface	Front-end loader	Komatsu WA1200	474000	6143555	1565	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.0998	0.0948	2.2466	0.0021	0.0010	0.0635
Surface	Hydraulic excavator	Cat 345CL	474747	6142396	345	0.2330	0.2214	4.1758	0.0049	0.0024	0.1461	0.0223	0.0212	0.4002	0.0005	0.0002	0.0140
Surface	Water truck	Cat 777	476000	6144000	950	0.2296	0.2181	5.168	0.0049	0.0024	0.1461	0.0606	0.0576	1.3638	0.0013	0.0006	0.0386
Grand total pit and surface												1.9117	1.8160	41.0134	0.0394	0.0193	1.1744

Note: CO - carbon monoxide; CO_2 - carbon dioxide; g/s - grams per second; HP - horsepower; mE - minutes east; mN - minutes north; NO_x - nitrogen oxide; $PM_{2.5}$ - particulate matter with an aerodynamic diameter no greater than 2.5 μm; PM_{10} - particulate matter with an aerodynamic diameter no greater than 10 μm; SO_2 - sulphur dioxide; UTM – Universal Transverse Mercator

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Design and sizing of the ventilation process [Hartman et al. 1997]

Airflow through mine openings and ducts

- Quantity control for air movement, direction and magnitude
- Ventilation:
  - prime control of mine air conditioning
  - has to supply enough air for human and products needs
  - modest need for human life ($\approx 0.01\ m^3/s$/person) but need to remove contaminents (gas/heat/moisture): 0.1 to 1 m^3/s/person $\Rightarrow$ 10-20 tons of air per ton of mined mineral
- Need to understand airflow to design long and tourtuous paths for mine ventilation
- While a crude approximation, air is typically considered as incompressible for mine ventilation design

Gas laws: behavior of air

Defining p = pressure, v = specific volume, w = specific weight, T = absolute temperature, H = head:

- Boyle's law: $p_1/v_1 = p_2/v_2$ at T constant
- Charle's law: $v_1/v_2 = T_1/T_2$ at p constant and $p_1/p_2 = T_1/T_2$ at v constant
- General gas law: $\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$
- Dalton's law: in a gas mixture, total $p = \sum$ partial p of individual gases, barometric p = dry air p + water vapor p
- Graham's law: Diffusion rate $\propto \sqrt{\frac{w}{w_g}} \propto \sqrt{\frac{1}{s_g}}$, where s_g is the specific gravity of the gas
- Effect of altitude: $w_2/w_1 = e^{-Z/RT}$, Z = elevation above sea level
- Pressure/head relationship: $p = w_1 H_1 = w_2 H_2$

Energy changes in fluid flow

General energy equation (steady-state):

- Total energy = $\sum$ internal + static + kinetic + potential + heat
- Total energy$_1$ = (total energy)$_2$ + (flow energy losses)$_{1\rightarrow 2}$

$$\frac{p_1}{w} + \frac{V_1^2}{2g} + Z_1 = \frac{p_2}{w} + \frac{V_2^2}{2g} + Z_2 + H_l$$

where V = velocity, and the energies: p/w static, $V^2/2g$ kinetic (velocity), Z potential, H_l flow losses (Bernoulli, for all fluid flow process and reduced here to the incompressible case)

- Each term is a specific energy (Pa) = measure of fluid head, termed "head":

$$H_{t_1} = H_{s_1} + H_{v_1} + H_{z_1} = H_{s_2} + H_{v_2} + H_{z_2} + H_l = H_{t_2} + H_l$$

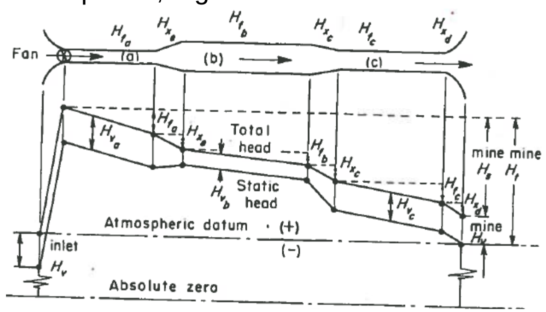
- Provide an expression encompassing all flow variables between any two points in the ventilation system.
- Simplified (no Z) if all static-head measurements/calculations are made on a gage-pressure basis in ref. to atmospheric p

Head losses and mine heads

- Head losses in fluid flow:
  - flow occurs from pressure difference and part of the provided energy is dissipated through losses
  - $H_l = H_f + H_x$: friction (ducts of constant area) and shock (in turns and restrictions + inlet/discharge, splits/junctions, obstructions)
  - compensating energy losses from the static head,
  - conversion static ↔ velocity heads (e.g. at area changes) accompanied by shock losses
- Overall or Mine heads
  - Def.: cumulative energy consumption of fans and other pressure systems
  - = difference in head (from Bernoulli) necessary to move the desired air quantity
  - Mine static head: mine $H_s = \sum H_l = \sum(H_f + H_x)$
  - Mine velocity head: at each change of duct area or number, mine $H_v = V^2/2g$, not cumulative but appears as a loss of kinetic energy into atmosphere
  - Mine total head: mine H_t = mine H_s + mine H_v

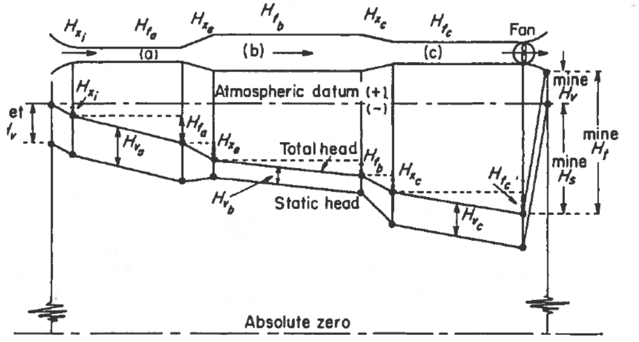
Head gradients

- 3 distinct gradients: elevation, static + elevation, total
- General rules:
  1. Total head = 0 at inlet, but = H_v (> 0) at discharge
  2. Static head always < 0, = H_v at inlet but 0 at discharge
  3. Total head at any point plotted first, then $H_s = H_t - H_v$
- Blower system:
  - located at the inlet and raises the head above atmospheric, e.g.



  - plot by starting from discharge ($H_s = 0$) toward inlet
  - $H_t = H_s + H_v$ at any point

Head gradients: Exhaust systems



- Result when the energy source is located at the exhaust
- Similar to blowers, except that the starting point = intake
- Below atmos. datum line since losses are negative and determined on a gage basis (succion), but same start/end of H_s and H_t
- $H_t = H_s + H_v$ at any point still holds, and mine heads are always positive (not exactly the same as a blower due to the shock at the discharge)

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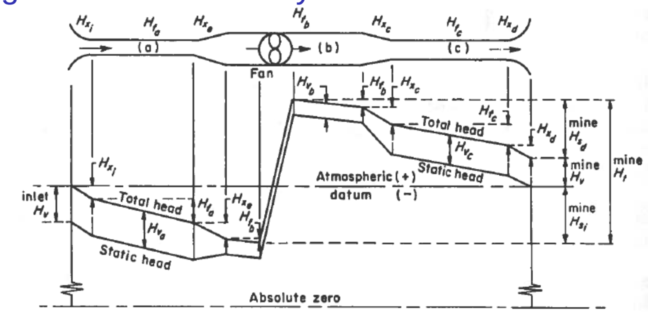
Head gradients: Booster systems



- Energy source at some point between inlet and discharge
- $H_s = H_{s_i} + H_{s_d}$, ≈ same as blowers and exhausts
- Plot from both ends and move toward the fan
- Hybrid system between blowers and exhausts, with shocks at both ends

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State of airflow in mine openings

- Distinct states of fluid flow: laminar, intermediate and turbulent
- Boundaries established from the Reynolds number R_e (laminar up to 2000 and turbulent above 4000):

$$R_e = \frac{\rho DV}{\mu} = \frac{DV}{\nu} = 67280\, DV \text{ for air at normal T (SI units)}$$

where ρ = fluid mass density, ν = kinematic viscosity, μ = absolute viscosity, D = conduit diameter, V = velocity

- Critical velocity for $R_e = 4000$: $V_c \approx 0.06/D$
- Need turbulent flow at openings for the dispersion and removal of contaminents, which typically occurs due to large exhausts (e.g. for $D = 0.9$ m, $V_c = 0.07$ m/s)
- Laminar flow in leakage through doors and stoppings in airways / exhaust through caves or filled areas

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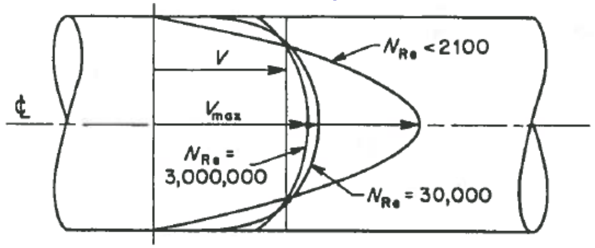
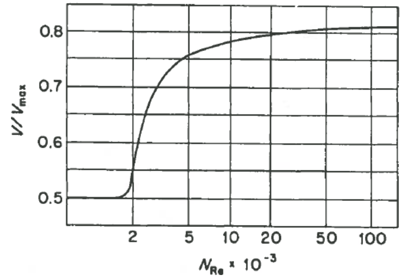
Effect of state of flow on velocity distribution



- V_{max} at the conduit center, determinable as a function of R_e (supposing circular cross section)



- Average value $V \approx 0.8 V_{max}$ for $Re > 10000$ (typical in mines)

Calculation of head losses

- Velocity head = kinetic energy to be supplied to maintain the flow; lost at discharge:

$$H_v = \frac{V^2}{2g} \text{ m of fluid} = \frac{\rho V^2}{2} = \frac{wV^2}{2g} \text{ Pa}$$

- Friction loss: $\approx 70 - 90\%$ of $\sum$ head loss, >> shock losses
  - loss in static pressure from drag, resistance of the walls and internal friction
  - Darcy-Weisbach: $H_l = f\frac{L}{D}\frac{V^2}{2g}$ where f is the friction coefficient (depends on Re but often considered constant in mines) and L the length.
  - Atkinson: defining the hydraulic radius $R_h \doteq A/O = D/4$ for circular conduit, $H_f = \frac{KOLV^2}{A}$ where O is the perimeter and K an empirical friction factor
  - Determination of airways friction factor: from pressure gradient difference at a given flow velocity, first approximation from tables or graphs

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Calculation of head losses (2)

- Shock loss: $\approx 10 - 30\%$ of $\sum$ head loss, important in major airways or in short length with many bends or area changes, $\propto V^2$ or H_v, computed:
  - directly as $H_x = XH_v$, where X = friction loss factor
  - from equivalent length $L_e = \frac{wR_hX}{2gK}$ m
- Combined head losses and mine heads:

$$H_l = H_f + H_x = \frac{KO(L + L_e)Q^2}{A^3}$$

where $Q = AV$ the air quantity

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Air power

- Required to overcome energy losses in an airstream, $P_a = pQ = \frac{HQ}{1000}$ kW
- Note: $P_a \propto Q^3$

Compressibility effects

- Start at relatively low pressure and induce, e.g. a 5 % difference for $\Delta p = 38$ mm Hg, $H = 5$ kPa, $\Delta Z = 430$ m
- At high pressure (> 5.0 kPa), use instead of Atkinson:

$$p_1^2 - p_2^2 = \frac{K_c Q^2 L}{D^5}$$

- Use for long ventilation-pipe and deep shafts

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Mathematical modeling for control from the 60s to the 90s

- Decentralized control (high/low) actions: control and optimization refer to preliminary design of the global system and automation devices.
- Mathematical modeling:
  - 1968 steady-state compartmental model for flow networks with complex topology [S. Tolmachev & E. Fainshtein];
  - 1973 experimental determination of turbulent diffusion coefficients [F. Klebanov & G. Martynyuk];
  - 90's first use of Navier-Stokes equations, with simplified chamber-like [G. Kalabin et al.] and general mine aerology models [N. Petrov et al.];
  - 1994 problems of nonlinearity and nonstationary behavior, high dimensionality and numerical issues [N. Petrov];
  - 2001 short and long term planning of ventilation requirements [E. Widzyk-Capehart & B. Watson].
- Today's energy constraints motivate optimized real-time control and new dynamical models.

Conclusions

- Ventilation control is of prime interest for regulating the mine environment
- Diesel engines are a main source of pollutants, need for combined emissions control in engines and removal of confined mine atmosphere
- Simple calculations are available for air conducts sizing and steady-state operation
- First steps on mathematical modeling of the dynamics for control
- Large potential for improvement using Information Technologies and Automatic Control methods!

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Mining Ventilation Control

Lesson 2: Some feedback control principles

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Sogamoso, April 2, 2013

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Outline

1. The process of control system design
2. Modeling dynamics in the time and frequency domains
3. The feedback principle
4. Stability and controllability
5. The robustness versus performance dilemna

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The process of control system design

An integrated approach:

1. Study the system: control objectives, physical model, scaled simplified model, main properties
2. Automation design: measurements & controlled outputs, sensors/actuators choice and location, controller architecture
3. Control: performance specifications & actuators constraints → controller design
4. Simulation: on computer or pilot plant, model-automation-control validation
5. Implementation: choose hardware and software for controller, tests & validation, final tuning

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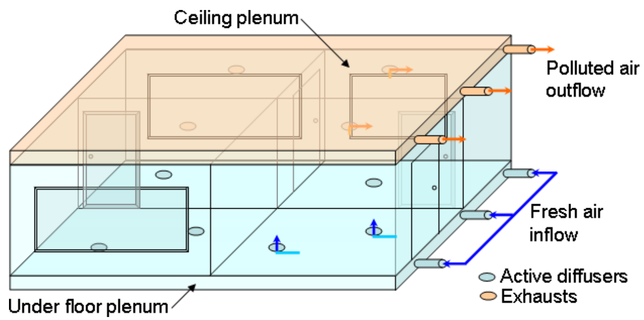
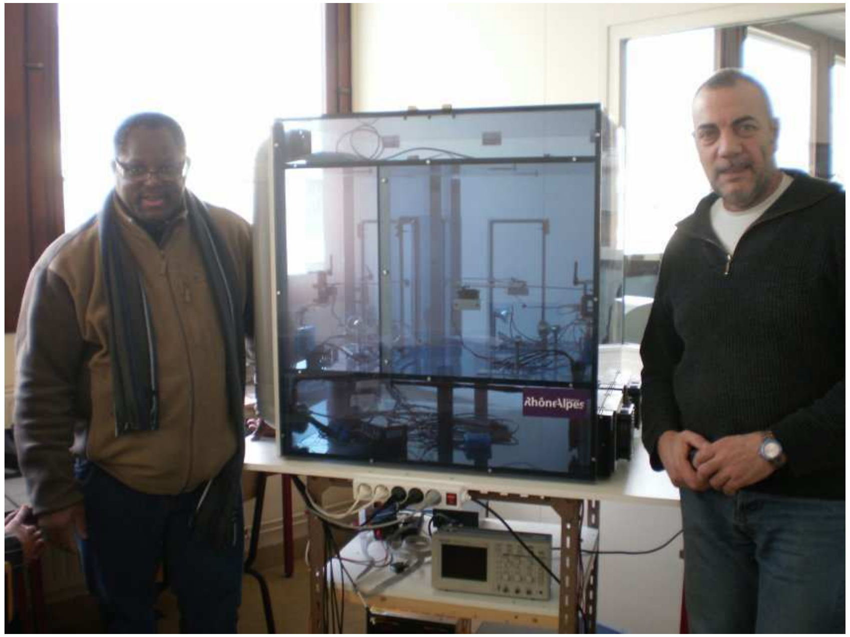
Example: Under Floor Air Distribution control



UJF experiment



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1. Study the system

- control objectives: regulate rooms temperatures independently, compensate doors perturbation, minimize global energy consumption
- physical model: from thermodynamics
- scaled simplified model: incompressible flow etc., normalized temperature, 0-D approximation
- main properties: interconnected system, discrete events, some nonlinear dynamics

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2. Automation design

- sensors: distributed temperature measurements in each room, wireless
- actuators: diffusers for UF airflow regulation
- controller architecture: local feedback loops embedded on diffusers with wireless data acquisition, global supervision

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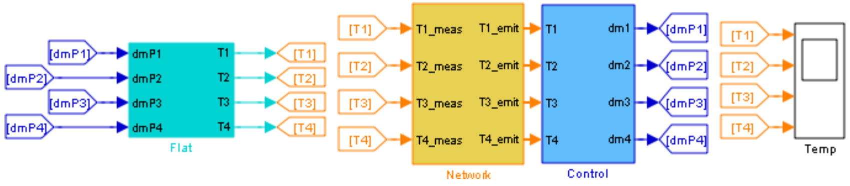
3. Control

- performance specifications: desired temperature setpoint, compensate external perturbations “sufficiently quickly”
- constraints: diffusers mass flow rate, communication capabilities
- controller design: robust design with limited inputs and bandwidth limitations, using linear model

4. Simulation



- on computer with rooms, WSN (wireless sensor network) and control blocks
- model-automation-control validation: check performance and contraints on nonlinear physical model

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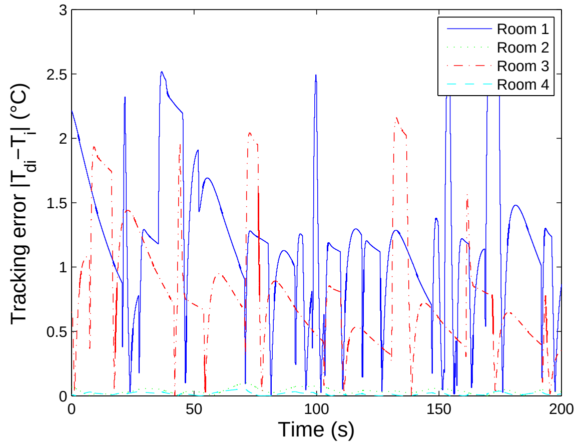

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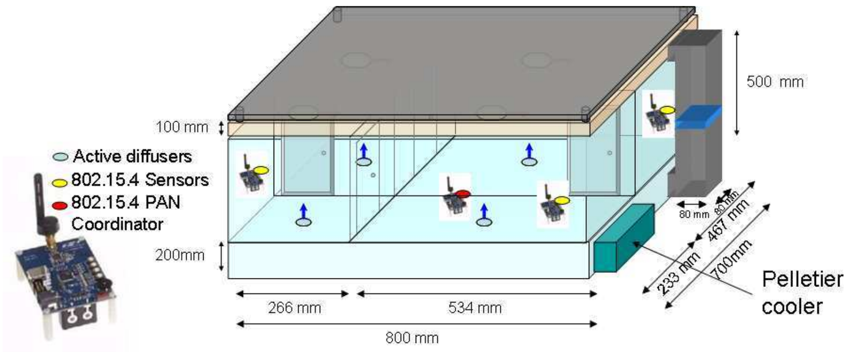
5. Implementation



- hardware: temperature sensors, 2.4 GHz *ZigBee* motes and embedded controller, active diffusers
- software: IEEE 802.15.4 protocols, embedded *C* algo.
- tests & validation: small scale experiment
- final tuning: performance/input/perturbation weights

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The control problem

Make output y behave in the desired way by manipulating input u according to a linear time invariant - LTI - model (disturbance d, models G G_d)

$$y = Gu + G_d d$$

- Regulator problem: counteract d
- Servo problem: track reference r

$\Rightarrow$ design controller K to minimize control error $e = y - r$

- Uncertain G, G_d: need for robustness

Definitions

- **NS** Nominal Stability: stable w/o model uncertainty
- **NP** Nominal Performance: perf. specs matched w/o model uncertainty
- **RS** Robust Stability: stable ∀ perturbed plants about the nominal model up to the worst case model uncertainty
- **RP** Robust Performance: perf. specs matched ∀ perturbed plants

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Modeling dynamics in the time and frequency domains

Transfer functions (TF)

- Insights from frequency-dependent plot
- Feedback specifications (bandwidth, CL peaks ...)
- Poles and zeros explicit in factorized TF
- Particularly suitable to model uncertainties (close models in freq. resp.)

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Example

$$\begin{aligned}\dot{x}_1(t) &= -a_1 x_1(t) + x_2(t) + \beta_1 u(t)\\ \dot{x}_2(t) &= -a_0 x_1(t) + \beta_0 u(t)\\ y(t) &= x_1(t)\end{aligned}$$

gives ($\dot{x}(t) \rightarrow sx(s) - x(t=0)$ and deviation variables)

$$\frac{y(s)}{u(s)} = G(s) = \frac{\beta_1 s + \beta_0}{s^2 + a_1 s + a_0}$$

$\Rightarrow$ Independent of the input!

General form

$$G(s) = \frac{\beta_{n_z} s^{n_z} + \ldots + \beta_1 s + \beta_0}{s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0}$$

n: order of the system (pole polynomial), $n - n_z$: pole excess or relative order.

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A system $G(s = j\omega)$ is

- strictly proper if $G(j\omega) \rightarrow 0$ as $\omega \rightarrow \infty$
- semi-proper or bi-proper if $G(j\omega) \rightarrow D \neq 0$ as $\omega \rightarrow \infty$
- improper if $G(j\omega) \rightarrow \infty$ as $\omega \rightarrow \infty$

For a proper system with $n \geq n_z$ we can use the state-space

$$\left.\begin{aligned}\dot{x} &= Ax + Bu\\ y &= Cx + Du\end{aligned}\right\} \Leftrightarrow G(s) = C(sI - A)^{-1}B + D$$

Remarks:

- D used to model HF effects (zero gain at HF for strictly proper systems)
- use of deviation variables in Laplace domain (remove y_0)
- superposition principle for linear systems: additive effect of the inputs

Scaling

Prime importance in applications to simplify model analysis and controller design (weight selection).
Original unscaled system:

$$\hat{y} = \hat{G}\hat{u} + \hat{G}_d\hat{d}; \quad \hat{e} = \hat{y} - \hat{r}$$

Make variables < 1: with respect to the max expected or allowed change:

$$d = \hat{d}/\hat{d}_{max} \text{ and } u = \hat{u}/\hat{u}_{max} \Rightarrow \hat{y} = \hat{G}\hat{u}_{max}u + \hat{G}_d\hat{d}_{max}d$$

same units of $\hat{y}$, $\hat{r}$, $\hat{e}$: norm. with respect to largest allowed e or largest expected change in r:

$$\begin{aligned} y &= \hat{y}/\hat{e}_{max}, \quad r = \hat{r}/\hat{e}_{max}, \quad e = \hat{e}/\hat{e}_{max} \\ \text{or } y &= \hat{y}/\hat{r}_{max}, \quad r = \hat{r}/\hat{r}_{max}, \quad e = \hat{e}/\hat{r}_{max} \end{aligned}$$

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- Defining the scaling factors

$$D_e \doteq \hat{e}_{max}, \; D_u \doteq \hat{u}_{max}, \; D_d \doteq \hat{d}_{max}, \; D_r \doteq \hat{r}_{max}$$

  we obtain the scaled variables

$$y = Gu + G_d d, \quad e = y - r$$

  with $G = D_e^{-1}\hat{G}D_u$ and $G_d = D_e^{-1}\hat{G}_d D_d$.
- Can also use the scaled reference

$$\tilde{r} = \hat{r}/\hat{r}_{max} = D_r^{-1}\hat{r} \Rightarrow r = R\tilde{r}, \; R \doteq D_e^{-1}D_r = \hat{r}_{max}/\hat{e}_{max}$$

- For the worst case with non-symmetric bounds around the nominal value, take the "max" distance from nominal value to bounds for disturbance and "min" for u and e.

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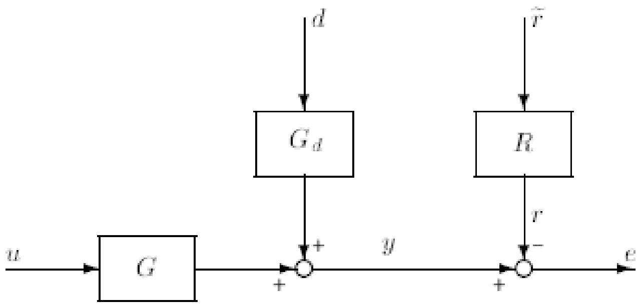
Input/output graphical representation with scaled reference



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Deriving linear models

1. Formulate nonlinear state space model from physics, i.e.

$$\dot{x} = f(x, u), \quad x(0) = x_0$$

2. Determine steady state operating point (or trajectory) x^* about which to linearize $\rightarrow u^*$ s.t. $\dot{x}^* = f(x^*, u^*) = 0$
3. Introduce deviation variables $(\delta x(t), \delta u(t))$ and linearize:
   a. subtract (x^*, u^*) to eliminate the terms involving only s.s. quantities $\tilde{x} = x - x^*$, $\tilde{u} = u - u^*$
   b. linearize using first order Taylor expansion ($\mathcal{O}(2) \approx 0$) for a small variation δ

$$f(x, u) \approx f(x^*, u^*) + (x^* + \delta x)\underbrace{\left.\frac{\partial f}{\partial x}\right|_{(x^*, u^*)}}_{A} + (u^* + \delta u)\underbrace{\left.\frac{\partial f}{\partial u}\right|_{(x^*, u^*)}}_{B}$$

   c. get the deviation dynamics with $\delta x \approx \tilde{x}$, $\delta u \approx \tilde{u}$

$$\dot{\delta x} = A\delta x + B\delta u, \quad \delta x(0) = x(0) - x^*$$

From Continuous Dynamics to Sampled Signals

Continuous-time signals and systems

Continuous-time signal	$y(t)$
Fourier transform	$Y(\omega) = \int_{-\infty}^{\infty} y(t)e^{-i\omega t}dt$
Laplace transform	$Y(s) = \int_{-\infty}^{\infty} y(t)e^{-st}dt$
Linear system	$y(t) = g * u(t)$
	$Y(\omega) = G(\omega)U(\omega)$
	$Y(s) = G(s)U(s)$

Derivation operator $p \times u(t) = \dot{u}(t)$ works as s-variable, but in time domain.

Example (0 IC)

$$\begin{aligned} y(t) &= 0.5\dot{u}(t) + u(t) \\ y(t) &= (0.5p + 1)u(t) \\ Y(s) &= (0.5s + 1)U(s) \end{aligned}$$

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Discrete-time signals and systems

Discrete-time signal	$y(kh)$
Fourier transform	$Y^{(h)}(\omega) = h\sum_{k=-\infty}^{\infty} y(kh)e^{-i\omega kh}$
z-transform	$Y(z) = \sum_{k=-\infty}^{\infty} y(kh)z^{-k}$
Linear system	$y(kh) = g * u(kh)$
	$Y^{(h)}(\omega) = G_d(e^{i\omega h})U^{(h)}(\omega)$
	$Y(z) = G_d(z)U(z)$

Shift operator $q \times u(kh) = u(kh + h)$ works as z-variable, but in time-domain.

Example (0 IC)

$$\begin{aligned} y(kh) &= 0.5u(kh) + u(kh - h) \\ y(kh) &= (0.5 + q^{-1})u(kh) \\ Y(z) &= (0.5 + z^{-1})U(z) \end{aligned}$$

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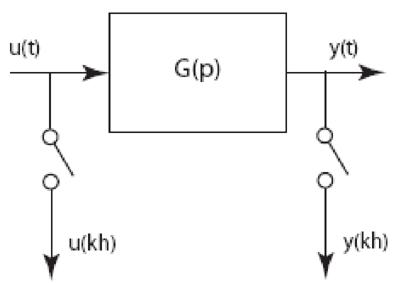
Sampled systems

Continuous-time linear system

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned}$$

$\Rightarrow G(s) = C(sI - A)^{-1}B + D$.
Assume that we sample the inputs and outputs of the system



Relation between sampled inputs $u[k]$ and outputs $y[k]$?

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Sampled systems (2)

Systems with piecewise constant input:

- Exact relation possible if $u(t)$ is constant over each sampling interval.
- Solving for $\dot{x}$ (i.e. use $x(t) = e^{At}k(t)$ and dummy $\mu = t - \mu'$) over one sampling interval gives

$$\begin{aligned} x[k+1] &= A_d x[k] + B_d u[k] \\ y[k] &= Cx[k] + Du[k] \\ G_d(z) &= C(zI - A_d)^{-1}B_d + D \end{aligned}$$

where $A_d = e^{Ah}$ and $B_d = \int_0^h e^{A\mu}Bd\mu$.

Sampled systems (3)

Example: sampling of scalar system

- Continuous-time dynamics

$$\dot{x}(t) = ax(t) + bu(t)$$

- Assuming that the input $u(t)$ is constant over a sampling interval

$$x[k+1] = a_d x[k] + b_d u[k]$$

where $a_d = e^{ah}$ and $b_d = \int_0^h e^{a\mu} b \, d\mu = \frac{b}{a}(e^{ah} - 1)$.

- Note: continuous-time poles in $s = a$, discrete-time poles in $z = e^{ah}$.

Sampled systems (4)

Frequency-domain analysis of sampling

- Transfer function of sampled system

$$G_d(z) = C(zI - A_d)^{-1} B_d + D$$

produces same output as $G(s)$ at sampling intervals.

- However, frequency responses are not the same! One has

$$|G(i\omega) - G_d(e^{i\omega h})| \le \omega h \int_0^\infty |g(\tau)| d\tau$$

where $g(\tau)$ is the impulse response for $G(s)$.

- Good match at low frequencies ($\omega < 0.1\omega_s$) $\Rightarrow$ choose sampling frequency $\omega_s > 10\times$ system bandwidth.

Sampling of general systems

- For more general systems,
  - nonlinear dynamics, or
  - linear systems where input is not piecewise constant

  conversion from continuous-time to discrete-time is not trivial.

- Simple approach: approximate time-derivative with finite difference:

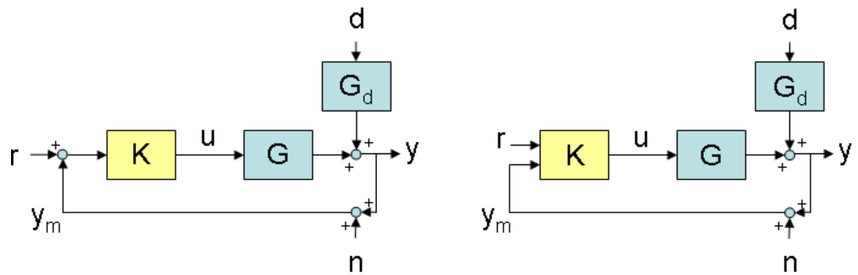
p	$\approx$	$\frac{q-1}{qh}$	Euler backward (stable)
p	$\approx$	$\frac{q-1}{h}$	Euler forward
p	$\approx$	$\frac{2}{h} \times \frac{q-1}{q+1}$	Tustins (trapezoidal) approximation[1] (typical for digital control)

$\ldots$

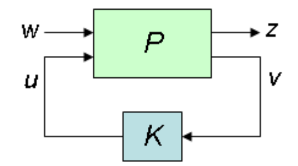
[1] e.g. using $q = e^{ph}$ and log approx. or trapezoidal rule

The feedback principle

Control configurations



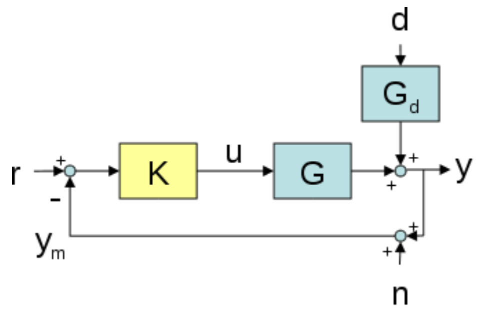
One degree of freedom *Two degrees of freedom*



General control configuration

Feedback control

One degree-of-freedom controller



Plant input

$$u = K(s)(r - y - n)$$

find $K(s)$ to minimize the control error $e = y - r$

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Closed-loop transfer functions

With a 1 dof controller the CL response is

$$\begin{aligned} y &= G(s)u + G_d(s)d \\ &= GK(r - y - n) + G_d d \\ &= \underbrace{(I + GK)^{-1}GK}_{T:\ \text{ref}\to y}\, r + \underbrace{(I + GK)^{-1}}_{S:\ \text{out dist}\to y}\, G_d d - \underbrace{(I + GK)^{-1}GK}_{T}\, n \end{aligned}$$

The control error ($S + T = I$) and plant input are

$$\begin{aligned} e &= y - r = -Sr + SG_d d - Tn \\ u &= KSr - KSG_d d - KSn \end{aligned}$$

Terminology:

$L = GK$ loop transfer function

$S = (I + GK)^{-1} = (I + L)^{-1}$ sensitivity function

$T = (I + GK)^{-1}GK = (I + L)^{-1}L$ complementary sens. fun.

S gives sensitivity reduction afforded by CL (w/o: board)

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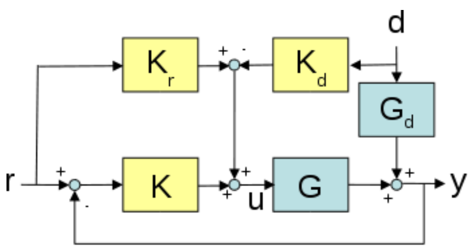
2 Degrees of freedom and feedforward dontrol



r and y_m independent, known d:

$$u = \underbrace{K(r - y_m)}_{\text{feedback}} + \underbrace{K_r r - K_d d}_{\text{feedforward}}$$

Suppose perfect measurement ($n = 0$, $y_m = y$):

$$\begin{aligned} y &= (I + GK)^{-1}[G(K + K_r)r + (G_d - GK_d)d] \\ e &= S(-S_r r + S_d G_d d) \end{aligned}$$

with $S = (I + GK)^{-1}$, $S_r = 1 - GK_r$, $S_d = GK_d G_d^{-1}$ (feedforward sensitivity functions).

If K, K_r and K_d = 0, then S, S_r and S_d = 1, else:

- SS_r small for reference tracking
- SS_d small for disturbance rejection

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Why feedback?

If invertible plant, feedforward (open-loop, known disturbances):

$$K = 0, \quad K_r(s) = G^{-1}(s), \quad K_d(s) = G^{-1}(s)G_d(s)$$

gives perfect tracking:

$$y = G(G^{-1}r - G^{-1}G_d d) + G_d d = r$$

but feedback is necessary to deal with

- signal uncertainty - unknown disturbance
- model uncertainty
- an unstable plant (only stabilized by FB)

Stability and controllability

Two methods are commonly used for evaluating the stability of linear systems

- Evaluate CL poles
  - zeros of $1 + L(s) = 0$ or eigenvalues of A in LHP
  - best suited for numerical calculations
  - need to approximate time delays as rational transfer functions (e.g. Padé approximations)
- Frequency response of $L(j\omega)$
  - *Nyquist* (encirclements of -1 = nb RHP poles) and *Bode* ($|L(j\omega_{180})| < 1$) stability criteria
  - nice graphical interpretation & can be used for time delays
  - measure of relative stability and basis for several robustness tests

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Input-Output Controllability

I. How well can the plant be controlled?
- Achievable specifications?

II. Which control structure should be used?
- Measurements, manipulated variables, combinations?

1. Control the outputs that are not self-regulating
2. Control the outputs that have favorable dynamic and static characteristics
3. Select inputs that have large effects on the outputs
4. Select inputs that rapidly affect the controlled variables

III. How might the process be changed to improve control?

Def. Ability to achieve acceptable control performance:
- to keep y within specified bounds or displacements from r
- in spite of unknown but bounded variations, such as d and plant changes
- using available inputs u and available measurements y_m or d_m

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Input-output controllability analysis

- Performance targeting
- Mostly qualitative - simulation - Fundamental properties?
- Rigorous approaches: need mathematical formulation, i.e. based on G and G_d
- Linear approach: most important nonlinearity (constrained input) can be handled linearly

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Scaling and performance

- Scaling such that performances expressed as:
  - bounds: keep y at $r \pm 1$ $\forall d \in [-1\ 1]$ or $\forall r \in [-R\ R]$ using $u \in [-1\ 1]$
  - frequency-by-frequency (i.e. $d(t) = \sin \omega t$): keep $|e(\omega)| \leq 1$ $\forall |d(\omega)| \leq 1$ or $\forall |r(\omega)| \leq R(\omega)$ using $|u(\omega)| \leq 1$]
- Only for frequencies within the system bandwidth
- Recall $r = R\tilde{r}$ and

$$e = y - r = Gu + G_d d - R\tilde{r}$$

$\rightarrow$ results for d applicable to r with $G_d \rightarrow -R$

Remarks on the term controllability

- *Ability of the process to achieve and maintain the desired equilibrium value* [Ziegler and Nichols'43]
- Differs from state controllability: *ability to bring a system from a given initial state to any final state within a finite time* [Kalman, 60's]
  - little practical interest if unstable modes are both controllable and observable
  - *most industrial plants are controlled quite satisfactorily though they are not state controllable* [Rosenbrock'70]

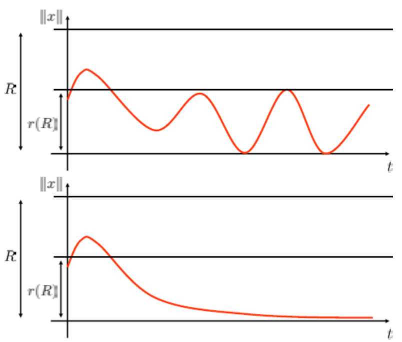
Stability for nonlinear systems [Marchand, 2009]

Consider the autonomous nonlinear system:

$$\dot{x} = f(x, u(x)) = g(x)$$

- Stability: the system is said to be stable at the origin if and only if (iff): $\forall R > 0, \exists\, r(R) > 0$ such that $\forall x_0 \in \mathcal{B}(r(R))$, $x(t; x0)$ solution with x_0 as initial condition, remains in $\mathcal{B}(R)$ for all $t > 0$.
- Attractivity: the origin is said to be attractive iff: $\lim_{t\to\infty} x(t; x_0) = 0$.
- Asymptotic stability: the system is said to be asymptotically stable at the origin iff it is stable and attractive.

Graphical interpretation



- For linear systems: Attractivity → Stability
- For nonlinear systems: Attractivity does not imply Stability!
- Stability and attractivity : properties hard to check?

Asymptotic stability and local linearizaton

Consider $\dot{x} = g(x)$ and its linearization at the origin $\dot{x} = \left.\frac{\partial g}{\partial x}\right|_{x=0} x$, then:

- Linearization with $eig < 0 \Leftrightarrow$ Nonlinear system is locally asymptotically stable
- Linearization with $eig > 0 \Leftrightarrow$ Nonlinear system is locally unstable
- Linearization with $eig = 0$: nothing can be concluded on the nonlinear system (may be stable or unstable)

$\Rightarrow$ Only local conclusions!

Lyapunov theory: Lyapunov functions

Definition: $V : \mathbb{R}^n \rightarrow \mathbb{R}$ is a Lyapunov function if continuous and such that:

1. (definite) $V(x) = 0 \Leftrightarrow x = 0$
2. (positive) $\forall x, V(x) \geq 0$
3. (radially unbounded) $lim_{||x|| \rightarrow \infty} V(x) = +\infty$

- Lyapunov functions are often related to energies

(First) Lyapunov theorem:

- (strictly decreasing) If $\exists$ a Lyapunov function $V : \mathbb{R}^n \rightarrow \mathbb{R}^+$ s.t. $V(x(t))$ is strictly decreasing for all $x(0) \neq 0$ then the origin is asymptotically stable.
- (decreasing) If $\exists$ a Lyapunov function $V : \mathbb{R}^n \rightarrow \mathbb{R}^+$ s.t. $V(x(t))$ is decreasing then the origin is stable.

Example: Pendulum equation with friction [Khalil 2002]

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -a \sin x_1 - b x_2 \end{aligned}$$

with the Lyapunov function

$$\begin{aligned} V(x) &= a(1 - \cos x_1) + \frac{1}{2} x_2^2 \\ \Rightarrow \dot{V}(x) &= a \dot{x}_1 \sin x_1 + x_2 \dot{x}_2 = -b x_2^2 \end{aligned}$$

- The origin is stable BUT $\dot{V}(x)$ is not negative definite because $\dot{V}(x) = 0$ for $x_2 = 0$ irrespective of x_1!
- The conditions of Lyapunov's theorem are only sufficient. Failure of a Lyapunov function candidate to satisfy the conditions for stability or asymptotic stability does not mean that the equilibrium point is not stable or asymptotically stable. It only means that such stability property cannot be established by using this Lyapunov function candidate

Example: Pendulum equation with friction (2)

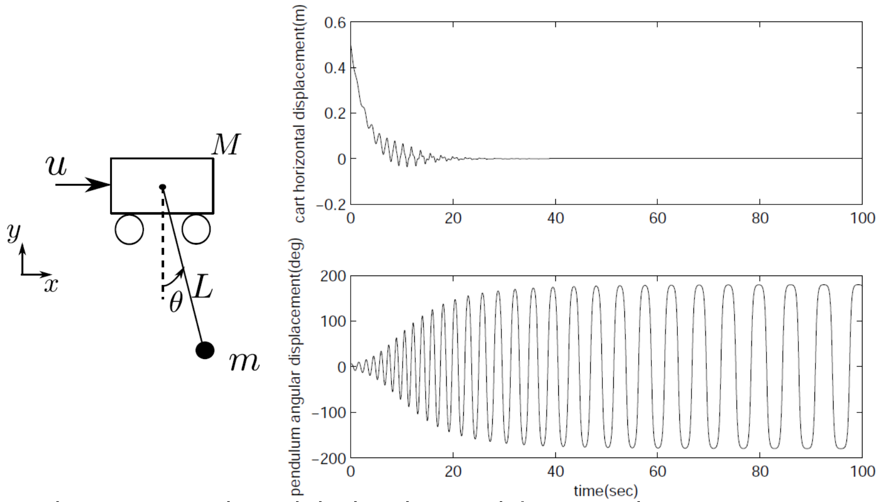
Try another Lyapunov function:

$$\begin{aligned} V(x) &= \frac{1}{2} x^T P x + a(1 - \cos x_1) \\ & p_{11} > 0, p_{11} p_{22} - p_{12}^2 > 0 \\ \Rightarrow \dot{V}(x) &= -\frac{1}{2} a b x_1 \sin x_1 - \frac{1}{2} b x_2^2 \end{aligned}$$

$V(x)$ is positive definite and $\dot{V}(x)$ is negative definite over $D = \{x \in R^2 | |x_1| < \pi\}$

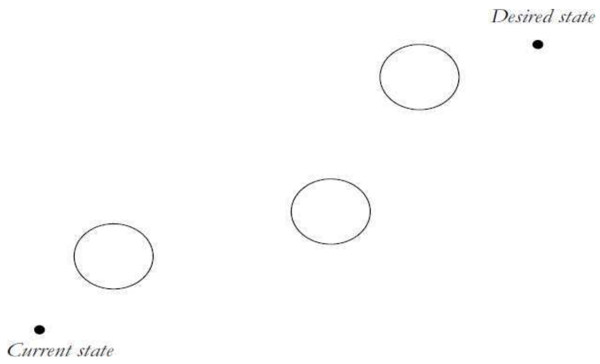
The origin is asymptotically stable

Example 2: Pendulum cart [Wang 2011]



Using Lyapunov-based design the pendulum's motion converges to the homoclinic orbit (zero energy motion), and the cart displacement converges to zero.

Nonlinear MPC: an intuitive strategy [Alamir, 2012]



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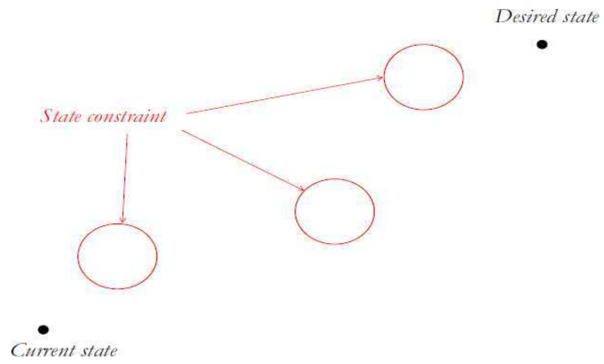

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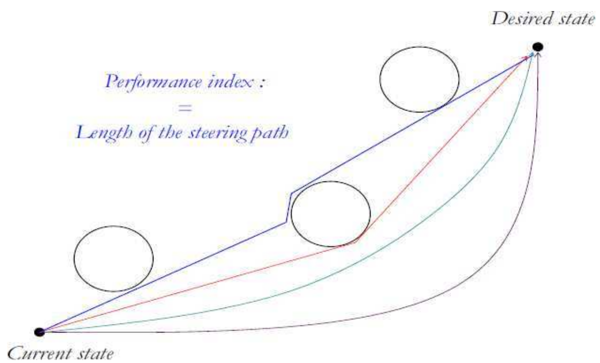

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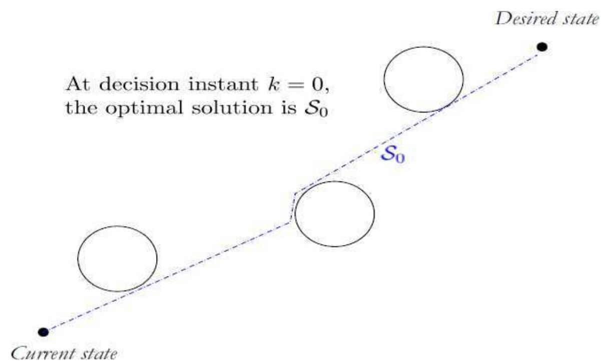

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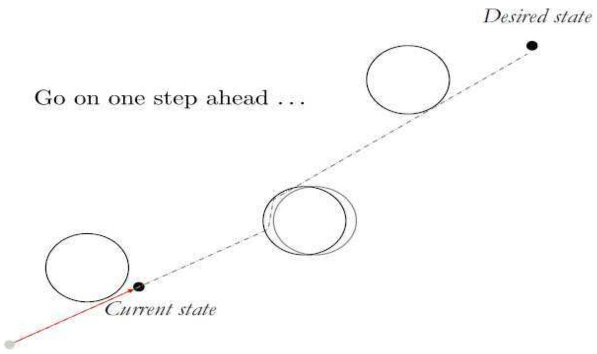

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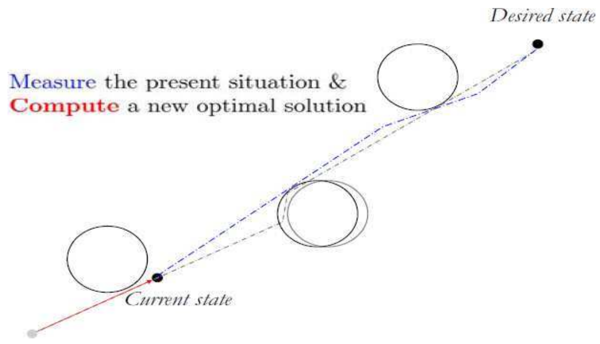

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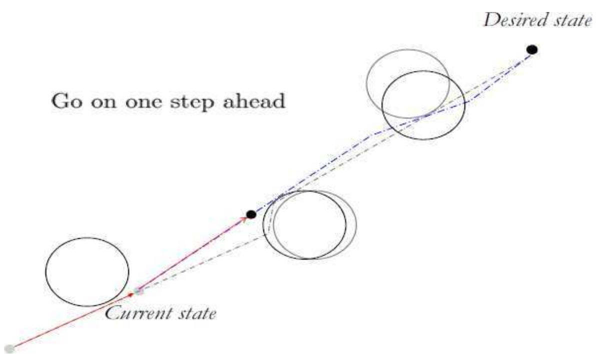

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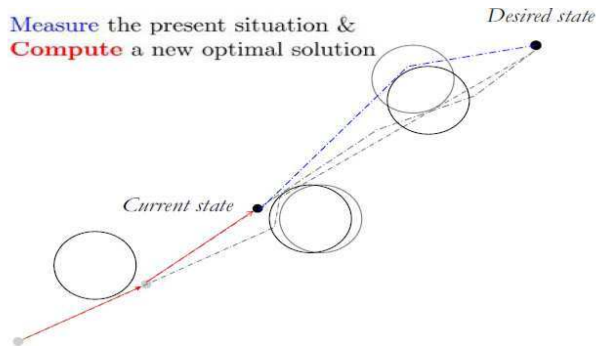

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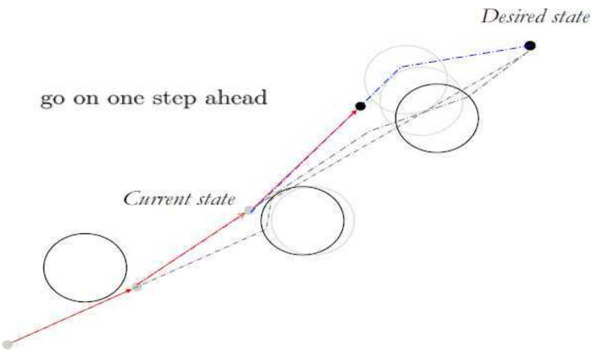

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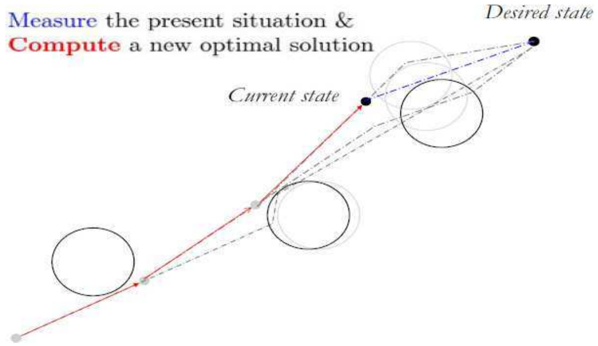

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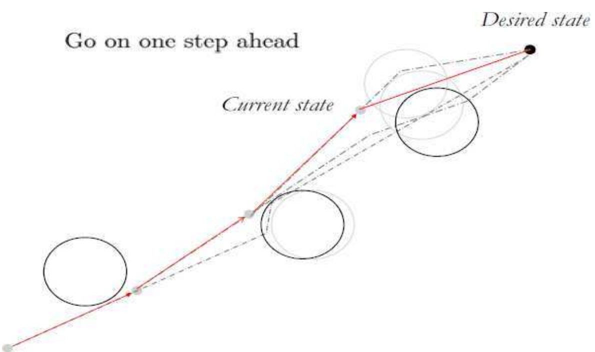

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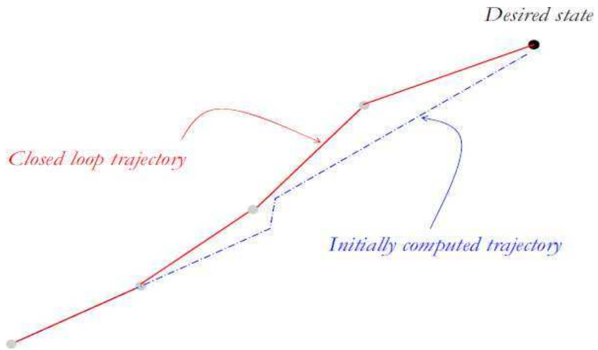
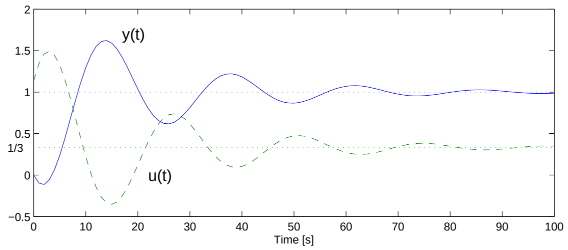


The robustness versus performance dilemna

Typical closed-loop response

Example: 2^{nd} order with a RHP zero, PI feedback tuned based on Ziegler-Nichols



- oscillatory, long settling time
- overshoot and large ratio btw. subsequent peaks
- too small phase and gain margins, high peaks

$\Rightarrow$ too agressive feedback

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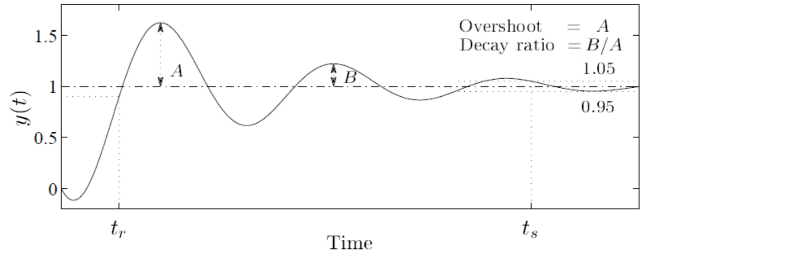
Time domain performance (step response)



- Speed: rise (reach 90 % of final) / settling (within ±5 % of final) times t_r & t_s
- Quality: overshoot (peak vs. final, $\leq$ 20 %), decay ratio (2^{nd} to 1^{st} peaks $\leq$ 0.3), steady-state offset (final - desired value), excess variation = 1 (total variation / overall change at steady state)
- both included in error $e(t) = y(t) - r(t)$ norm, e.g. $\mathcal{L}_2$ norm (good trade-off and related to optimization)

$$\|e(t)\|_2 = \sqrt{ISE},\ ISE = \int_0^\infty |e(\tau)|^2 d\tau \text{ (integral squared error)}$$

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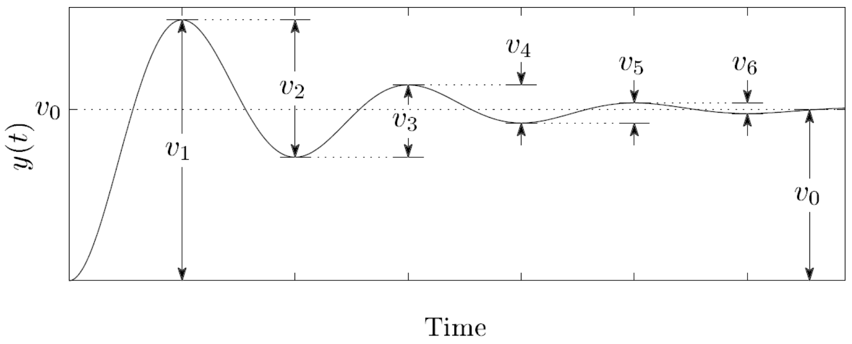
Excess variation computation



Total variation is $TV = \sum_i v_i$ and Excess variation is $TV/v_0 \Rightarrow$ as close to 1 as possible!

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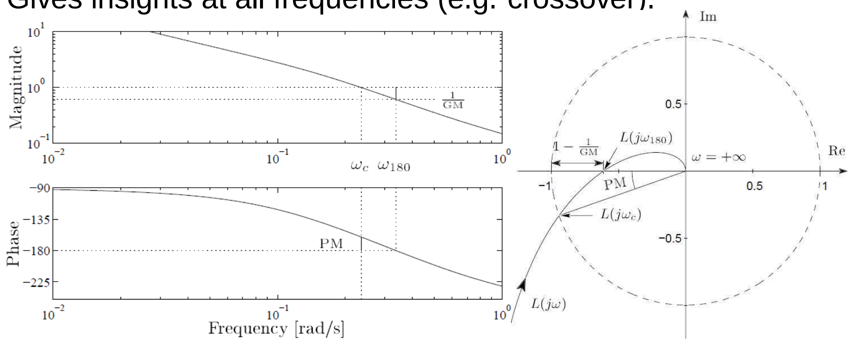
Frequency domain performance: Gain & phase margins

Gives insights at all frequencies (e.g. crossover).



- Gain margin (> 2, phase cross-over freq ω_{180}):

$$GM = 1/|L(j\omega_{180})|, \text{ where } \angle L(j\omega_{180}) = -180°$$

- Phase margin (> 30°, gain cross-over freq ω_c):

$$PM = \angle L(j\omega_c) + 180°, \text{ where } |L(j\omega_c)| = 1$$

safeguard against time-delay: $\tau_{max} = PM/\omega_c$

$\Rightarrow$ Good trade-off between performance and stability

Frequency domain performance: Maximum peak criteria

Maximum peaks of sensitivity and complementary sensitivity:

$$M_S = \max_\omega |S(j\omega)|; \quad M_T = \max_\omega |T(j\omega)|$$

Relate to the quality of the response:

- Typically, $M_S < 2$ (6 dB) and $M_T < 1.25$ (2 dB), if large: poor performance & robustness
- Motivation: $e = S(G_d d - r) \rightarrow \searrow |e(t)| \forall \omega$ where $|S| < 1$; typically small at LF, peak at intermediate F, 1 at HF: M_S measures worst-case performance degradation
- Relationships with gain & phase margins:

$$GM \geq \frac{M_S}{M_S - 1}; \quad PM \geq 2\sin^{-1}\left(\frac{1}{2M_S}\right) \geq \frac{1}{M_S}\ [rad]$$

$$GM \geq 1 + \frac{1}{M_T}; \quad PM \geq 2\sin^{-1}\left(\frac{1}{2M_T}\right) > \frac{1}{M_T}\ [rad]$$

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Relationship between time and frequency domain peaks

Example: second order system

	Time domain		Frequency domain	
ζ	Overshoot	Total variation	M_T	M_S
2.0	1	1	1	1.05
1.5	1	1	1	1.08
1.0	1	1	1	1.15
0.8	1.02	1.03	1	1.22
0.6	1.09	1.21	1.04	1.35
0.4	1.25	1.68	1.36	1.66
0.2	1.53	3.22	2.55	2.73
0.1	1.73	6.39	5.03	5.12
0.01	1.97	63.7	50.0	50.0

$\Rightarrow$ Correlation between ζ and M_T, which is often used as an approximation of the total variation TV ($M_T \leq TV \leq (2n+1)M_T$, where n is the order of T) = classical control on response quality.

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Bandwidth and crossover frequency

Bandwidth relates to response speed:

- large: faster t_r (HF signals more easily passed to outputs) but high sensitivity to noise and parameter variations
- small: t_r slow and more robust system
- defined as the frequency range $[\omega_1, \omega_2]$ ($[0, \omega_B]$) over which control is "effective", in terms of:
  - improving performance ($e/r = -S$ small): ω_B *when* $|S(j\omega)|$ *first crosses* $1/\sqrt{2}$ *from below*
  - impact on output / tracking ($y/r = T$ large): ω_{BT} *is highest freq. when* $|T(j\omega)|$ *crosses* $1/\sqrt{2}$ *from above*
  - close in most cases, ω_B more reliable

Gain crossover frequency ω_C: where $|L(j\omega)|$ first crosses 1 from above.

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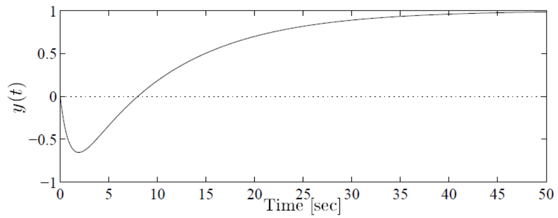
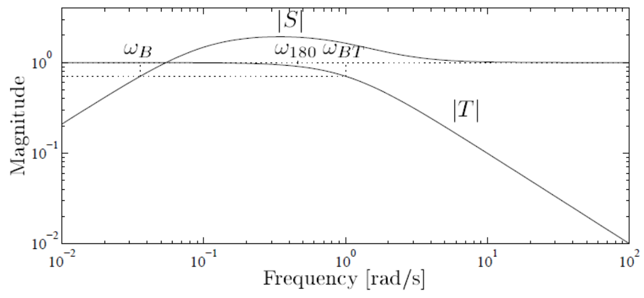
Example: comparison of ω_B and ω_{BT} as indicators of performance.

Consider the system with

$$L(s) = \frac{-s+z}{s(\tau s + \tau z + 2)}, \quad T(s) = \frac{-s+z}{s+z}\frac{1}{\tau s + 1}, \quad z = 0.1, \ \tau = 1$$



- both L and T have RHP zeros, $GM = 2.1$, $PM = 60.1°$, $M_S = 1.93$ and $M_T = 1$ (within acceptable bounds)
- $\omega_B = 0.036$ & $\omega_C = 0.054 < z$ (response limited by zero) but $\omega_{BT} = 1/\tau = 1.0 = 10 \times z$
- step: $t_r = 31.0\ s \approx 1/\omega_B = 28.0\ s \neq 1/\omega_{BT}$



- $|T| \approx 1$ up to ω_{BT} but phase drop ($-40° \to -220°$) between ω_B and ω_{BT}: poor tracking performance!
- i.e. at $\omega_{180} = 0.46$, $T \approx -0.9$ and response to sin ref completely out of phase

$\Rightarrow$ |T| not sufficient, consider phase also.

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Design objective	L
Performance, good disturbance rejection Performance, good command following Stabilization of unstable plant	large
Mitigation of meas. noise on plant outputs	small
Small magnitude of input signals	K & L small
Physical controller must be strictly proper	$K \to 0$ at HF
Nominal stability (stable plant)	(RHP z, delays)
Robust stability (stable plant)	(uncertain dyn.)

Generally in different frequency ranges: $|L| > 1$ at LF (below ω_c) and $|L| < 1$ at HF

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Conclusions

- Control is part of a system design process
- Transfer functions is a key system representation
- Obtained after scaling and linearization
- Specific care is needed on the sampling stage
- Interest for frequency response and main characterizations
- Feedback and CL transfer $\to$ sensitivity functions
- Quality criteria of CL response (time and frequency)

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UFR de Physique

MINING VENTILATION CONTROL

Lesson 3: Model of mine ventilation network system

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Universidad Pedagógica y Tecnológica de Colombia, Sogamoso, April 2, 2013

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Fundamentals of Physical modeling [Ljung et al. 1994]

- Most common relationships within a number of areas in physics.
- More general relationships become visible.

⇒ General modeling strategy.

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Electrical Circuits

Fundamental quantities:

voltage u (volt) and current i (ampere).

Components:

Nature	Relationship (law)	Energy
Inductor (L henry)	$i(t) = \frac{1}{L}\int_0^t u(s)ds, \quad u(t) = L\frac{di(t)}{dt}$	$T(t) = \frac{1}{2}Li^2(t)$ (magnetic field E storage, J)
Capacitor (C farad)	$u(t) = \frac{1}{C}\int_0^t i(s)ds, \quad i(t) = C\frac{du(t)}{dt}$	$T(t) = \frac{1}{2}Cu^2(t)$ (electric field E storage)
Resistor (R ohm)	$u(t) = Ri(t)$	
Nonlinear resistance	$u(t) = h_1(t)i(t), \quad i(t) = h_2(t)u(t)$	$P(t) = u(t)\cdot i(t)$ (loss, in watts, $1\ W = 1\ J/s$)
Ideal rectifier	$h_2(t) = \begin{cases} x, & x > 0 \\ 0, & x \le 0 \end{cases}$	

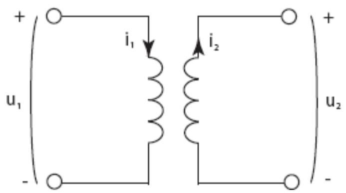
Interconnections (Kirkhhoff's laws):

$$\sum_k i_k(t) \equiv 0 \ (nodes), \quad \sum_k u_k(t) \equiv 0 \ (loops).$$

Ideal transformer:

transform voltage and current s.t. their product is constant:

$$u_1 \cdot i_1 = u_2 \cdot i_2, \quad u_1 = \alpha u_2, \quad i_1 = \frac{1}{\alpha} i_2$$



Mechanical Translation

Fundamental quantities:

force F (newton) and velocity v (m/s), 3-D vectors (suppose constant mass $\dot{m} = 0$).

Components:

Nature	Relationship (law)	Energy
Newton's force law	$v(t) = \frac{1}{m}\int_0^t F(s)ds, \quad F(t) = m\frac{dv(t)}{dt}$	$T(t) = \frac{1}{2}mv^2(t)$ (kinetic E storage)
Elastic bodies (k N/m)	$F(t) = k\int_0^t v(s)ds, \quad v(t) = \frac{1}{k}\frac{dF(t)}{dt}$	$T(t) = \frac{1}{2k}F^2(t)$ (elastic E storage)
Friction	$F(t) = h(v(t))$	
Air drag	$h(x) = cx^2 sgn(x)$	$P(t) = F(t) \cdot v(t)$ (lost as heat)
Dampers	$h(x) = \gamma x$	
Dry friction	$h(x) = \begin{cases} +\mu & if\ x > 0 \\ F_0 & if\ x = 0 \\ -\mu & if\ x < 0 \end{cases}$	

Interconnections:

$$\sum_k F_k(t) \equiv 0 \text{ (body at rest)}$$

$$v_1(t) = v_2(t) = \ldots = v_n(t) \text{ (interconnection point)}$$

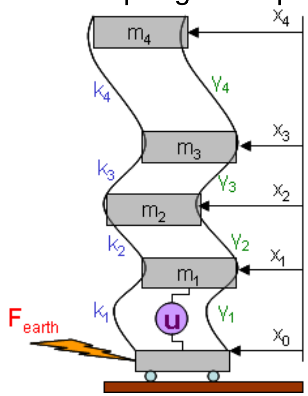
Ideal transformer:

force amplification thanks to levers:

$$F_1 \cdot v_1 = F_2 \cdot v_2$$
$$F_1 = \alpha F_2$$
$$v_1 = \frac{1}{\alpha} v_2$$

Example: active seismic isolation control [Itagaki & Nishimura, 2004]

Mass - spring - damper approximation:



$$\begin{cases} m_4\ddot{x}_4(t) = \gamma_4(\dot{x}_3 - \dot{x}_4) + k_4(x_3 - x_4) \\ m_i\ddot{x}_i(t) = [\gamma_i(\dot{x}_{i-1} - \dot{x}_i) + k_i(x_{i-1} - x_i)] \\ \qquad +[\gamma_{i+1}(\dot{x}_{i+1} - \dot{x}_i) \\ \qquad +k_{i+1}(x_{i+1} - x_i)], \quad i = 2, 3 \\ m_1\ddot{x}_1(t) = [\gamma_1(\dot{x}_0 - \dot{x}_1) + k_1(x_0 - x_1)] \\ \qquad +[\gamma_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1)] \\ \qquad +u(t) \\ m_1\ddot{x}_0(t) = F_{earth}(t) \\ y(t) = [\ddot{x}_0 + \ddot{x}_1 \quad x_2 - x_1]^T \end{cases}$$

Mechanical Rotation

Fundamental quantities:

torque M $[N \cdot m]$ and angular velocity ω $[rad/s]$.

Components:

Nature	Relationship (law)	Energy
Inertia J $[Nm/s^2]$	$\omega(t) = \frac{1}{J}\int_0^t M(s)ds, \quad M(t) = J\frac{d\omega(t)}{dt}$	$T(t) = \frac{1}{2}J\omega^2(t)$ (rotational E storage)
Torsional stiffness k	$M(t) = k\int_0^t \omega(s)ds, \quad \omega(t) = \frac{1}{k}\frac{dM(t)}{dt}$	$T(t) = \frac{1}{2k}M^2(t)$ (torsional E storage)
Rotational friction	$M(t) = h(\omega(t))$	$P(t) = M(t)\cdot\omega(t)$

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Interconnections:

$$\sum_k M_k(t) \equiv 0 \text{ (body at rest).}$$

Ideal transformer:

a pair of gears transforms torque and angular velocity as:

$$\begin{aligned} M_1\cdot\omega_1 &= M_2\cdot\omega_2 \\ M_1 &= \alpha M_2 \\ \omega_1 &= \frac{1}{\alpha}\omega_2 \end{aligned}$$

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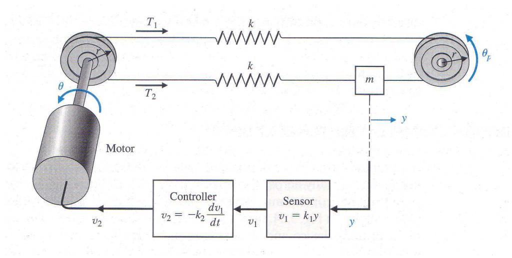
Example: printer belt pulley [Dorf & Bishop 2001]



$$\left\{\begin{aligned} &\text{Spring tension:} & T_1 &= k(r\theta - r\theta_p) = k(r\theta - y) \\ &\text{Spring tension:} & T_2 &= k(y - r\theta) \\ &\text{Newton:} & T_1 - T_2 &= m\frac{d^2y}{dt^2} \\ &\text{Motor torque (resistance, } L = 0\text{:} & M_m &= K_m i = \frac{K_m}{R}v_2 \\ &\text{drives belts + disturb.:} & M_m &= M + M_d \\ &T \text{ drives shaft to pulleys:} & M &= J\frac{d^2\theta}{dt^2} + h\frac{d\theta}{dt} + r(T_1 - T_2) \end{aligned}\right.$$

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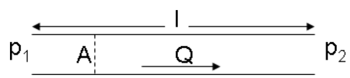
Flow Systems

Fundamental quantities:

for incompressible fluids, pressure p $[N/m^2]$ and flow Q $[m^3/s]$.

Fluid in a tube:

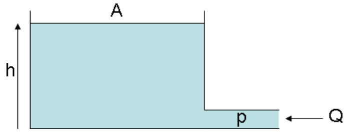


Pressure gradient	∇p	force	$p \cdot A$
mass	$\rho \cdot l \cdot A$	flow	$Q = v \cdot A$
inertance $[kg/m^4]$	$L_f = \rho \cdot l/A$		

Constitutive relationships (Newton: sum of forces = mass × accel.):

$$Q(t) = \frac{1}{L_f}\int_0^t \nabla p(s)ds, \quad \nabla p(t) = L_f\frac{dQ(t)}{dt} \qquad T(t) = \frac{1}{2}L_f Q^2(t) \text{ (kinetic E storage)}$$

Flow in a tank:



- Volume $V = \int Qdt$, $h = V/A$, and fluid capacitance $C_f \doteq A/\rho g$ $[m^4 s^2/kg]$.
- Constitutive relationships:

  Bottom pres. $p = \rho \cdot h \cdot g$ $\quad p(t) = \frac{1}{C_f}\int_0^t Q(s)ds \quad$ $T(t) = \frac{1}{2} C_f p^2(t)$ (potential E storage)

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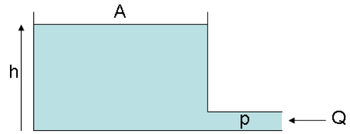
Flow through a section reduction:



- Pressure p, Flow resistance R_f, constant $\mathcal{H}$.
- Constitutive relationships:

  Pressure drop $\quad p(t) = h(Q(t))$

  d'Arcy's law $\quad p(t) = R_f Q(t)$, $P(t) = p(t) \cdot Q(t)$

  area change $\quad p(t) = \mathcal{H} \cdot Q^2(t) \cdot sgnQ(t)$

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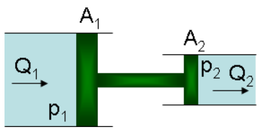
Interconnections:

$$\sum_k Q_k(t) \equiv 0 \text{ (flows at a junction)}, \quad \sum_k p_k \equiv 0 \text{ (in a loop)}$$

Ideal transformer:



$$p_1 \cdot Q_1 = p_2 \cdot Q_2, \quad p_1 = \alpha p_2, \quad Q_1 = \frac{1}{\alpha} Q_2.$$

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Thermal Systems

Fundamental quantities:

temperature T $[K]$ and heat flow rate q $[W]$.

Body heating:

Fourier's law of conduction

Thermal capacity C $[J/(K \cdot s)]$ $\quad T(t) = \frac{1}{C}\int_0^t q(s)ds, \quad q(t) = C\frac{dT(t)}{dt}$

Interconnections:

$$q(t) = W\Delta T(t) \text{ (heat transf. btw. 2 bodies)}$$
$$\sum_k q_k(t) \equiv 0 \text{ (at one point).}$$

where W $[J/(K \cdot s)]$ is the heat transfer coefficient.

Some Observations

Obvious similarities

among the basic equations for different systems!

Some physical analogies:

System	Effort	Flow	Eff. storage	Flow stor.	Static relation
Electrical	Voltage	Current	Inductor	Capacitor	Resistor
Mechanical:					
- Translational	Force	Velocity	Body (mass)	Spring	Friction
- Rotational	Torque	Angular V.	Axis (inertia)	Torsion s.	Friction
Hydraulic	Pressure	Flow	Tube	Tank	Section
Thermal	Temperature	Heat flow rate	-	Heater	Heat transfer

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Characteristics:

1. Effort variable e;
2. Flow variable f;
3. Effort storage: $f = \alpha^{-1} \cdot \int e$;
4. Flow storage: $e = \beta^{-1} \cdot \int f$;
5. Power dissipation: $P = e \cdot f$;
6. Energy storage via I.: $T = \frac{1}{2\alpha} f^2$;
7. Energy storage via C.: $T = \frac{1}{2\beta} e^2$;
8. Sum of flows equal to zero: $\sum f_i = 0$;
9. Sum of efforts (with signs) equal to zero: $\sum e_i = 0$;
10. Transformation of variables: $e_1 f_1 = e_2 f_2$.

- Note: analogies may be complete or not (i.e. thermal).

$\Rightarrow$ Create systematic, application-independent modeling from these analogies: see Bond Graphs.

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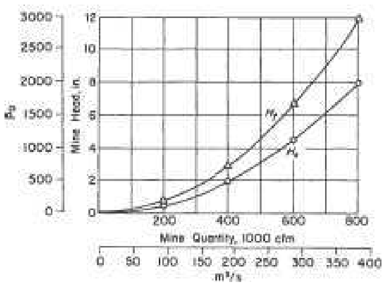
Mine ventilation circuits and networks [Hartman et al. 1997]

Relationship between head and quantity

- Head loss, static, velocity and total proportional to squared airflow quantity: H_l, H_s, H_v, $H_t \propto Q^2$

- Characteristic curve:

$$\frac{H_1}{H_2} = \left(\frac{Q_1}{Q_2}\right)^2 \Leftrightarrow H_1 = H_2 \left(\frac{Q_1}{Q_2}\right)^2$$



Example: fan whose $H_s = 2$ in. water, $H_t = 3$ in. water at 400,000 cfm:

- Airway resistance R from Atkinson: $H_l = RQ^2$ with $R = \frac{KO(L+L_e)}{A^3}$ N·s²/m⁸ (equiv. Ohm's law).

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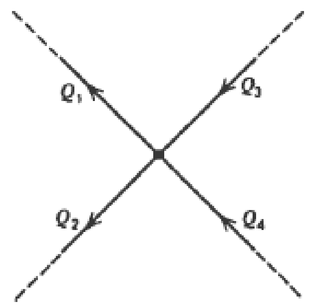
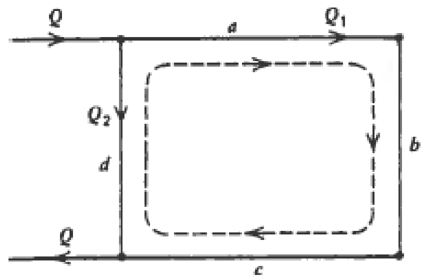
Kirchhoff's laws

First: current or junction law:
$\sum Q = 0 = Q_1 + Q_2 - Q_3 - Q_4$



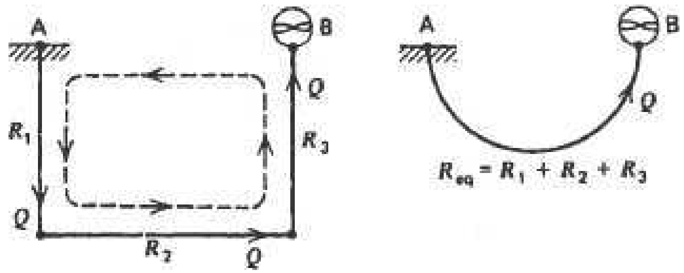
Second: voltage or loop:
$\sum H_l = 0 = H_{l_a} + H_{l_b} + H_{l_c} - H_{l_d}$



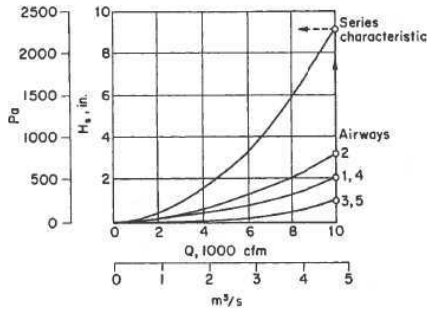
$H_l = R|Q|Q$ to keep sign convention.

E.g. $\sum H_l = R_a|Q_1|Q_1 + R_b|Q_1|Q_1 + R_c|Q_1|Q_1 - R_d|Q_2|Q_2 = 0$ and add pressure sources as negative pressure drops (head loss)

Series circuits: End to end airways

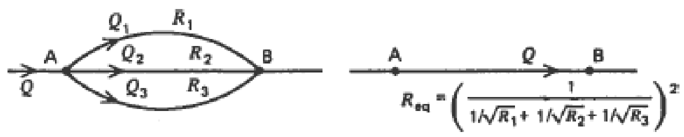


- quantity of air conserved $Q = Q_1 = Q_2 = Q_3 = \dots$



- fan head = total head loss (static): $H_{l_1} + H_{l_2} + H_{l_3} - H_{fan} = 0$
- equivalent resistance obtained as: $H_l = R_1|Q|Q + R_2|Q|Q + R_3|Q|Q + \dots = R_{eq}Q^2$ with $R_{eq} = \sum R_i$

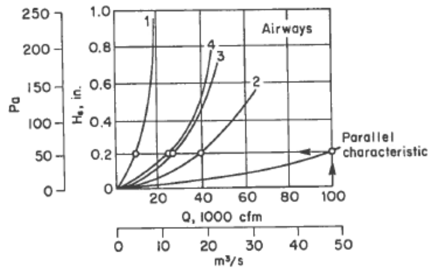
Parallel circuits: airflow splitting (natural or controlled)



- Kirchhoff's first law $Q = Q_1 + Q_2 + Q_3 + \dots$
- Second law: $H_{l_1} = H_{l_2} = H_{l_3} = \dots$
- Equivalent resistance obtained as:
  $Q = \sqrt{H_l/R_1} + \sqrt{H_l/R_2} + \sqrt{H_l/R_3} = \sqrt{H_l/R_{eq}}$ with
  $\frac{1}{\sqrt{R_{eq}}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} + \frac{1}{\sqrt{R_3}} + \dots$
- Quantity-divider rule: $R_{eq}Q^2 = R_1Q_1^2 = R_2Q_2^2 = \dots$ gives $Q_1 = Q\sqrt{R_{eq}/R_1}$, $Q_2 = Q\sqrt{R_{eq}/R_2}$, etc.
- In N_a airways of same characteristics: $H_l = \frac{R}{N_a^2}Q^2$, in Atkinson's equation: total perimeter N_aO and total area N_aA

Parallel circuits (2)

- Characteristic curves: cumulative for a given head →



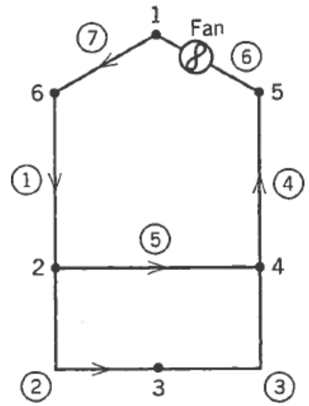
- Controlled splitting:
  - artificial resistance (regulators) in all but one branch (free branch, with highest head)
  - raise head and power requirements
  - regulators = variable openings, larger means smaller shocks. Size from shock-loss formula (circular):

$$X = \frac{H_x}{H_v} = \left[\frac{1/C_c - N}{N}\right]^2,\ C_c = \frac{1}{\sqrt{z - zN^2 + N^2}} \Rightarrow N = \frac{A_r}{A} = \sqrt{\frac{z}{X + 2\sqrt{X} + z}}$$

where X = shock-loss factor, H_x = needed shock loss, N = ratio of orifice (regulator) area A_r to airway area A, C_c = coef. of contraction, z = contraction factor (e.g. 2.5 for mine).
  - i.e. given Q, H_x and A, find A_r

Ventilation networks: some definitions

- Node: point where ≥ 2 airways intersect = "junction"
- Branch (arc): connecting line (airway) between 2 nodes
- Graph: set of nodes, with certain pairs connected by branches
- Connected graph: all nodes are connected together by branches
- Network: graph with a flow associated with each branche, can be connected
- Directed network: sign/direction associated with each branch
- Degree of a node: number of connected branches
- Mesh (cycle): connected path in which every node is of deg. 2 with respect to the path
  - (spanning) tree: connected graph without mesh
  - Branch in a tree: branch contained in a spanning tree



Ventilation networks: some definitions (2)

- Chord (basic branch): in the network but not in a given spanning tree
- Basic mesh: contains only one chord and the unique path formed by branches in the tree between 2 nodes of the chord
- Chord set: set containing all the chords of a network, unique for a given spanning tree
- Mesh base: set containing all basic meshes, unique for a given spanning tree
- Network degree: equal to the number of chords

⇒ Series and parallel circuits sufficients for analysing simple graphs, but advanced definitions necessary for complex networks

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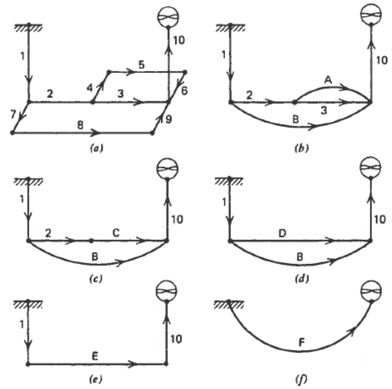
Solution of simple networks with natural splitting

To combine series or parallel airways:

- Algebraic solution: alternate algebraic solving of each branch and mesh

→ provides R_{eq} to solve: Mine $H_s = H_l = Q^2 R_{eq}$



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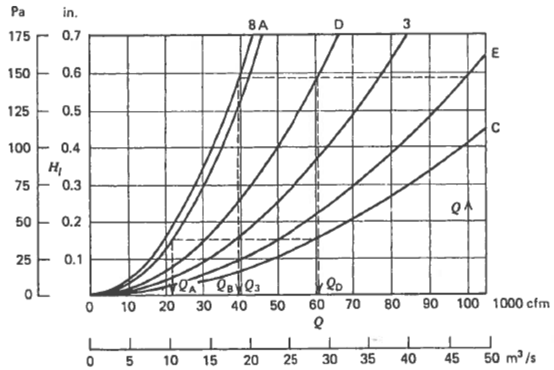
Solution of simple networks with natural splitting (2)

- Graphical solution: use the characteristic curve

- sum the quantities for loops
- sum the heads for series



1. combine all series airways
2. plot main splits (e.g. B and D), then the equivalent one (E)
3. determine the quantity flowing in each branch for the mine quantity Q
4. plot the secondary splits then determine Q in each branch

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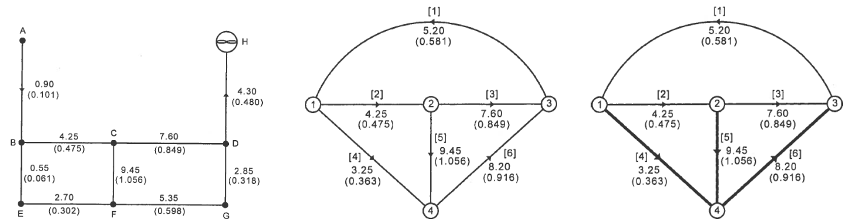
Analysis of complex networks

Based on spanning trees and chords, i.e. create the tree as:

1. choose any node
2. arbitrarily connect another node that is one branch away → connected set of nodes
3. arbitrarily connect another node that is one branch away from the connected set
4. if all nodes ∈ connected set: stop, else: go to step 3

Example: R in in·min^2/ft^6 $\times 10^{10}$ (N·s^2/m^8)



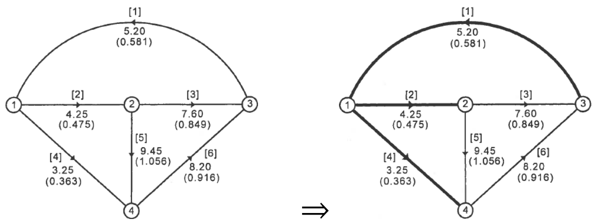
Complex networks: minimum-resistance spanning tree

Consider the resistance as a distance:

1. choose any node and connect to its closest adjacent node
2. find the unconnected node nearest to a connected node and connect the two
3. if all nodes are connected: stop, else: go to step 2

⇒ Identical regardless of the starting node unless ties occur when the final branches are chosen

Example:



Complex networks: some properties

- ∃ at least one tree in every connected network
- For a given tree in a connected network with N_n nodes and N_b branches, there are exactly $N_n - 1$ branches in the tree and $N_m = N_b - (N_n - 1)$ chords = network degree
- Any fluid flowing through the network is at equilibrium if Kirchhoff's laws are satisfied
- The quantity Q flowing in each branch ∈ chord set are independant and the Q of any branch ∈ tree is a linear combination of the Q flowing in the chords.
- Kirchhoff's 1^{st} law satisfied for Q at every node
- The set of head losses H_l of the branches ∈ tree uniquely determines the chord H_l.
- H_l in branches satisfying Kirchhoff's 2^{nd} law for a mesh base satisfy it also ∀ other mesh and mesh base in the network.

Complex networks: Mathematical representation

Given a network with N_n nodes and N_b branches, find Q, H_l and R in each branch → 3 N_b variables:

- Banch equations: $H_{l_j} = R_j|Q_j|Q_j$, $j = 1 \dots N_b \Rightarrow N_b$ nonlinear independant eq.
- Node equations: $\sum_{j=1}^{N_b} a_{ij}Q_j = 0$, $i = 1 \dots N_n$ where

$$a_{ij} = \begin{cases} -1 & \text{if the starting node of branch j = i} \\ 0 & \text{if neither of the nodes of branch j = i} \\ 1 & \text{if the end node of branch j = i} \end{cases}$$

The resulting matrix $E_Q = [a_{ij}]$ is called the incidence matrix, ⇒ $(N_n - 1)$ linear independant eq.

Complex networks: Mathematical representation (2)

- Mesh equations: N_m independent ones in the mesh base relating the N_b head losses: $\sum_{j=1}^{N_b} b_{kj}H_j = 0$, $k = 1 \dots N_m$, where

$$b_{kj} = \begin{cases} -1 & \text{if branch j} \in \text{basic mesh corresponding to chord k and if, travelling the mesh from the starting node of the chord toward its end node, the end node of branch j is found first} \\ 0 & \text{if branch j not in basic mesh corresponding to chord k} \\ 1 & \text{if branch j} \in \text{basic mesh corresponding to chord k and if the starting node of branch j is found first} \end{cases}$$

The resulting matrix $E_H = [b_{kj}]$ is called the fundamental-mesh matrix

Complex networks: Mathematical representation (3)

Balance between variables and independent equations:

Number of variables		Number of independent equations	
Quantities	N_b	Branch equations	N_b
Head losses	N_b	Node equations	$N_n - 1$
Resistances	N_b	Mesh equations	$N_b - (N_n - 1)$
Total	3 N_b		2 N_b

$\Rightarrow$ Need N_b initial known variables to solve the ventilation network problem.

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Dynamic models of the network

[Hu, Koroleva, Krstic 2003]

Pipe flow dynamics

- Due to an unsteady incompressible fluid
- Head drop = Head loss + Energy storage due to a change in the flow quantity:

$$H_{tj} = R_j|Q_j|Q_j + L_{f_j}\frac{dQ_j}{dt} \Leftrightarrow \frac{dQ_j}{dt} = -K_jR_j|Q_j|Q_j + K_jH_{tj}$$

where $K_j = A_j/(\rho l_j)$ is the inverse of the inertance (L_f), A_j the branch cross-section area and l_j the branch length.

- Node and mesh eq. with one fan: $E_Q Q = 0$ and $E_H H = 0$ with $E_Q \in \mathbb{R}^{(N_n-2)\times N_b}$ full rank and $E_H \in \mathbb{R}^{N_m \times N_b}$
- Fan in branch m: $e_{Q_m} Q = Q_m$, $e_{H_m} H = H_m$ and dynamics in branch set by $H_m = d - R_m Q_m$, d = pressure drop generated by the fan.

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Non-minimal model of the network

Distinguish the $N_b - (N_n - 1)$ chords from the $N_n - 1$ branches in the tree to partition the air flow quantities and heads ($H = H_t$) as

$$Q = \begin{bmatrix} Q_c \\ Q_a \end{bmatrix} = \begin{bmatrix} Q_1 \\ \vdots \\ Q_{N_b-(N_n-1)} \\ Q_{N_b-(N_n-2)} \\ \vdots \\ Q_{N_b} \end{bmatrix}, \quad H = \begin{bmatrix} H_c \\ H_a \end{bmatrix} = \begin{bmatrix} H_1 \\ \vdots \\ H_{N_b-(N_n-1)} \\ H_{N_b-(N_n-2)} \\ \vdots \\ H_{N_b} \end{bmatrix}$$

Defining

$$Q_D^2 = diag(|Q_j|Q_j, \ldots, |Q_j|Q_j), \quad K = diag(K_1, \ldots, K_{N_b})$$

we obtain the dynamics: $\dot{Q} = -KQ_D^2R + KH$

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Non-minimal model of the network (2)

Proposition 1 [Hu et al. 2003]: There exists matrices Y_{RQ}, Y_Q and Y_d of appropriate dimensions so that the full order model of the mine ventilation network can be expressed as:

$$\begin{aligned} \dot{Q} &= -K(I - Y_{RQ})Q_D^2R + KY_QQ + KY_dd \\ H &= Y_{RQ}Q_DR + Y_QQ + Y_dd \end{aligned}$$

Proof and matrix construction: use of the chords/tree partition, see paper.

Notes for control:

- $Q \in \mathbb{R}^{N_b}$
- "Bilinear" in the state
- Linear in d but input-to-state couplings in R

Minimal model of the network

Proposition 2 [Hu et al. 2003]: There exist matrices A_c, A_{ca}, B_c, C_c, Y_{RQ_c}, Y_{RQ_a}, Y_{Q_c} and Y_d of appropriate dimensions so that the minimal model of mine ventilation network system can be expressed as:

$$\begin{aligned} \dot{Q}_c &= A_c Q_{cD}^2 R_c + A_{ca} Q_{aD}^2 R_a + B_c Q_c + C_c d \\ H_a &= Y_{RQ_c} Q_{cD}^2 R_c + Y_{RQ_a} Q_{aD}^2 R_a + Y_{Q_c} Q_c + Y_d d \end{aligned}$$

where Q_c is the state, R_c, R_a and d are the control inputs, and H_a is the system output, and:

$$\begin{aligned} Q_{cD}^2 &= diag(Q_1|Q_1|, \ldots, Q_{N_b-(N_n-1)}|Q_{N_b-(N_n-1)}|) \\ Q_{aD}^2 &= diag(Q_{N_b-(N_n-2)}|Q_{N_b-(N_n-2)}|, \ldots, Q_{N_b}|Q_{N_b}|) \\ R &= [R_c^T \quad R_a^T]^T \end{aligned}$$

Proof and matrix construction: see paper.

Note: $Q_c \in \mathbb{R}^{N_b-(N_n-1)} \Rightarrow$ State dimension reduced by $(N_n - 1)$!

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Simulation softwares

- VENTSIM: simulate airflows, pressure and heats from a modeled network of airways. `http://www.ventsim.com/`
- VUMA-3D: mine ventilation, cooling and environment control. `http://www.vuma.co.za/`
- VnetPC PRO+: branch templates, fans, shock loss. `http://www.mvsengineering.com/`
- ...

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Conclusions

- A process typically involves to consider multiple physical domains: some general rules can be drawn and appropriate tools for multi-physics modeling exist (e.g. bond graphs)
- Modeling and analysis of the mine ventilation network:
  - from the mine topology, establish the steady-state model: ventilation design and equilibrium behavior
  - simplify the graph to size the fans/forced ventilation apparatus
  - include the dynamics by considering the inertia of the air volume
  - simulate the minimal model
- Several simulation softwares can be used

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Mining Ventilation Control

Lesson 4: Air flow modeling in deep wells

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Fluid dynamics
General form of a conservation law
Convection-diffusion
Euler and Navier-Stokes
Firn example
Cryogenics/QRL
Lumped models
0-D model: main characteristics
Bond graph modeling overview
Fans, rooms and pollutant sources
Simulation results
Volume-averaging and transport coefficients
Parameter estimation
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Outline

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The basic equations of fluid dynamics [Hirsch 2007]

- Model from physics: subatomic, atomics or molecular, microscopic, macroscopic, astronomical scale
- Fluid dynamics = study of the interactive motion and behavior of a large number of elements
- System of interacting elements as a continuum
- Consider an elementary volume that contains a sufficiently large number of molecules with well defined mean velocity and mean kinetic energy
- At each point we can thus infer, e.g. velocity, temperature, pressure, entropy etc.

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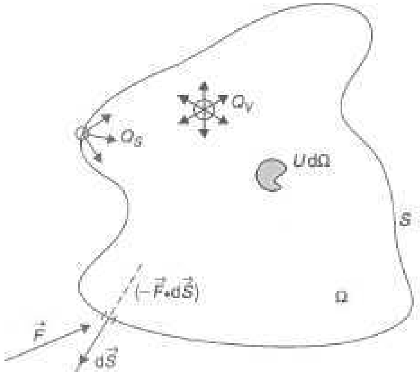
General form of a conservation law

- Conservation: the variation of a conserved (intensive) flow quantity U in a given volume results from internal sources and the quantity, the *flux*, crossing the boundary
- Fluxes and sources depend on space-time coordinates, + on the fluid motion
- Not all flow quantities obey conservation laws. Fluid flows fully described by the conservation of
  1. mass
  2. momentum (3-D vector)
  3. energy

  ⇒ 5 equations
- Other quantities can be used but will not take the form of a conservation law

Scalar conservation law

Consider:
- a scalar quantity per unit volume U,
- an arbitrary volume Ω fixed in space (control volume) bounded by
- a closed surface S (control surface) crossed by the fluid flow



- Total amount of U inside Ω: $\int_\Omega U d\Omega$ with variation per unit time $\frac{\partial}{\partial t}\int_\Omega U d\Omega$
- Flux = amount of U crossing S per unit time: $F_n dS = \vec{F}\cdot d\vec{S}$ with $d\vec{S}$ outward normal, and net total contribution $-\oint_S \vec{F}\cdot d\vec{S}$ ($\vec{F} > 0$ when entering the domain)
- Contribution of volume and surface sources: $\int_\Omega Q_V d\Omega + \oint_S \vec{Q}_S \cdot d\vec{S}$

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Scalar conservation law (2)

Provides the integral conservation form for quantity U:

$$\frac{\partial}{\partial t}\int_\Omega U d\Omega + \oint_S \vec{F}\cdot d\vec{S} = \int_\Omega Q_V d\Omega + \oint_S \vec{Q}_S \cdot d\vec{S}$$

- valid $\forall$ fixed S and Ω, and any point in flow domain
- internal variation of U depends only of fluxes through S, not inside
- no derivative/gradient of F: may be discontinuous and admit shock waves

$\Rightarrow$ relate to *conservative numerical scheme* ar the discrete level (e.g. conserve mass)

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Differential form of a conservation law

Obtained using Gauss' theorem $\oint_S \vec{F}\cdot d\vec{S} = \int_\Omega \vec{\nabla}\cdot\vec{F} d\Omega$ as:

$$\frac{\partial U}{\partial t} + \vec{\nabla}\cdot\vec{F} = Q_V + \vec{\nabla}\cdot\vec{Q}_S \Leftrightarrow \frac{\partial U}{\partial t} + \vec{\nabla}\cdot(\vec{F} - \vec{Q}_S) = Q_V$$

- the *effective flux* $(\vec{F} - \vec{Q}_S)$ appear exclusively under the gradient operator $\Rightarrow$ way to recognize conservation laws
- more restrictive than the integral form as the flux has to be differentiable (excludes shocks)
- fluxes and source definition provided by the quantity U considered

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Convection-diffusion form of a convection law

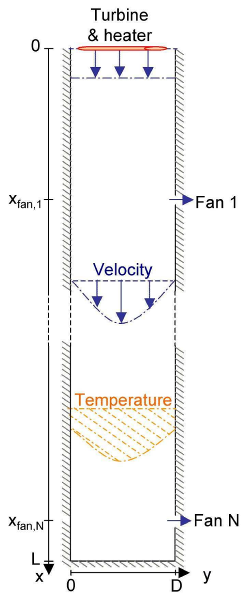
Flux = convective transport + molecular agitation (even at rest)

- Convective flux:
  - amount of U carried away or transported by the flow (velocity $\vec{v}$): $\vec{F}_C = U\vec{v}$
  - for fluid density $U = \rho$, local flux through $d\vec{S}$ is the local mass flow rate: $\rho\vec{v}\cdot d\vec{S} = d\vec{m}$ (kg/s)
  - for $U = \rho u$ (u the quantity per unit mass), $\vec{F}_C \cdot d\vec{S} = \rho u\vec{v}\cdot d\vec{S} = u d\vec{m}$
- Diffusive flux:
  - macroscopic effect of molecular thermal agitation
  - from high to low concentration, in all directions, proportional to the concentration difference
  - Fick's law: $\vec{F}_D = -\kappa\rho\vec{\nabla}u$, where κ is the diffusion coefficient (m^2/s)
- Provides the transport equation:

$$\frac{\partial\rho u}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}u) = \vec{\nabla}\cdot(\kappa\rho\vec{\nabla}u) + Q_V + \vec{\nabla}\cdot\vec{Q}_S$$

$\Rightarrow$ *Backbone of all mathematical modeling of fluid flow phenomena*

Euler and Navier-Stokes equations



- From the conservation of mass, momentum and energy:

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho\vec{v}\\ \rho E\end{bmatrix}+\nabla\cdot\begin{bmatrix}\rho\vec{v}\\ \rho\vec{v}^T\otimes\vec{v}+p\mathbf{I}-\tau\\ \rho\vec{v}H-\tau\cdot\vec{v}-k\nabla T\end{bmatrix}=\begin{bmatrix}0\\0\\ \dot{q}\end{bmatrix},$$

with shear stress (Navier-Stokes only)

$$\begin{bmatrix}\tau_{xx}\\ \tau_{xy}\\ \tau_{yy}\end{bmatrix}=\begin{bmatrix}\lambda\\ \mu\\ \lambda\end{bmatrix}(\nabla\cdot\vec{v})+2\mu\begin{bmatrix}u_x\\0\\v_y\end{bmatrix}$$

and viscosity [*Stokes* & *Sutherland*]

$$\lambda=-\frac{2}{3}\mu \quad \text{and} \quad \frac{\mu}{\mu_{sl}}=\left(\frac{T}{T_{sl}}\right)^{3/2}\frac{T_{sl}+110}{T+110}.$$

- Discrete boundary conditions (potential numerical instabilities).

Example: solving the air continuity in polar firns and ice cores

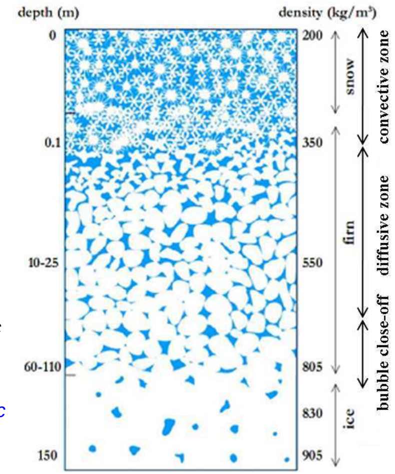
From poromechanics, firn = system composed of the ice lattice, gas connected to the surface (open pores) and gas trapped in bubbles (closed pores). Air transport is driven by:

$$\frac{\partial[\rho_{ice}(1-\epsilon)]}{\partial t}+\nabla[\rho_{ice}(1-\epsilon)\vec{v}]=0$$

$$\frac{\partial[\rho^o_{gas}f]}{\partial t}+\nabla[\rho^o_{gas}f(\vec{v}+\vec{w}_{gas})]=-\vec{r}^{o\to c}$$

$$\frac{\partial[\rho^c_{gas}(\epsilon-f)]}{\partial t}+\nabla[\rho^c_{gas}(\epsilon-f)\vec{v}]=\vec{r}^{o\to c}$$

with appropriate boundary and initial conditions.



Scheme adapted from [Sowers et al.'92, Lourantou'08].

Firn example: from distributed to lumbed dynamics

- Defining $q=\rho^c_{gas}(\epsilon-f)$ and considering the 1-D case, we have to solve

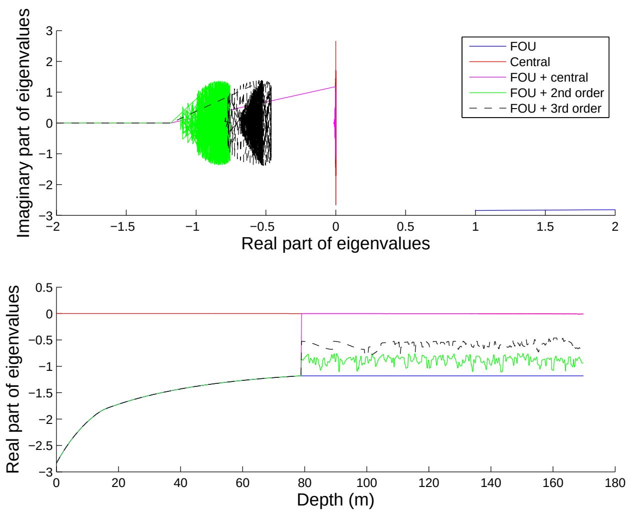
$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial z}[qv]=r^{o\to c}$$

- Approximate $\partial[qv]/\partial z$, i.e. on uniform mesh:
  - backward difference: $(u_z)_i=\frac{u_i-u_{i-1}}{\Delta z}+\frac{\Delta z}{2}(u_{zz})_i$
  - central difference: $(u_z)_i=\frac{u_{i+1}-u_{i-1}}{2\Delta z_i}-\frac{\Delta z^2}{6}(u_{zzz})_i$
  - other second order: $(u_z)_i=\frac{u_{i+1}+3u_i-5u_{i-1}+u_{i-2}}{4\Delta z_i}+\frac{\Delta z^2}{12}(u_{zzz})_i-\frac{\Delta z^3}{8}(u_{zzzz})_i$
  - third order: $(u_z)_i=\frac{2u_{i+1}+3u_i-6u_{i-1}+u_{i-2}}{6\Delta z_i}-\frac{\Delta z^3}{12}(u_{zzzz})_i$
- Provides the computable *lumped model*:

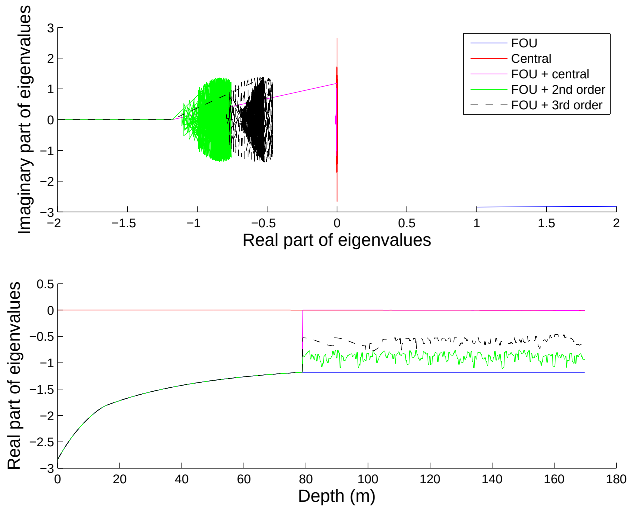
$$\frac{dq}{dt}=Aq+r^{o\to c}$$

- The choice of the discretization scheme directly affects the definition of A and its eigenvalues distribution: need to *check stability and precision!*

e.g. eig(A) for CH_4 at NEEM with $dt=1$ month



e.g. eig(A) for CH_4 at NEEM with $dt \approx 1$ week



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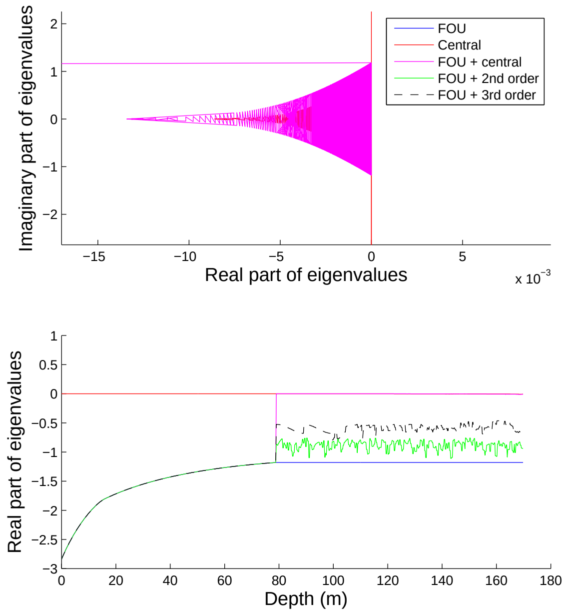
e.g. eig(A) for CH_4 at NEEM with $dt \approx 1$ week, zoom



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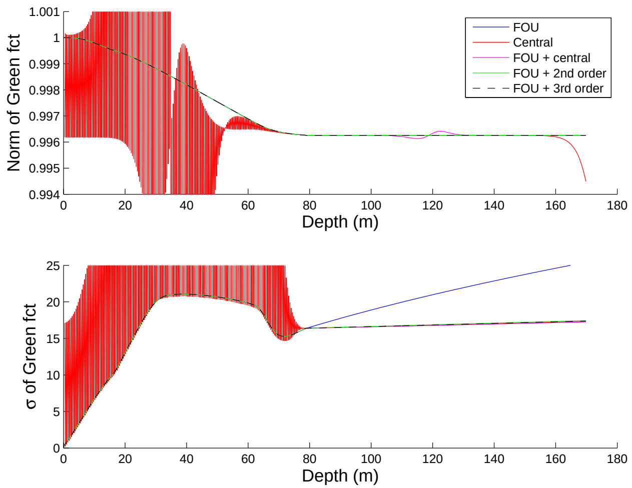
e.g. Impulse response (Green's function) for CH_4 at NEEM with $dt = 1$ month



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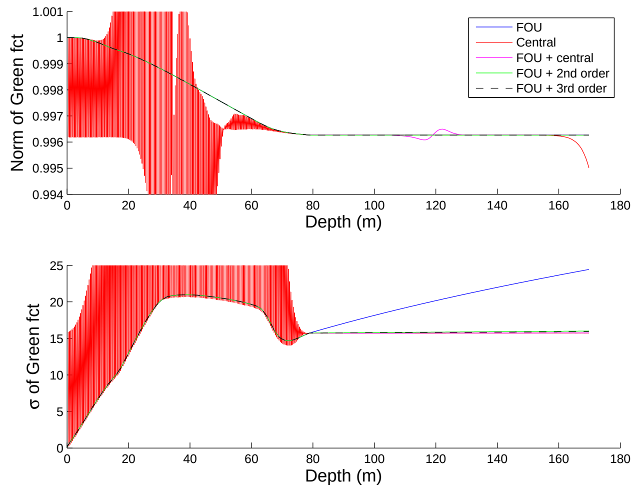
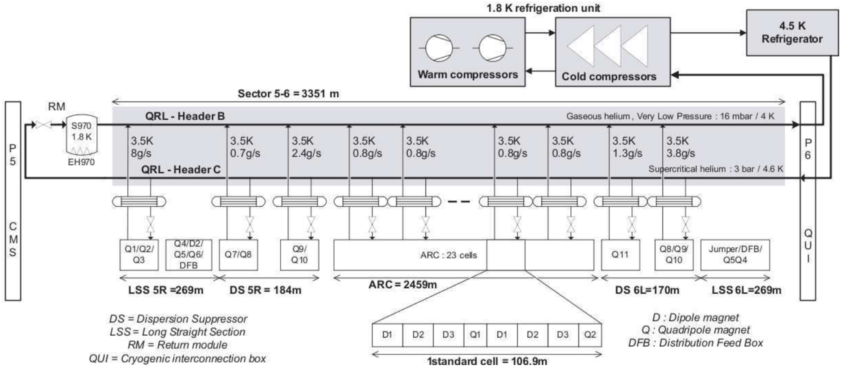


Example 2: Travelling wave modeling cryogenics [Bradu, Gayet, Niculescu, W'10]

LHC sector 5-6 with the main cooling loops for the superconducting magnets:



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Method

Assumptions:

- model using Euler equation
- flux according to the x direction only (the main flow direction) : $V = V_x$ and $M = \rho \cdot V_x$;
- straight line. The QRL curvature (radius of curvature of 4.3 km) has a negligible impact on the flow;
- in operational conditions, the kinetic component can be neglected: $\rho \cdot |\vec{V}|^2 << P$, which implies that $\rho \cdot \vec{V}^T \otimes \vec{V} + P \cdot I \approx P \cdot I$.

Euler equation expressed in 1D as:

$$\frac{\partial X(x,t)}{\partial t} + F(X) \cdot \frac{\partial X(x,t)}{\partial x} = Q(x,t)$$

where $X = [\ \rho \quad M \quad E\ ]^T$ is the state vector, F is the Jacobian flux matrix and $Q = [\ 0 \quad 0 \quad q\ ]^T$ is the source vector.

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Method (2): space discretization

From the Jacobian (empirical formulation for the helium internal energy)

$$F = \begin{bmatrix} 0 & 1 & 0 \\ \frac{(\gamma-3)V^2}{2} - u_0\hat{\gamma} & (3-\gamma)V & \hat{\gamma} \\ \hat{\gamma}V^3 - \frac{\gamma V E}{\rho} & \frac{\gamma E}{\rho} - \hat{\gamma}(\frac{3V^2}{2} + u_0) & \gamma V \end{bmatrix}$$

we obtain the state-space matrices from:

$$\dot{X}_i(t) + \frac{A_i(X_i)}{\Delta x} X_i(t) + \frac{B_i(X_i)}{\Delta x} X_{i-1}(t) + \frac{C_i(X_i)}{\Delta x} X_{i+1}(t) = Q_i(t)$$

where i denotes the value at x_i and $X_i = \left[\ \rho_i \quad M_i \quad E_i\ \right]$
+ add the interconnections with external inputs in Q_i

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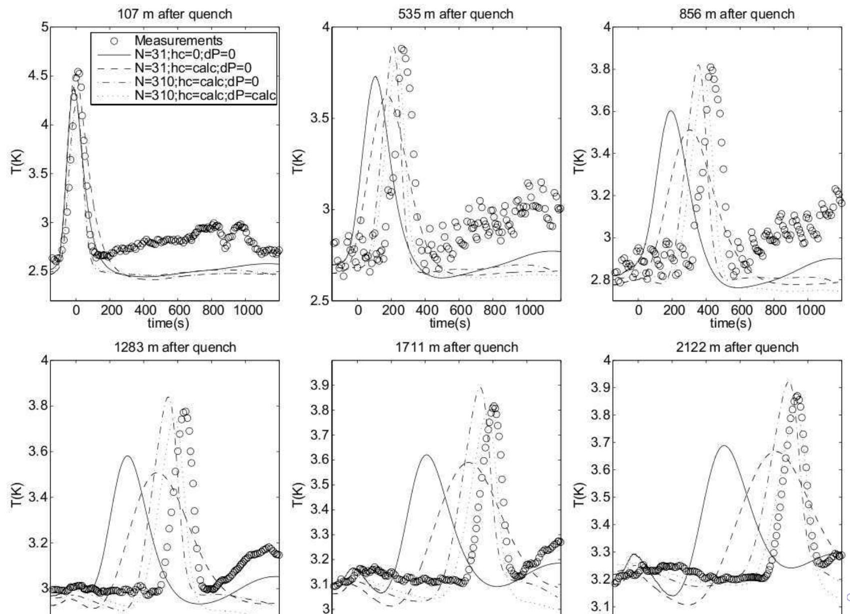
Temperature transport

Impact of convection heat, hydrostatic pressure and friction pressure drops:



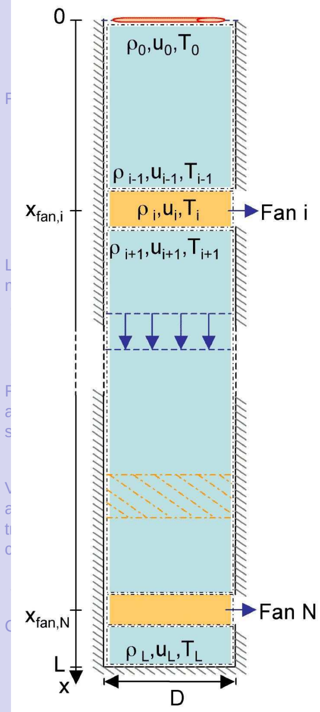
From Euler equations to lumped models

(0-D) Control-oriented model

- Non-dimensional modeling has an increasing use in design, validation and tuning of control laws.
- Two main advantages:
  - integration of as much physical properties as possible (avoid data mapping);
  - reduced computation: close to real-time, ≈ 10× slower in worst cases.
- Flow/effort model inferred from Euler equations:

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho\vec{v}\\ \rho E\end{bmatrix}+\nabla\cdot\begin{bmatrix}\rho\vec{v}\\ \rho\vec{v}^T\otimes\vec{v}+p\mathbf{I}\\ \rho\vec{v}H\end{bmatrix}=\begin{bmatrix}0\\0\\0\end{bmatrix}.$$

0-D model: main characteristics



- Energy approach: equivalent to finite volume method → physically consistent averaging of the dynamics.
- Hypotheses:
  1. only static pressure considered in energy conservation;
  2. impulsive term negligible compared to pressure in momentum conservation;
  3. momentum dynamics simplified using Saint-Venant equations → algebraic relationship.

⇒ Algebro-differential model with numerically robust ODE description.

Bond graph modeling overview [V. Talon, *PhD*'04]

- Defining the mass flow $Q_m(t) = L/S\int_0^t \Delta p(s)ds$ and the enthalpic flow $Q_h = Q_m c_p T$, the conservation equations write as

$$\frac{d}{dt}\begin{bmatrix}m\\ Q_m\\ U\end{bmatrix}=\begin{bmatrix}Q_{m,i}-Q_{m,o}\\ S/L\ (p_i-p_o)\\ Q_{h,i}-Q_{h,o}\end{bmatrix}.$$

- Pressure and temperature obtained from first Joule law ($U = mc_vT$) and the perfect gas relationship:

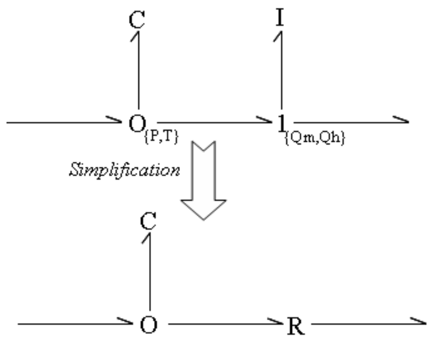
$$T=\frac{\gamma-1}{R}\frac{U}{m}\quad\text{and}\quad p=(\gamma-1)\frac{U}{v}$$

- Pressure losses from Bernoulli's equation (supposing incompressibility) as $\Delta P = \zeta Q_m^2/(2\rho S^2)$, where ζ is a friction coefficient.
- Saint Venant $Q_m = \rho C_d S\sqrt{\gamma RT}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$: momentum represented as a resistive element.

Bond graph model (2)

- Power conjugate variables:

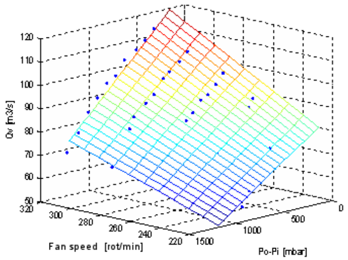
Conservation equation	Effort	Flow	Relation
Mass	mass m	flow rate Q_m	effort storage **C**
Momentum (hydraulic)	pressure p	flow rate Q_m	flow storage **I**
Energy (thermal)	internal energy E	enthalpic flow Q_h	effort storage **C**



Fans, rooms and pollutant sources

- Additional features: friction losses and pollutant tracking.
- Turbine and fans:
  - compressors that generate a flow depending on a pressure gradient and a rotational speed;
  - characteristics depend on specification maps →
  - enthalpic flow $Q_h = Q_m c_p T$ and output temperature is obtained as

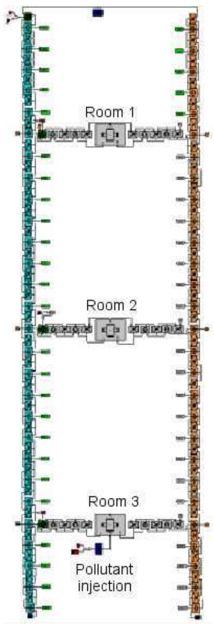
$$T_o = T_i \left\{ \frac{1}{\eta_c} \left[\left(\frac{P_o}{P_i} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] + 1 \right\};$$



$\Rightarrow$ capacitive and resistive elements.

- Room included as (mostly) inertia elements

Simulation results

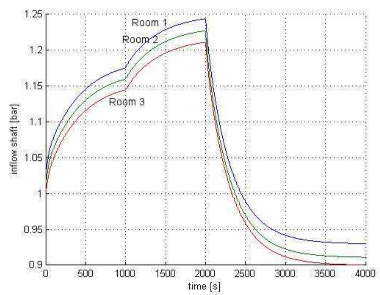


Simulator properties:

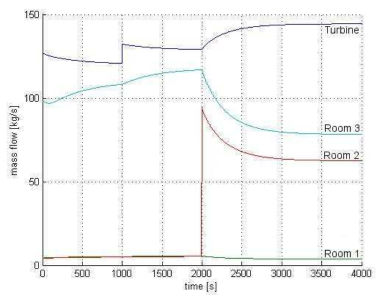
- ventilation shafts ≈ 28 control volumes (CV), 3 extraction levels
- regulation of the turbine and fans
- flows, pressures and temperatures measured in each CV
- Computation time 34× faster than real-time

Case study:

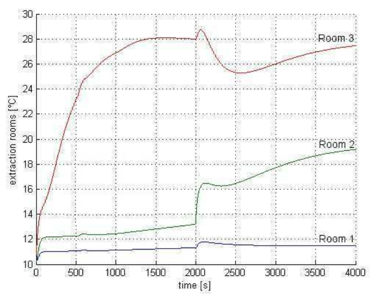
- 1st level fan not used (natural airflow), 2nd operated at 1000 s (150 rpm) and 3rd runs continuously (200 rpm)
- CO pollution injected in 3rd level
- measurement of flow speed, pressure, temperature and pollution at the surface and extraction levels



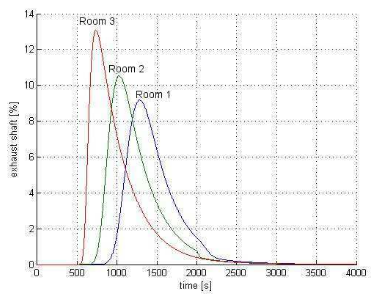
(a) Pressure losses in the inflow shaft



(b) Extraction rooms ventilation rate



(c) Extraction rooms temperature



(d) CO pollutant concentrations in the exhaust shaft

Simulation results (3)

- Physical and chemical airflow properties:
  - pressure losses = energy losses;
  - rooms ventilation rate = physical interconnections and importance of a global control strategy;
  - temperature: geothermal effect and fans compression;
  - pollutant transport: time-delay effect;
- Computation time 34× faster than real-time.

Volume-averaging and estimation of the transport coefficients

Volume-averaged model

- Volume-averaged impact of momentum and density:

$$\bar{M}(t) \doteq \frac{1}{\mathcal{V}}\oint_{\mathcal{V}} M(v,t)dv \quad \text{and} \quad \bar{\rho}(t) \doteq \frac{1}{\mathcal{V}}\oint_{\mathcal{V}} \rho(v,t)dv,$$

- Energy losses = pressure losses (friction and exhausts):

$$\dot{q}(x,t)R/c_v = s(x,t) + r(t)p(x,t),$$

- Give the transport model with boundary (controlled) input:

$$\begin{cases} \tilde{p}_t = c(t)\tilde{p}_x + r(t)\tilde{p} + s(x,t), \\ \tilde{p}(0,t) = p_{in}(t) \end{cases}$$

$\Rightarrow$ Given distributed measurements, estimate transport coefficients and set feedback $p_{in}(t)$

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Observer-based online parameter estimation

Theorem (parameter estimation for affine PDE): Consider the class of systems

$$\begin{cases} p_t = \mathcal{A}(p, p_x, p_{xx}, u, \vartheta)\vartheta \\ a_1 p_x(0,t) + a_2 p(0,t) = a_3 \\ a_4 p_x(L,t) + a_5 p(L,t) = a_6 \end{cases}$$

with distributed measurements of $p(x,t)$ and for which we want to estimate ϑ. Then

$$\|p(x,t) - \hat{p}(x,t)\|_2^2 = e^{-2(\gamma+\lambda)t}\|p(x,0) - \hat{p}(x,0)\|_2^2$$

if

$$\begin{cases} \hat{p}_t = \mathcal{A}(\hat{p}, \hat{p}_x, \hat{p}_{xx}, u, \hat{\vartheta})\hat{\vartheta} + \gamma(p - \hat{p}) \\ a_1 \hat{p}_x(0,t) + a_2 \hat{p}(0,t) = a_3 \\ a_4 \hat{p}_x(L,t) + a_5 \hat{p}(L,t) = a_6 \\ \dot{\hat{\vartheta}} = \mathcal{A}(\hat{p}, \hat{p}_x, \hat{p}_{xx}, u, \hat{\vartheta})^{\dagger}[p_t + \lambda(p - \hat{p})] \end{cases}$$

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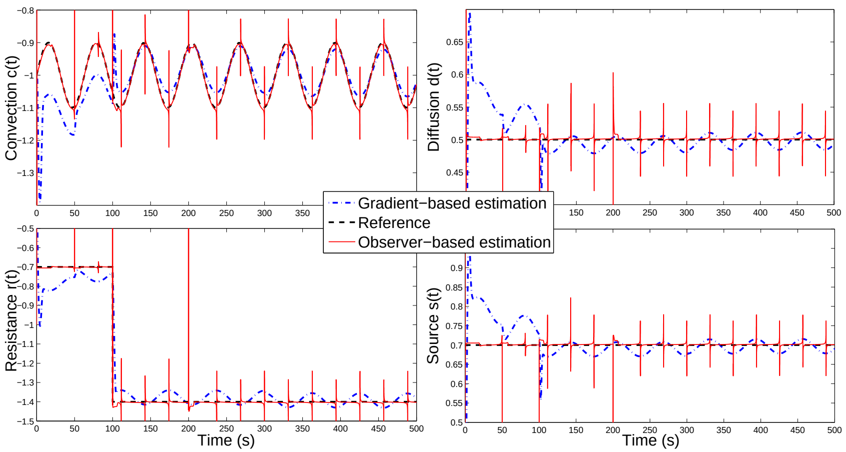
Example: comparison with gradient-descent algorithm

$$p_t = d(t)p_{xx} + c(t)p_x + r(t)p + s(t)p_{ext}(x,t)$$



$\Rightarrow$ very accurate results, need to add a filter.

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Time-delay model

Consider the convective-resistive flow:

$$p_t(x,t) - c(t)p_x(x,t) = r(t)p(x,t)$$

with $p(0,t) = u(t)$, $p(x,0) = \psi(x)$. Applying the method of characteristics with the new independent variable θ as

$$p(\theta) \doteq p(x(\theta), t(\theta))$$

It follows that (solution including time axis)

$$p(L,t) \doteq u(t-\theta_f)exp\left(\int_0^{\theta_f} r(\eta)d\eta\right) \text{ with } L = -\int_{t-\theta_f}^{t} c(\eta)d\eta$$

The average pressure $\xi(t) \doteq \int_0^L p(\eta,t)d\eta$ is provided by the Delay Differential Equation

$$\frac{d}{dt}\xi = -c(t)\left[u(t) - u(t-\theta_f)exp\left(\int_0^{\theta_f} r(\eta)d\eta\right)\right] + r(t)\xi(t)$$

Conclusions

- Physical model provided by a nonlinear coupled partial differential equation, but provides physical understanding
- Physics can be partly conserved using energy-based model reduction
- Volume-averaging provides the model structure for estimators / feedback strategies
- Flow convection represented by time-delays

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UFR de Physique

Mining Ventilation Control

Lesson 5: Extraction rooms air quality model

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Universidad Pedagógica y Tecnológica de Colombia, Sogamoso, April 3, 2013

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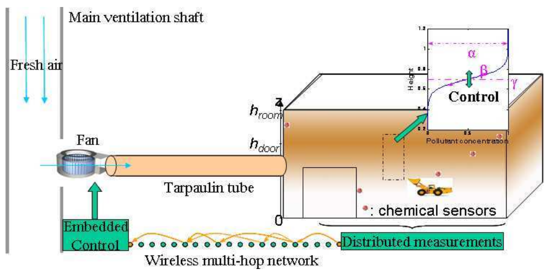
Stratified flows



- Unknown environements
- WSN automation
- Global conservation constraints - 0/1 D modeling

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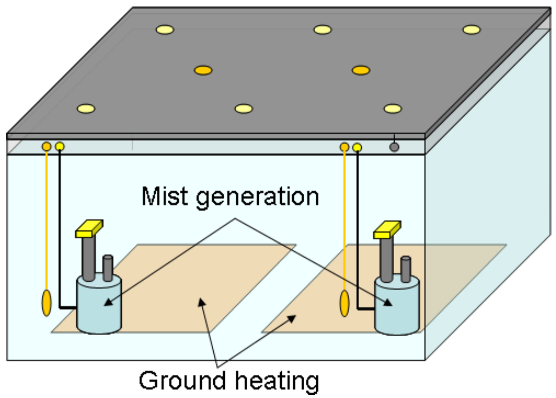
Stratified flows and forced plumes

- Air/mist experiment for qualitative behavior



- relatively slow process
- clear stratification when different gravities
- extendable to temperature variation effect

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Outline

1. Gas dynamics in chamber-like mine workings
2. Fluid statics: buoyancy force
3. Stratified flows and forced plumes
4. Constrained shape of the pollutants profile
5. Peripheral dynamics induced by fans and tarpauline tubes

Gas dynamics in chamber-like mine workings [Kalabin et al., 1990]

- Estimates of the velocity field and turbulent viscosity over the volume of the underground chamber

⇒ analysis of the scattering and entrainment of harmful impurities by ventilation jets

- Complexity from recirculation regions and breakaway flows
- 2-D mathematical model provided by non-steady Navier-Stokes (turbulent & incompressible) + continuity:

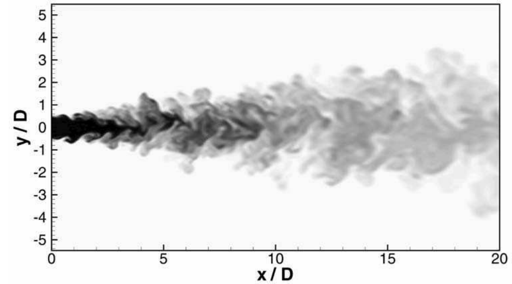
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{\rho}\left(\frac{\partial \tau_{11}}{\partial x} + \frac{\partial \tau_{12}}{\partial y}\right)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{\rho}\left(\frac{\partial \tau_{21}}{\partial x} + \frac{\partial \tau_{22}}{\partial y}\right)$$

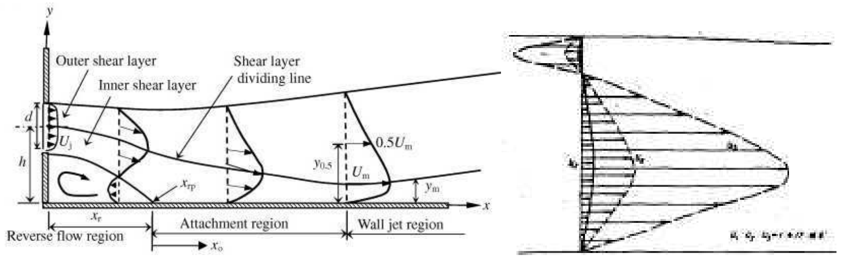
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

where τ_{ij} is the Reynolds stress (viscosity-dependent).

Turbulence in jets



https://engineering.purdue.edu/Engr/AboutUs/News/Publications/EngEdge/2002/environment_spotlight_



Offset jets [Agelin-Chaab & Tachie, 2011] (left) and jets in rooms (right)

The importance of turbulence control

Turbulent viscosity ν_t

1. Simplest model: ν_t constant for recirculation regions and near-wall interactions
2. Small-scale motion of subgrid scale (Smagorinskii): effective viscosity in terms of mean flow characteristics, numerical determination
3. $(k - L)$: add turbulent kinetic energy k

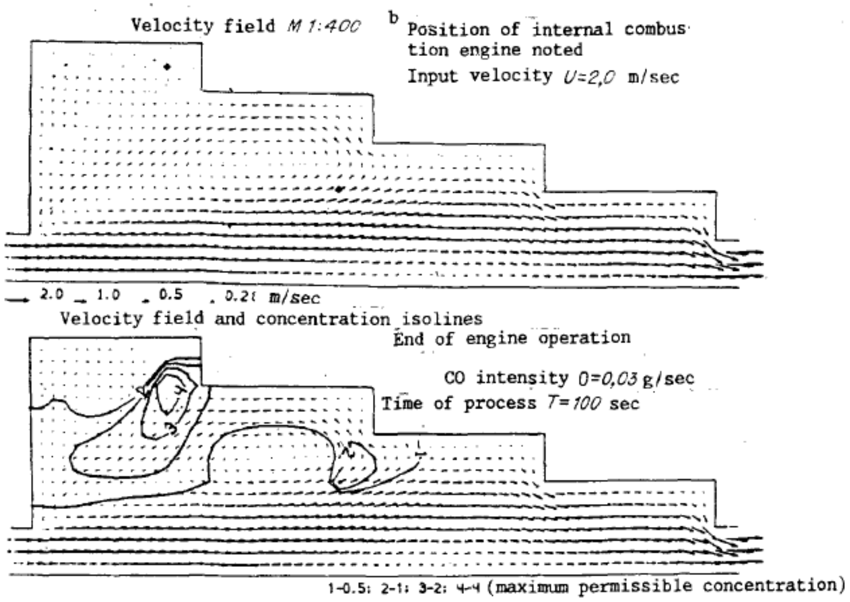
$$\frac{\partial k}{\partial t} + u\frac{\partial k}{\partial x} + v\frac{\partial k}{\partial y} = \frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial y}\right) + \nu_t G + \frac{C_D k^{3/2}}{L}$$

where G = turbulent energy generation, L = scale of turbulence (transverse vortices), σ_k - C_D = numerical constant, $\nu_t = C_\mu \sqrt{k}L$ where $C_\mu \approx 1$.

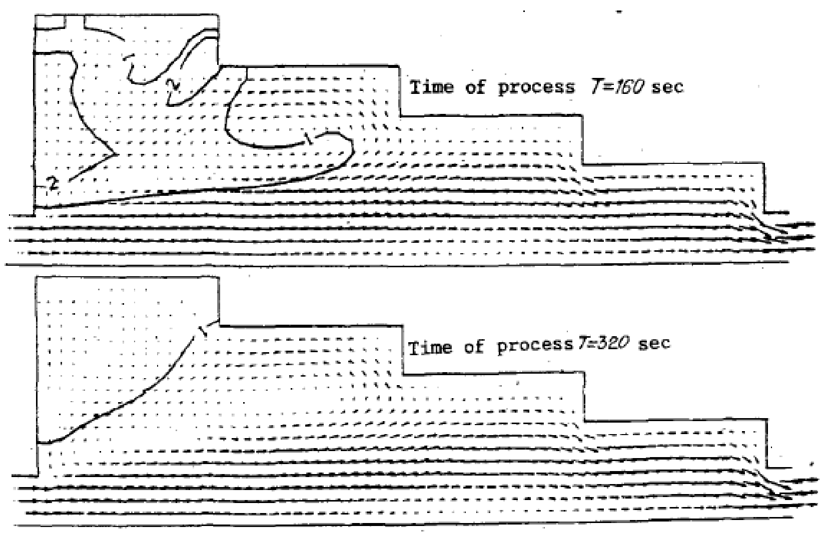
4. Standard $(k - \epsilon)$: add energy dissipation rate ϵ and solve 2 transport equations

+ appropriate boundary conditions

Example: $(k-\epsilon)$ after trucks CO pollution



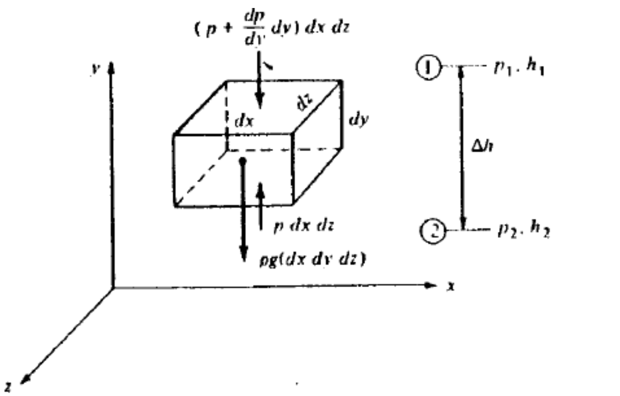
Example: $(k-\epsilon)$ after trucks CO pollution (2)



Fluid statics and buoyancy force

[Anderson, 1991]

- Def.: force applied on the fluid in statics
- On an infinitesimal element:



Net pressure force

$$= dp\,(dx\,dz)$$

$$-\left(p + \frac{dp}{dy}dy\right)(dx\,dz)$$

$$= -\frac{dp}{dy}(dx\,dy\,dz)$$

Gravity force

$$= -\rho(dx\,dy\,dz)g$$

$$\Rightarrow \text{Sum of forces} = 0 \quad = \quad -\frac{dp}{dy}(dx\,dy\,dz) - \rho(dx\,dy\,dz)g$$

Provides the Hydrostatic equation $dp = -\rho g dy$

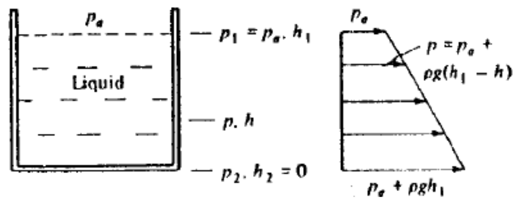
Hydrostatic equation (2)

Integral form:

$$\int_{p_1}^{p_2} dp = -\rho g \int_{h_1}^{h_2} dy \Leftrightarrow p_2 + \rho g h_2 = p_1 + \rho g h_1$$

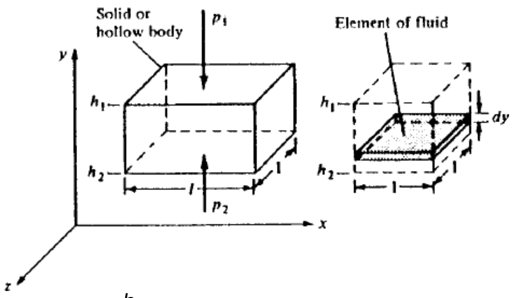
$$\Leftrightarrow p + \rho g h = \text{constant}$$

e.g. on the walls of a container:



Buoyancy force

Consider a body immersed in a stagnant fluid (ρ can vary), i.e.



Force on body due to pressure:

$$F = (p_2 - p_1) l \times 1$$
$$= l(1) \int_{h_1}^{h_2} \rho g dy$$

Note: $\int_{h_1}^{h_2} \rho g dy$ = weight of a column of unit area and height $(h_1 - h_2)$, and F = weight of l columns side by side. Consequently (Archimedes principle):

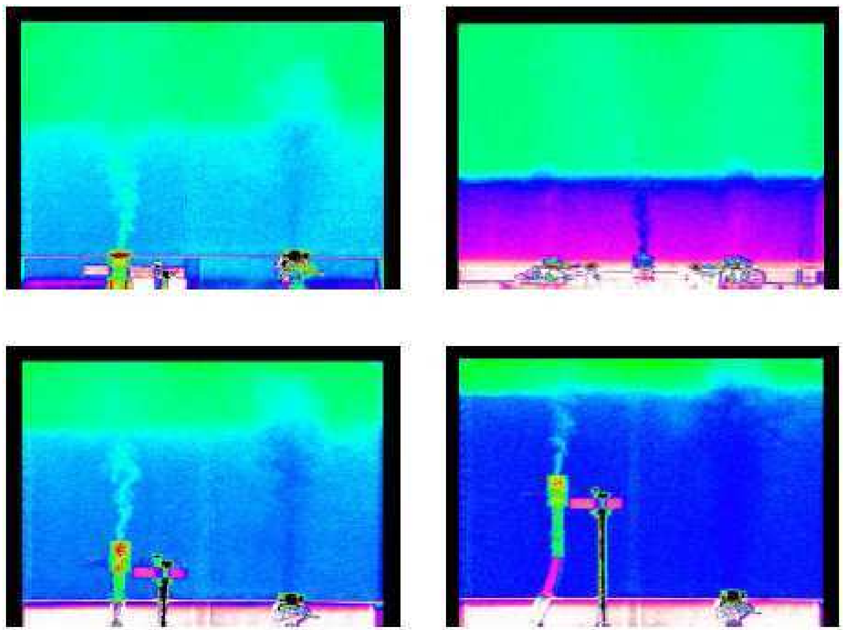
Buoyance force on body = weight of fluid displaced by body

Stratified flows and forced plumes

[Liu & Linden, 2006]

- Heat source represented as a buoyant plume in a stratified (layered) environment [Morton, Taylor & Turner, 1956, Yih 1969]
- Based on entrainement coefficients [Linden, Lane-Serff & Smeed, 1990]
- Air "thrown" with an initial momentum and higher temperature settles by negative buoyancy

Experiment: 1 heat source + 1-2 diffusers



Plume equations

- Flow above heat source = plume with buoyancy B, mean radius b, vertical velocity $w(r, z)$ and reduced gravity $g' = g(\rho_0 - \rho)/\rho_s \propto (T - T_0)$, where ρ_s = reference, ρ_0 = ambient and ρ = plume densities
- Entrainment assumption [Morton'58]: the rate of entrainment at the edge of a plume $\propto$ vertical velocity at that height:
  - gaussian distributions of vertical velocity $w(r, z) = \bar{w}(z)e^{-r^2/b^2}$, and mean buoyancy $g'(r, z) = \bar{g}'(z)e^{-r^2/\lambda^2 b^2}$, with characteristic length-scales b and λ
  - resulting static space distributions:

$$\frac{d}{dz}(b^2\bar{w}) = 2\alpha b\bar{w}, \quad \frac{d}{dz}(b^2\bar{w}^2) = 2\lambda^2 b^2 \bar{g}', \quad \frac{d}{dz}(\lambda^2 b^2 \bar{w}\bar{g}') = 0$$

where α = entrainment coef of the plume. Can be solved analytically.

Fountain equations

- Fountain: flow from diffuser = negatively-buoyant turbulent jet which rises a certain height until the negative buoyancy reduces its upward momentum → 0. Then the flow reverses and falls down in an annular region outside the rising jet [Turner 1966].
- Non-dimensional variables based on the initial source volume flux Q_0, momentum flux M_0 and buoyancy flux F_0 of the fountain:

$$\tilde{z} = M_0^{-3/4} F_0^{1/2} z,\ \tilde{b} = M_0^{-3/4} F_0^{1/2} b,\ \tilde{u} = M_0^{1/4} F_0^{-1/2} \bar{w},\ \tilde{g}' = M_0^{5/4} F_0^{-3/2} \bar{g}'$$

defining the dimensionless fluxes of volume $\tilde{Q} = \tilde{b}^2\tilde{u}$, momentum $\tilde{M} = \tilde{b}^2\tilde{u}^2$, and buoyancy $\tilde{F} = \tilde{b}^2\tilde{u}\tilde{g}'$:

$$\frac{d}{d\tilde{z}}(\tilde{b}^2\tilde{u}) = 2\alpha_f \tilde{b}\tilde{u},\ \frac{d}{d\tilde{z}}(\tilde{b}^2\tilde{u}^2) = 2\lambda^2\tilde{b}^2\tilde{g}',\ \frac{d}{d\tilde{z}}(\lambda^2\tilde{b}^2\tilde{u}\tilde{g}') = 0$$

where α_f = entrainment coef of the fountain.

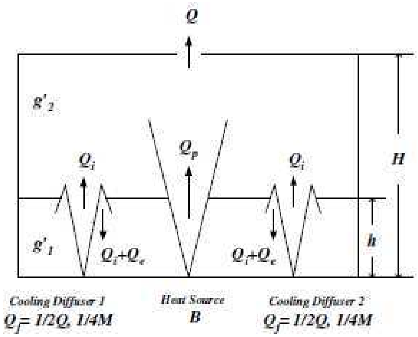
Additional issues for the interface

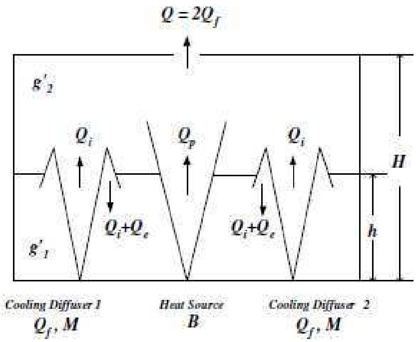
- 2-layers stratification hypothesis from experimental observations
- penetrative entrained volume flux Q_e across density interface $\propto$ impinging volume flux Q_i at density interface: $Q_e = Q_i E$ where E = penetrative entrainement rate

Fixed heat load and total ventilation rate

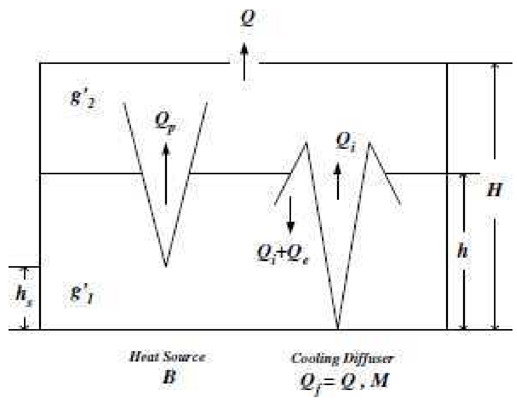
- Consider the effect of multiple diffusers of the same air
- For one diffuser/heat source:
  - at interface height h, plume and each fountain carry Q_p and Q_i, respectively
  - an amount of upper layer fluid Q_e is entrained back into the lower layer by the fountain above each cooling diffuser

  ⇒ net flow rate Q = total ventilation rate through the system.
- Multiple diffusers (n): momentum divided by n^2 if same flux source





Elevated heat source

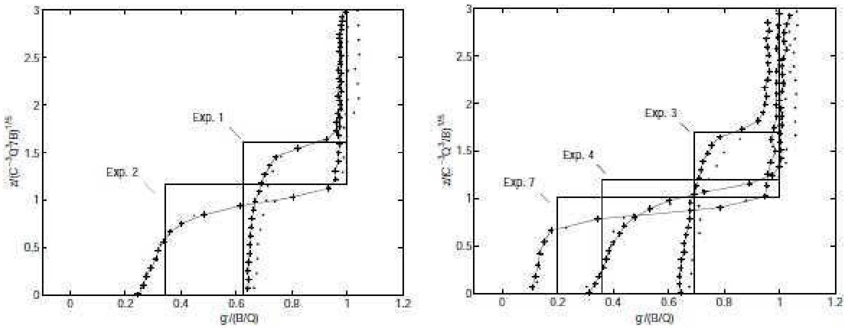


Addapt the fow computation by including the distance of the interface from the flow origin $(h - h_s)$:

$$Q_p = C[B(h - h_s)^5]^{1/3}$$

Experimental results

- Dyed salt solution injected in clear rectangular tanks filled with fresh water. Measurements at steady-state.
- Buoyancy profiles with multiple diffusers with fixed heat load and ventilation rate:



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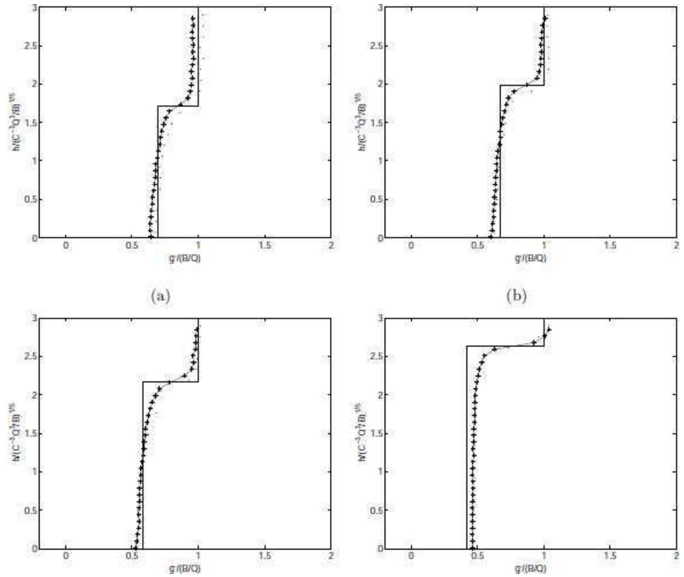
Experimental results (2): sources at different heights



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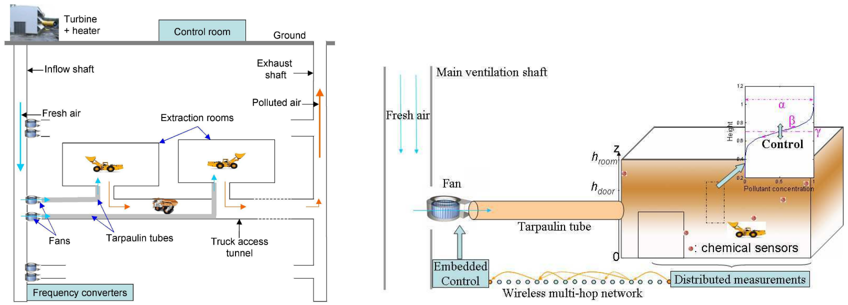
Constrained shape of the pollutants profile [Witrant et al., 2010]



- Seek model simplifications based on measurements from a wireless sensor network
- Constrain the dynamics from global (0-D) conservation laws
- Use an heuristic approximation of concentration distributions

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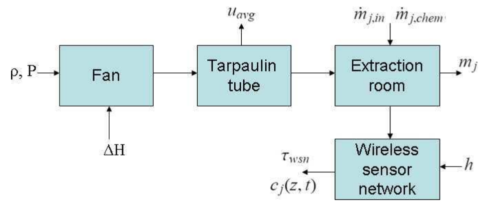
Problem structure

- Division into subsystems:
  - fan / tarpaulin tube / extraction room / wireless sensor network.
- Corresponding block diagram:



Main variables

- Inputs to the system:
  - ρ: air density in vertical shaft;
  - P: air pressure in vertical shaft;
  - ΔH: variation of pressure produced by the fan;
  - $\dot{m}_{j,in}$: incoming pollutant mass rate due to the engines;
  - $\dot{m}_{j,chem}$: mass variation due to chemical reactions between components;
  - h: time-varying number of hops in WSN.
- Outputs from the system:
  - $c_j(z,t)$ pollutants (CO_x or NO_x) volume concentration profiles, where $z \in [0; h_{room}]$ is the height in the extraction room;
  - u_{avg} is the average velocity of the fluid in the tarpaulin tube;
  - m_j pollutant mass in the room;
  - τ_{wsn} delay due to the distributed measurements and wireless transmission between the extraction room and the fan.

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Basic equations for the concentration profiles

- Conservation law: conservation of mass

$$\dot{m}_j(t) = \dot{m}_{j,in}(t) - \dot{m}_{j,out}(t) - \dot{m}_{j,chem}(t)$$

- Constitutive relationship:

$$\begin{aligned} m_j(t) &= S_{room}\int_0^{h_{room}} c_j(z,t)dz \\ &= S_{room}\left[\int_0^{h_{door}} c_j(z,t)dz + \alpha_j(t)\Delta h\right], \end{aligned}$$

and hypothesis

$$c_j(z,t) = \frac{\alpha_j(t)}{1+e^{-\beta_j(t)(z-\gamma_j(t))}}.$$

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Basic equations for the concentration profiles (2)

The mass conservation equation sets the shape parameters dynamics with:

$$\begin{aligned} \dot{m}_j(t) &\approx S_{room}\left[\int_0^{h_{door}} \dot{c}_j(z,t)dz + \dot{\alpha}_j(t)\Delta h\right], \\ \dot{m}_{j,out}(t) &\approx \frac{Q_{out}}{h_{door}}\int_0^{h_{door}} c_j(z,t)dz, \\ \dot{m}_{j,chem}(t) &= S_{room}\left[\int_0^{h_{door}} \nu_{jk}c_j(z,t)c_k(z,t)dz + \nu_{jk}\alpha_j(t)\alpha_k(t)\Delta h\right], \end{aligned}$$

where $Q_{out} = S_t\,\eta u_{fan}(t-\tau_{tarp})$ is the volume rate of flow leaving the room = Q_{in} and $\nu_{jk} = -\nu_{kj}$ is the chemical reaction rate

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Extraction room model

- shape parameters α, β and γ chosen as the state: $x(t) = [\alpha,\ \beta,\ \gamma]^T$;
- time derivative from mass conservation:

$$E_j\begin{bmatrix}\dot{\alpha}_j(t)\\ \dot{\beta}_j(t)\\ \dot{\gamma}_j(t)\end{bmatrix} = \dot{m}_{j,in}(t) - B_j\,u_{fan}(t-\tau_{tarp}) - D_{jk},\ \text{with}$$

$$E_j \doteq S_{room}\left(V_{int}\begin{bmatrix}\vdots & \vdots & \vdots\\ \frac{\partial C_{j,i}}{\partial \alpha_j} & \frac{\partial C_{j,i}}{\partial \beta_j} & \frac{\partial C_{j,i}}{\partial \gamma_j}\\ \vdots & \vdots & \vdots\end{bmatrix} + \begin{bmatrix}\Delta h\\ 0\\ 0\end{bmatrix}^T\right)$$

$$B_j \doteq \frac{1}{h_{door}}V_{int}\begin{bmatrix}\vdots\\ C_{j,i}\\ \vdots\end{bmatrix}\times S_{tarp}\,\nu,\ D_{jk} = S_{room}\left[V_{int}\begin{bmatrix}\vdots\\ \eta_{jk,i}\,C_{j,i}\,C_{k,i}\\ \vdots\end{bmatrix} + \eta_{jk}\alpha_j\alpha_k\Delta h\right]$$

Peripheral dynamics (fans, tubes and network) [Witrant et al., 2010]

Simplified model obtained considering:

- Physical delay + energy losses for the tarpauline tube
- A locally regulated fan
- Network delay + packet losses for the wireless sensor network

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Physical delay in the tarpauline tube

- Simplified flow transport equation:

$$\frac{\partial}{\partial t}\begin{bmatrix} u \\ T_{tarp} \end{bmatrix} + \begin{bmatrix} u & r \\ \gamma T_{tarp} & u \end{bmatrix} \frac{\partial}{\partial x}\begin{bmatrix} u \\ T_{tarp} \end{bmatrix} = 0,$$

where $r = 287.045\ J/kg.K$ is the air gas constant and $\gamma = 1.4$ is the ratio of specific heat coefficients.

- Characteristic velocities $v(x,t)$ of the traveling waves:

$$\det\begin{vmatrix} -v+u & r \\ \gamma T_{tarp} & -v+u \end{vmatrix} = 0 \quad \Leftrightarrow \quad v_{1,2}(x,t) = u(x,t) \pm \sqrt{r\gamma T_{tarp}(x,t)}.$$

- Down-flow time-delay approximated as:

$\tau_{tarp}(t) \approx \dfrac{L_t}{\bar{u}(t) + \sqrt{r\gamma \bar{T}_{tarp}(t)}}$, where L_t is the length of the tarpaulin tube, $\bar{u}(t)$ and $\bar{T}_{tarp}(t)$ are the space-averaged flow speed and temperature, respectively.

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Energy losses in the tarpauline tube

- Loss of airflow energy due to curves (concentrated losses ξ_c) and length (distributed losses ξ_d)
- Conservation of energy (Bernoulli's equation, incompressible):

$$P_{fan} - P_{room} = \rho\Delta H = \xi_d + \xi_c + \rho\frac{u_{room}^2}{2} - \rho\frac{u_{fan}^2}{2},$$

  - Darcy-Weisbach eqn: $\xi_d = L_t \rho u_{avg}^2 f/(2D_t)$, where D_t = tube diameter, f = friction losses, u_{avg} = average velocity of the fluid in the tube.
  - ξ_c introduced by the curves considering an *effective* length $L_e = \sigma L_t$, $\sigma > 1$ depends on curvature and diameter of the tube $\Rightarrow \xi_d + \xi_c = L_e \rho u_{fan}^2 f/(2D_t)$
  - friction for turbulent flow (i.e. high Reynolds number Re):

$$f = (1.82\log_{10} Re - 1.64)^{-2} \Rightarrow \xi = \xi_d + \xi_c = \frac{1}{2}\frac{L_e}{D_t}\rho\left(\frac{u_{fan}}{1.82\log_{10} Re - 1.64}\right)^2$$

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Energy losses in the tarpauline tube (2)

- Supposing $2\Delta H/(\rho u_{fan}^2) << 1$ (reasonable for incompressible flow) and solving for $u_{room}(t)$:

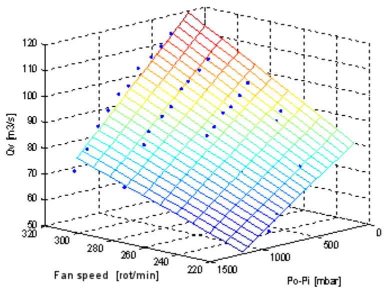
$$u_{room}(t) \approx \eta \times u_{fan}(t - \tau_{tarp}),$$

$$\eta \doteq \sqrt{1 - \frac{\sigma L_t}{D_t}\left(\frac{1}{1.82\ln Re - 1.64}\right)^2},$$

where $\eta < 1$ represents the energy losses associated with the tarpaulin tube and $Re \approx 67280 D_t \times u_{fan}$.

Locally regulated fan

Typical models involve complex datamaps:



Alternative: three-phase asynchronous motor model with fan as load to determine the fan power consumption [Krause, 1986].

Main principle:

- Let n_2 be the speed of the motor, then: $n_2 = \frac{60 f_1}{p}(1-s)$ where f_1 = supply frequency and p = number of motor winding poles.
- slip factor of the motor is defined as $s \doteq (n_1 - n_2)/n_1$, where n_1 is the speed of the rotating magnetic field.
- Local feedback control loop set by varying the supply frequency while maintaining a constant voltage-frequency ratio: scalar V/Hz control

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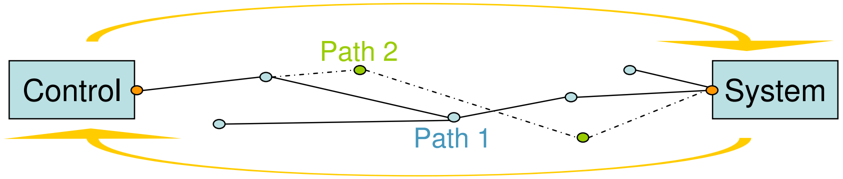
Wireless sensor networks



Network characteristics:

- time-varying channel and network topology;
- dynamic selection of $h(t)$ hops;
- next node ensures progress toward destination;
- i.e. random sleep to save energy.

Delay associated with each node i:

- α_i: time to wait before sending a packet (random);
- F: propagation and transmission;
- β_i: Automatic Repeat reQuest (ARQ): retransmission;

$$\Rightarrow \tau(t) = h(t)F + \sum_{i=1}^{h(t)} (\alpha_i + \beta_i)$$

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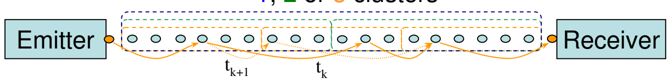
Clusters and dynamic selection of hops

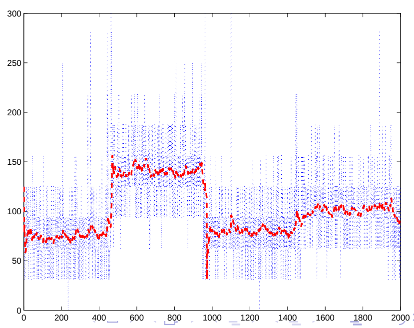


- Sleeping strategy depending on traffic and network conditions,
- Optimize energy consumption in a clustered environment [Bonivento & al.'06],

⇒ Dynamical organization in clusters [P.G. Park MS'07].

Three possible behaviors:

- Low freq. = changes in the number of clusters,
- Medium freq. = node selection within a cluster,
- High freq. = transmissions between nodes.



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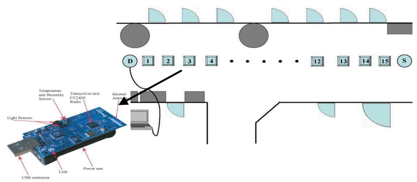
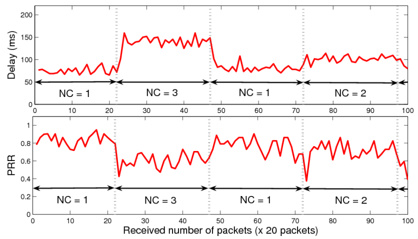
Network setup and experimental measurements



- Tmotes Sky nodes
  - radio controller Chipcon CC2420 (2.4GHz)
  - IEEE 802.15.4

- 20 packets/s
- Randomized Protocol



Conclusions

- Aerodynamics in chambers driven by turbulence vs. main flow
- Plumes and fountains lead to a stratified distribution
- Simplified grey-box model of the 2-layers profile
- Periferal dynamics included with energy losses (tube), time-delay (tube + network) and locally regulated fan

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UFR de Physique

MINING VENTILATION CONTROL

Lesson 6: Principals control strategies for mining ventilation

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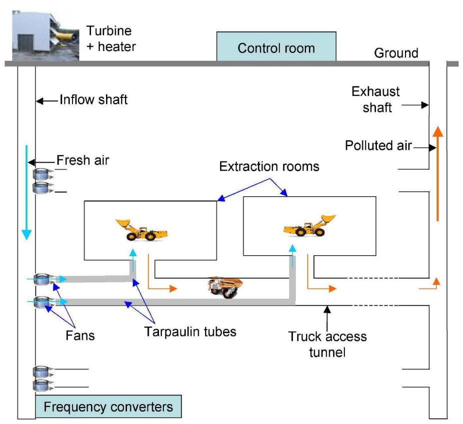
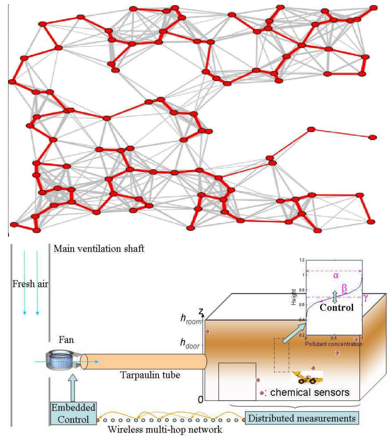
Universidad Pedagógica y Tecnológica de Colombia, Sogamoso, April 4, 2013

Motivation: 3 control problems in mining ventilation





Outline

1. Nonlinear control of the ventilation network
2. Distributed dynamics control in deep wells
3. Predictive and hybrid control of the extraction rooms

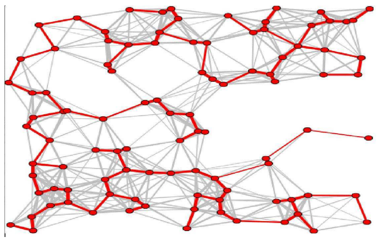
Control of the ventilation network

[Hu et al. 2003]

- Historically based on multivariable linear models (allows for classical control)
- New objective: exploit non-linear tools to prevent the sensitivity to operating conditions
- Two different control objectives:
  1. actuation in all branches of the network and global regulation
  2. actuation only in branches not belonging to the tree of the graph (independent, link branches) and regulation around the operating point
- System peculiarity: control inputs always multiplied by quadratic nonlinearities (cf. Lesson 3)

Design with controls in all branches

- Based on the link/tree partitionning (resp. c/a) with resistance (R_c and R_a) and fan pressure drop (d)
- R_a and d are auxiliary inputs (not necessary but improve efficiency) and R_c is sufficient to control the system



http://www.geeksforgeeks.org/applications-of-

Choose control laws as:

$$\begin{aligned} R_c &= (K_c Q_{cD}^2)^{-1}(K_c H_{cr} + \lambda Q_{ce}) \\ R_a &= (K_a Q_{aD}^2)^{-1}(K_a H_{ar} + \lambda Q_{ae}) \\ d &= H_{mr} + R_m Q_m \end{aligned}$$

where r = reference (equilibrium) values of controlled heads (m = fan branch); deviations from equilibrium quantities: $Q_{c/a\,e} = Q_{c/a} - Q_{c/a\,r}$; λ = constant; K = inverse of inertance.

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Theorem: closed-loop system properties and stability

For the system described by

$$\begin{aligned} \dot{Q} &= -K(I - Y_{RQ})Q_D^2 R + KY_Q Q + KY_d d \\ H &= Y_{RQ} Q_D R + Y_Q Q + Y_d d \end{aligned}$$

and the previous control laws, the following results hold:

i. $H(t) \doteq H_r = [H_{cr}^T,\ H_{ar}^T]^T$
ii. $Q = Q_r = [Q_{cr}^T,\ Q_{ar}^T]^T$ is exponentially stable
iii. suppose that $Q_i(0) \geq 0$, $Q_{ir} > 0$ and $\lambda < \min_i K_i R_{ir} Q_{ir}$, then $R_i(t) > 0$, $\forall t \geq 0$, where $i = 1, \ldots, n$.

Proof (main idea): use of the alebraic properties of the system, Kirchhoff's law and input-to-state linearization.
Note: $\min R$ = branch resistor when the actuator "door" is fully open.

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Design with controls in co-tree only

- Control objective using only R_c (constant R_a and d):

$$\begin{aligned} R_c &= (K_c Q_{cD}^2)^{-1}(K_c H_c + \lambda Q_{ce}) \\ R_a &= (K_a Q_{aD}^2)^{-1} K_a H_{ar} \\ d &= H_{mr} + R_m Q_{mr} \end{aligned}$$

- Implies the dynamics

$$\left.\begin{aligned} \dot{Q}_c &= -K_c Q_{cD}^2 R_c + K_c H_c \\ \dot{Q}_a &= -K_a Q_{aD}^2 R_a + K_a H_a \end{aligned}\right\} \Rightarrow \left\{\ \dot{Q}_c = -\lambda Q_{ce}\right.$$

Exponential stability is obtained BUT the constraint $R > 0$ may not be satisfied (need implementable feedback)

- Refined feedback ($\dot{Q}_a = \lambda E_{Q_c} Q_{ce}$ and model prop.):

$$\begin{aligned} R_c(Q_c) = &\ (K_c Q_{cD}^2)^{-1}[\lambda(I - K_c S_{H_a} K_a^{-1} E_{Q_c})Q_{ce} + K_c S_{H_a} Q_{aD}^2(Q_c) R_{ar} \\ &+ K_c S_d d_r - K_c R_m S_d e_{Q_{mc}} Q_c] \end{aligned}$$

where $e_{Q_{mc}}$ and S describe the connections topology.

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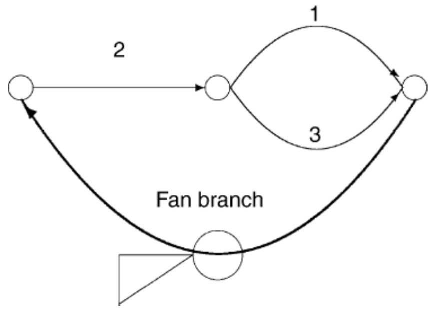
Theorem: feasibility region

Let $\mathcal{F} = \{Q_c \in R^{N-n_c+1} | Rci(Q_c) \geq R_{ci}^{min}, i = 1 \ldots N - n_c + 1\}$ be the feasible control set, where R_{ci}^{min} is the minimum feasible control values. Define also the set $B_r = \{\|Q_e\| \leq r\}$.
Let r^* be the largest r such that $B_r \in \mathcal{F}$.
Then, $Q = Q_r$ is exponentially stable with the region of attraction that includes B_{r^*}.

Proof (idea): exponential convergence from the analysis of the Lyapunov function $V = \frac{1}{2}\|Q_{ce}\|^2$.

Example: Mine ventilation networksystem with 4 branches



Model obtained by choosing branches 3 and *m* as the tree of the network

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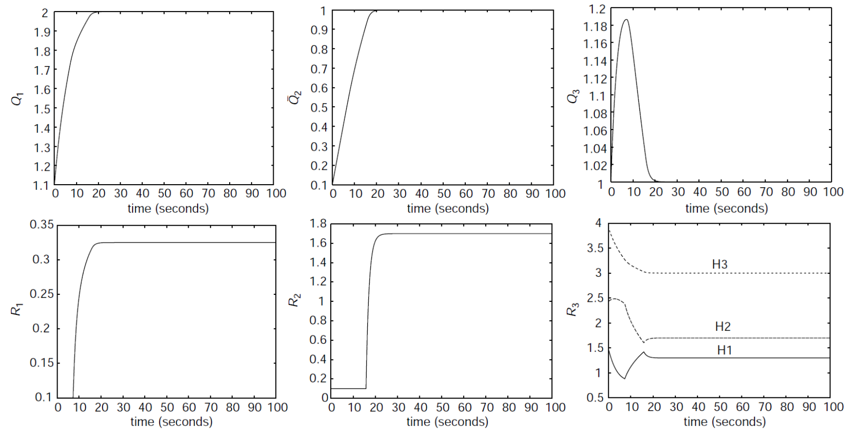
Example: without auxiliary controller



Disturbance due to actuator saturation but the controller eventually recovers to bring the system in its feasibility region.

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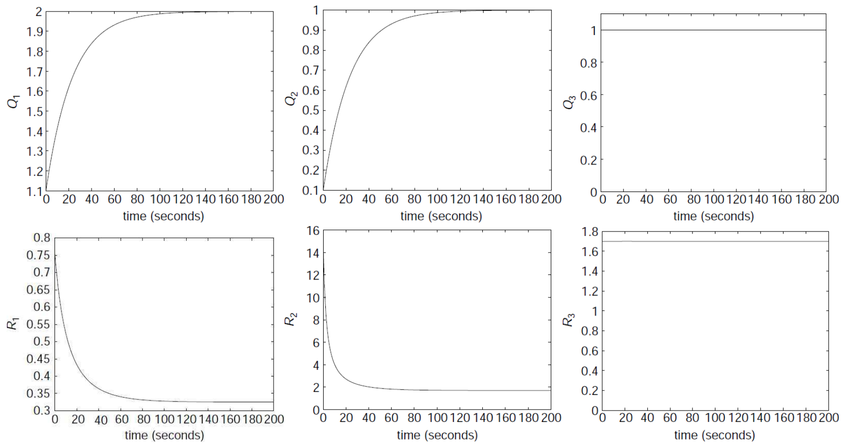
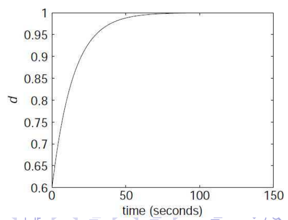
Example: with auxiliary controller



- due to particular choice of initial conditions (made to saturate the inputs in previous case), auxiliary control R_3 not active
- *d* allows R_1 and R_2 not to saturate
- *d* varies in wide range and R_1 and R_2 have trends opposite to previous case



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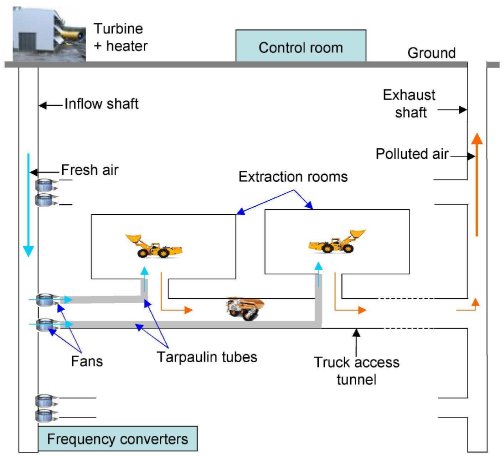
Controlling the distributed dynamics in deep wells: coping with convection and resistance



- Well known topology
- Essential impact of fluid dynamics
- Control air transport and energy dissipation
- Infinite-dimentional analysis (PDE, Time-delays)

Problem formulation

- Hypothesis 1: heater operated based on atmospheric conditions (i.e. external input) and regulated input = turbine downflow pressure (a local control loop is set on the turbine to adjust its rotational speed according to a desired pressure).
- Control problem: ensure a minimum pressure within the shaft (at each extraction level) based on the turbine actuation.
- As pressure $\nearrow$ as we go deeper, control = ensuring a minimum pressure at the bottom of the pit.
- Hypothesis 2: distributed pressure measurements are available to set a state feedback control law.

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Fast model predictive control (MPC): principles [W. & Marchand 2008]

- Predictive control: widely used in process industry for its robustness and slow dynamics of the processes.
  - + Control of multi-variable coupled dynamical systems
  - + Handling constraints on the state and on the control input
  - + Express optimality concerns
  - + Conceptually easy handling of nonlinearities in the system model.
  - - Find the extremum of an optimization problem that can hardly be guaranteed (i.e. for PDEs).
- Fast MPC: enables an analytical solution to the predictive control problem without any optimization by using the structure of the system.

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Fast MPC for pressure distribution

Hyp.: slowly varying coeff. and neglect diffusion $\Rightarrow$ $p_t(x,t) = cp_x(x,t) + rp(x,t) + sp_{ext}(x)$. MPC =

- find an open-loop control profile $\tau \rightarrow p(0,\tau)$ at t such that the solution of the dynamical system has "some" properties (e.g. stability, robustness, optimality ...) on a time horizon $[t, t+w]$ where w is the prediction horizon (may be ∞)
- open-loop control profile applied at its first instant $p(0,0)$ and the scheme is repeated at the next time instant $t + dt$.
- control objective: give inflow pressure control profile $p(0,\tau)$ to ensure a given down pressure $p(L,\infty)$ in closed loop;
- once steady state achieved, a corresponding constant inflow pressure $p(0,\infty)$ ensures the desired down pressure $p(L,\infty)$
- hyp. at t: start with some constant initial inflow $p(0,t)$, $p(L,t)$ at the bottom and an established steady state pressure profile:

$$p_{st}(x,p_0) = p_0 e^{-\frac{r}{c}x} - \frac{s}{c}\int_0^x e^{-\frac{r}{c}(x-z)} p_{ext}(z)dz$$

Note: $p(L,\infty) = p_{st}(L, p(0,\infty))$ and, as soon as the system is in a steady state regime at t, $p(L,t) = p_{st}(L, p(0,t))$.

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Fast MPC for pressure distribution (2)

Approximate the pressure open-loop (OL) profile $p(x, t+\tau)$, $\tau \in [0, +\infty]$, by:

$$\tilde{p}(x, t+\tau) = pe^{-\alpha x} e^{-\beta\tau} + p_{st}(x, p(0,\infty))$$

- when $\tau \nearrow$, $\tilde{p}(x, t+\tau) \rightarrow p_{st}$ that ensures desired $p(L,\infty)$
- at t ($\tau = 0$), take: $p = e^{\alpha L}[p(L,t) - p_{st}(L, p(0,\infty))]$ to ensure the initial condition at $x = L$
- to ensure $\tilde{p}$ solution of the PDE, impose $\beta = \alpha c - r$.

α is a free parameter, but:

- $\alpha > r/c$ necessary: OL trajectory $\rightarrow p(L,\infty)$
- convergence speed $\propto^{-1}$ difference between α and r/c
- the closer α is to r/c, the closer $\tilde{p}(x,t)$ is to $p(x,t)$ (exact solution of PDE)

Resulting OL control law at t $\forall \tau > 0$, is therefore:

$$\begin{aligned} \tilde{p}(0, t+\tau) &= (p(L,t) - p(L,\infty))\, e^{-\alpha(x-L)} e^{-\beta\tau} + p(0,\infty) \\ p(0,\infty) &= e^{\frac{r}{c}L}\left[p(L,\infty) + \frac{s}{c}\int_0^L e^{-\frac{r}{c}(L-z)} p_{ext}(z)dz\right] \end{aligned}$$

Simulation results

- Two scenarii are compared:
  1. the inflow pressure is set at some value that ensures a down pressure of 1 *hPa* for the initial ventilation topology;
  2. the inflow pressure is automatically computed and adapted online according to the above control law using the down pressure measurement.
- In both cases, consider test case in Lesson 4 with 2^nd level fan operated at $t = 1000\,s$ instead of $t = 2000\,s$.
- Control not directly set on the system but acts as a reference to the turbine outflow pressure (shaft inflow pressure set using the corresponding turbine speed by means of a local PI control law on the turbine).

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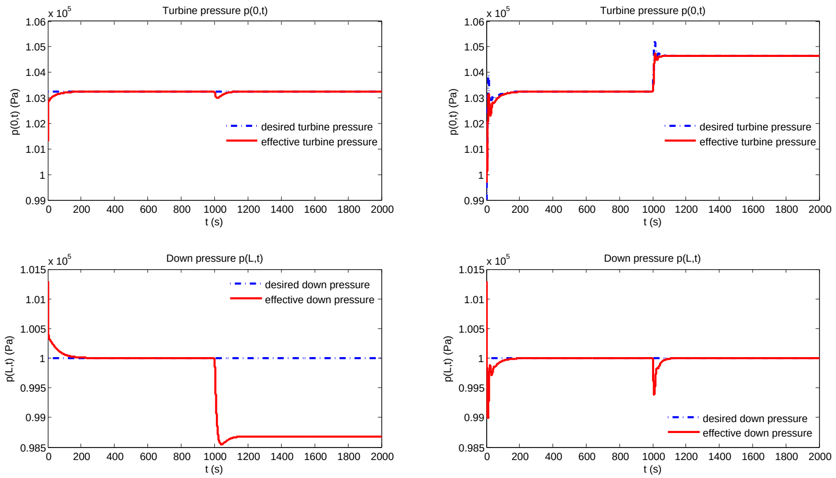
Simulation results (2)



Down pressure regulation in a mine with (right) and without (left) fast predictive control

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Time-delay compensation approach [W. & Niculescu, 2010]

- Recall from Lesson 4: convective-resistive flow modelled with a delay (functional) differential equation
- Control objective: design a feedback such that the average distributed pressure $\bar{p}(t) = \frac{1}{L}\int_0^L p(x,t)dx$ tracks reference $\bar{p}_r(t)$, with

$$\dot{\bar{p}}(t) = -\frac{c(t)}{L}\left[u(t) - u(t-\theta_f)exp\left(\int_0^{\theta_f} r(\eta)d\eta\right)\right] + r(t)\bar{p}(t).$$

- Achieved if (fixed point theorem): $\dot{\bar{p}}(t) - \dot{\bar{p}}_r(t) + \lambda(\bar{p}(t) - \bar{p}_r(t)) = 0$
- Using the previous DDE and solving for $u(t)$, it follows that

$$u(t) = \frac{L}{c(t)}\left[r(t)\bar{p}(t) + \lambda(\bar{p}(t) - \bar{p}_r)\right] + p(L,t)$$

ensures $|\bar{p}(t) - \bar{p}_r| = |\bar{p}(0) - \bar{p}_r|e^{-\lambda t}$

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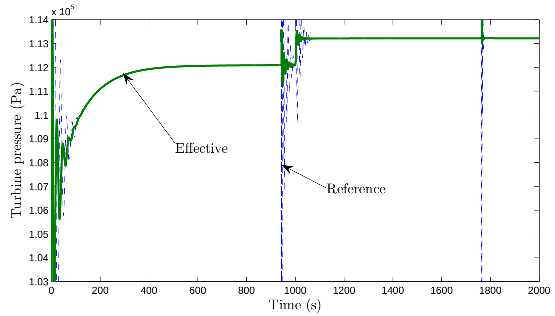
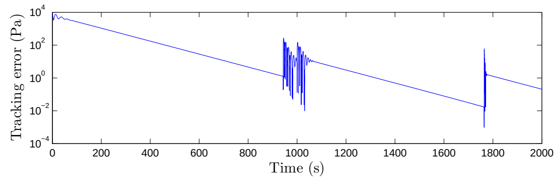
Application to the mine ventilation process

Reference and effective (filtered) turbine output pressure:

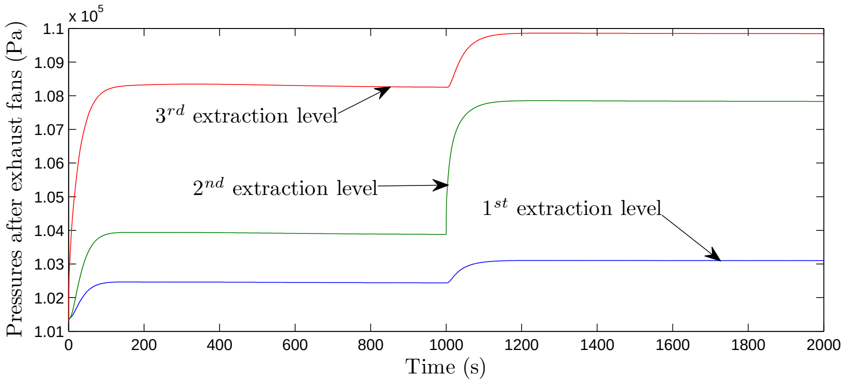


Feedback tracking error:



$\Rightarrow$ Sensitivity to initial conditions and some numerical integration errors but exponential convergence verified!

Application to the mine ventilation process ($\bar{p}_r = 1.1\ hPa$)



Pressures provided to the extraction rooms at the three levels.

Dynamic Boundary Stabilization of Quasi-Linear Hyperbolic Systems [Castillo, W., Prieur, Dugard, 2012]

Let n be a positive integer and Ω be an open non-empty convex set of $\mathbb{R}^n$. Consider the general class of strict quasi-linear hyperbolic systems of order n defined as follows:

$$\partial_t s(x,t) + F(s(x,t))\partial_x s(x,t) = 0 \qquad (1)$$

where $s(x,t) \in \Omega$ and $F : \Omega \to \mathbb{R}^{n\times n}$ (continuously differentiable function). Consider system (1) in Riemann coordinates (coupled transport equations):

$$\partial_t \xi(x,t) + \Lambda(\xi)\partial_x \xi(x,t) = 0 \quad \forall\, x \in [0,1], t \geq 0$$

where $\xi \in \Theta$, Λ is a diagonal matrix function $\Lambda : \Theta \to \mathbb{R}^{n\times n}$ such that $\Lambda(\xi) = diag(\lambda_1(\xi), \lambda_2(\xi), ..., \lambda_n(\xi))$ with

$$\underbrace{\lambda_1(\xi) < ... < \lambda_m(\xi)}_{\xi_-} < 0 < \underbrace{\lambda_{m+1}(\xi) < ... < \lambda_n(\xi)}_{\xi_+}, \quad \forall\, \xi \in \Theta$$

Boundary Conditions

State partition: $\xi = \begin{bmatrix} \xi_- & \xi_+ \end{bmatrix}^T$ where $\xi_- \in \mathbb{R}^m$ and $\xi_+ \in \mathbb{R}^{n-m}$.
Most approaches consider the following static boundary control for (**??**):

$$\underbrace{\begin{pmatrix} \xi_-(1,t) \\ \xi_+(0,t) \end{pmatrix}}_{Y_c} = G \underbrace{\begin{pmatrix} \xi_-(0,t) \\ \xi_+(1,t) \end{pmatrix}}_{Y_\xi}$$

where the map $G : \mathbb{R}^{n\times n} \to \mathbb{R}^{n\times n}$ vanishes at 0.
Instead, we consider the dynamic boundary conditions defined:

$$\begin{aligned} \dot{X}_c &= A\,X_c + B\,K\,Y_\xi \\ Y_c &= X_c \end{aligned} \qquad (2)$$

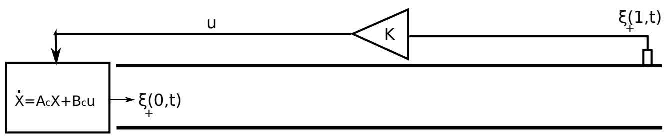
where $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times n}$ are given matrices and $K \in \mathbb{R}^{n\times n}$ is to be designed

Initial Condition

- Consider that there exists a $\delta_0 > 0$ and a continuously differentiable function $\xi^0 : [0,1] \to \Theta$ that satisfies the zero-order and one-order compatibility conditions such that $|\xi^0|_{H^2((0,1,R^n))} < \delta_0$. Then, the initial condition can be defined for system (1) as:

$$\xi(x,0) = \xi^0(x), \quad X_c(0) = X_c^0, \quad \forall\, x \in [0,1] \qquad (3)$$

- The control problem is to find a control gain K such that the system (1) with the boundary condition (2) is Lyapunov stable $\forall\, \xi \in \Xi \subseteq \Theta$.



Theorem: exponential stability

Consider the system (1) with BC (2) and IC (3). Assume that there exists a diagonal positive definite matrix $Q \in \mathbb{R}^{n\times n}$ and a matrix $Y \in \mathbb{R}^{n\times n}$ such that the following LMI is satisfied $\forall i \in [1, ..., N_\varphi]$

$$\begin{bmatrix} QA^T + AQ + \Lambda(w_i)Q & BY \\ Y^T B^T & -\Lambda(w_i)Q \end{bmatrix} \prec 0$$

Let $K = YQ^{-1}$, then there exist two constants $\alpha > 0$ and $M > 0$ such that, for all continuously differentiable functions $\xi^0 : [0,1] \to \Xi$ satisfying the zero-order and one-order compatibility conditions, the solution of (1), (2) and (3) satisfies, for all $t \geq 0$,

$$\|X_c(t)\|^2 + \|\xi(x,t)\|_{L^2(0,1)} \leq Me^{-\alpha t}\left(\|X_c^0\|^2 + \|\xi^0(x)\|_{L^2(0,1)}\right)$$

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Euler Equations

Consider the Euler equations (quasi-linear hyperbolic system) expressed in terms of the primitive variables (density (ρ), velocity (u) and pressure (p)):

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{A(V)}\frac{\partial \mathbf{V}}{\partial x} + \mathbf{C(V)} = 0$$

$$\mathbf{V} = \begin{bmatrix} \rho \\ u \\ p \end{bmatrix}; \mathbf{A} = \begin{bmatrix} u & \rho & 0 \\ 0 & u & \frac{1}{\rho} \\ 0 & a^2\rho & u \end{bmatrix}; \mathbf{C} = \begin{bmatrix} 0 \\ G \\ (\gamma - 1)\rho(q + uG) \end{bmatrix}$$

$a = \sqrt{\frac{\gamma p}{\rho}}$ is the speed of sound, γ is the specific heat ratio and $C(V)$ is a function that describes the friction losses and heat exchanges. As the isentropic case is analyzed, then $C(V) = 0$.
Video: A change of reference from $V_{ref} = [1.16, 20, 100000]^T$ to $V_{ref} = [1.2, 30, 105000]^T$ is introduced.

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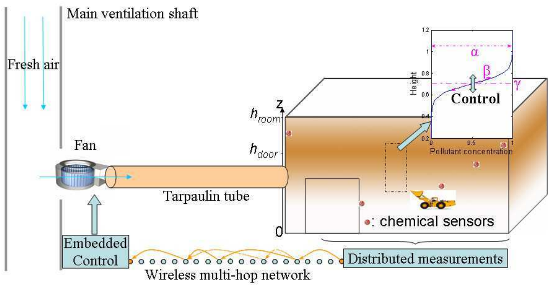
Predictive and hybrid control of the extraction rooms [IJRNC 2010]



- Barely known topology
- Involve turbulence and flow sources in a stratified distribution

- Simplified grey-box model of the 2-layers profile
- Periferal dynamics included with energy losses (tube), time-delay (tube + network) and locally regulated fan

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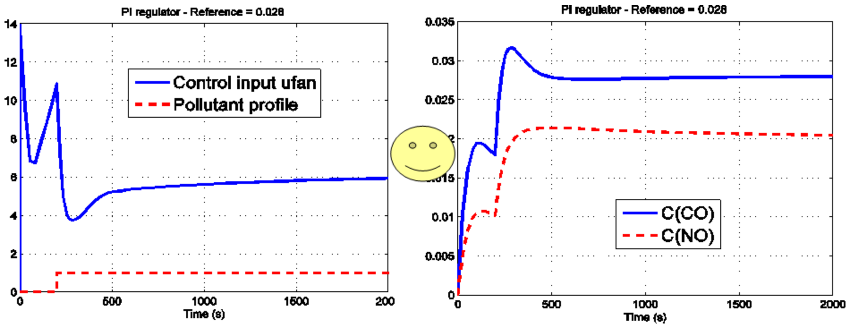
Problem formulation

- Control objective: minimize the fan energy consumption while ensuring an acceptable air quality in the extraction room
- Height-dependent model → objective rephrased as guaranteeing a maximum pollutant concentration at a given height z_r:
$$\max_{\forall j} y_j(t) \leq \bar{y}_j,$$
where $\bar{y}_j$ is the threshold value on pollutant j (i.e. CO_x or NO_x) and z_r = highest height where the air quality has to be guaranteed and around which the sensors should be placed
- Communication constraints (delays, timeout, packet losses and bandwidth limitations) should also be included.

Adequacy of linear controllers?

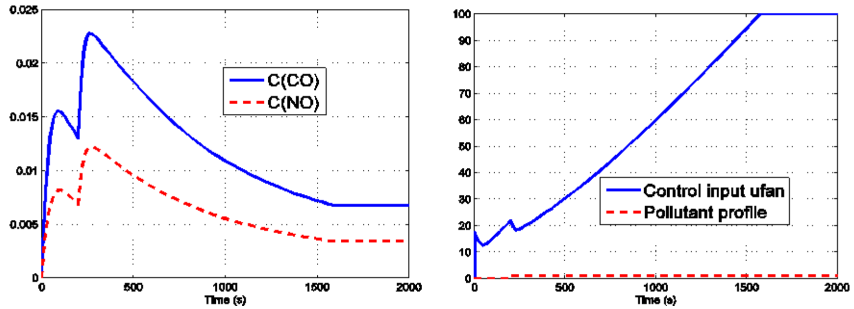
Test: PI tuned to regulate CO at 0.028



Very satisfactory !! But. . .

Adequacy of linear controllers (2)

But, changing the reference to 0.035



$\Rightarrow$ Non linearities of the system have to be carefully taken into account

NLMPC: Receding horizon control

- Control objectif: regulate the level of pollutants $y_j(t) \to y_{des,j}(t)$
- Constraints to be satisfied: $\max_t y_j(t) \leq \bar{y}_j$

Open loop: control

$$\min_{\{u_i, i=1,\dots,N_u\}} \int_{\tau=kT}^{kT+N} \left((\hat{y}_j(\tau) - y_{j,des}(\tau))^2 + \lambda u_{fan}^2(\tau)\right) d\tau$$

with $u_{fan}(\tau) = u_i, \quad \tau \in \left[kT + (i-1)\frac{N_u}{N}, kT + i\frac{N_u}{N}\right[$

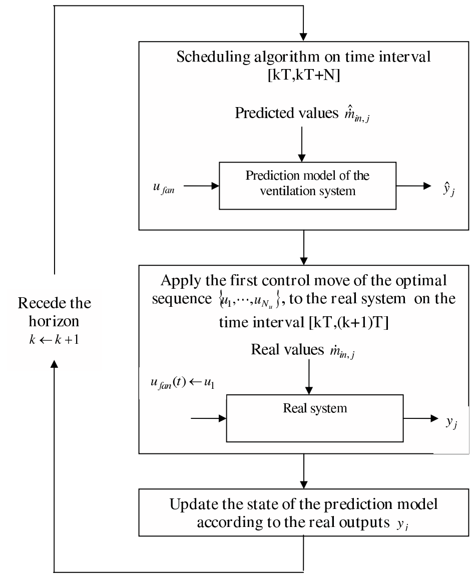
Computed from prediction model

- Control tuning parameters:
  - N: prediction horizon, long enough for transient behavior
  - N_u: number of degrees of freedom: precision vs. complexity
  - λ: weight control effort vs. tracking performances

$\Rightarrow$ Intuitive tuning based on system response

Problem: robustness against pollutant emissions predictions

$\rightarrow$ Need of a closed loop control architecture

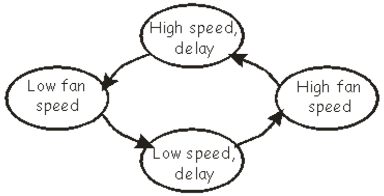


Scheduling algorithm based on prediction model (maximum value of the delay)

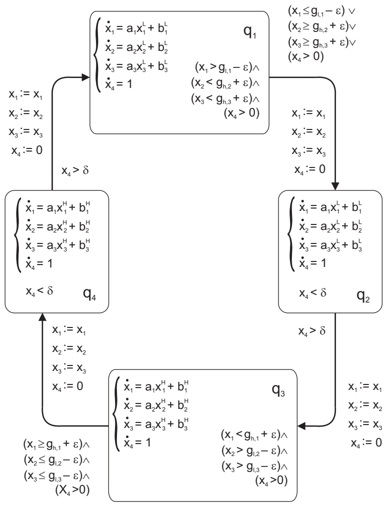
$\Rightarrow$ constrained MPC with on-line solution of successive optimization problems

Hybrid Control Strategy

Affine hybrid model → threshold control



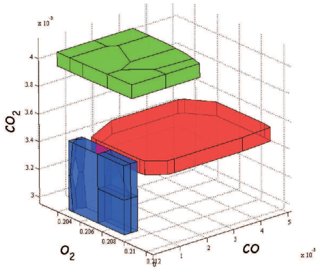
Abstraction of hybrid automaton with affine dynamics, which preserves temporal properties expressed by CTL and TCTL formulae (temporal logics constraints)



Safety Control

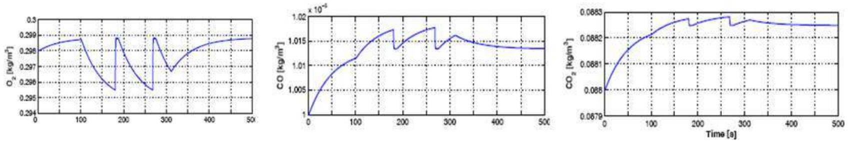
- Automatically verify if for a given control strategy the hybrid automaton satisfies Safety and Comfort properties
- Unfortunately, model checking in general undecidable even for affine hybrid automata
  - construct an abstraction of a hybrid automaton with affine dynamics, which preserves temporal properties expressed by CTL and TCTL formulae (temporal logics constraints)
  - abstract model belongs to a subclass of timed automata, called durational graph

Example



Automatic verification procedure on the hybrid model using the following set of thresholds (high and low, 3 gases)

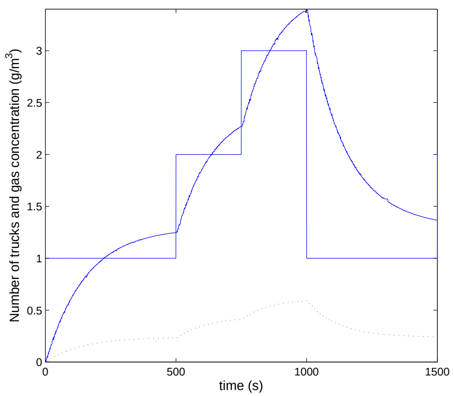
$$\begin{aligned} gl1 &= 0.2955, & gh1 &= 0.2975\,[Kg/m3] \\ gl2 &= 0.5\times 10^{-3}, & gh2 &= 2.5\times 10^{-3}\,[Kg/m3] \\ gl3 &= 0.0885, & gh3 &= 0.091\,[Kg/m3] \end{aligned}$$



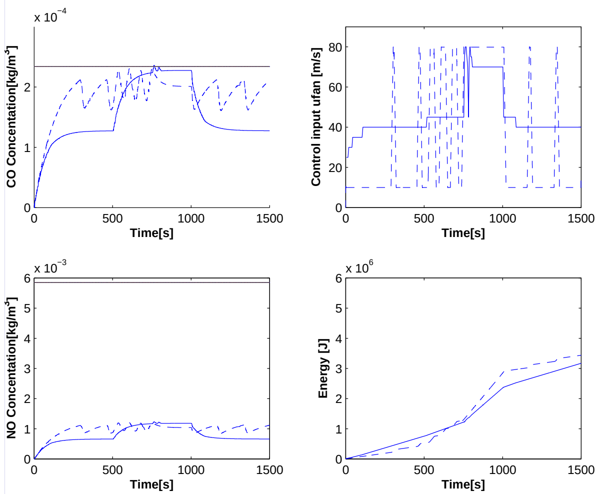
Safe original hybrid system and maximum time of uncomfortable air < 62 s

Comparison between the two approaches

Test case (CO and NO concentrations)



Comparison: regulation efficiency



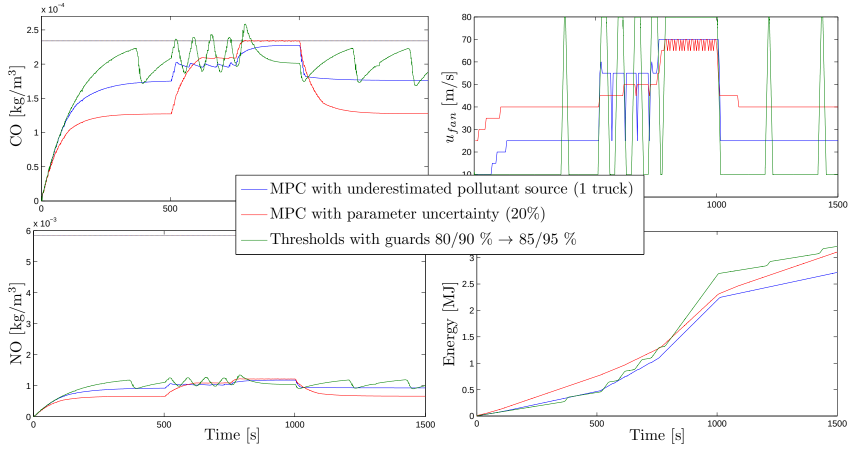
MPC (solid line):

- direct trade-off regulation efficiency vs. energy min.
- better ratio

Threshold (dashed line):

- easy tuning
- find the tighter band for guards

Comparison between the two approaches



Thresholds:	MPC:
O(1) complexity,	time consuming but still realistic (RT/2.5)
comparisons betw. meas. and safety thresholds	hard optimization problems
can be embedded on WSN	centralized control
fails safety if too tight guards	finer tuning and more robust

Conclusions

- Variety of control problems
- Necessitate appropriate control laws considering, i.e.
  - algebraic structure from the graph and nonlinearities for network control
  - distributed dynamics (PDE) for large convective flows
  - peripheral dynamics and height-dependent distributions for rooms
- Preliminary mathematical and simulation analysis that motivate experimental validation

Main references

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- E. W. and N. Marchand, ”Modeling and Feedback Control for Air Flow Regulation in Deep Pits”, Cambridge Scientific Publishers, 2008. `http://www.gipsa-lab.grenoble-inp.fr/~e.witrant/papers/11_CSP_Witrant.pdf`
- E. W., S.I. Niculescu, “Modeling and Control of Large Convective Flows with Time-Delays”, *Mathematics in Engineering, Science and Aerospace*, Vol 1, No 2, 191-205, 2010. `http://www.gipsa-lab.grenoble-inp.fr/~e.witrant/papers/10_Witrant_MESA.pdf`
- E. W., A. D'Innocenzo, G. Sandou, F. Santucci, M. D. Di Benedetto, A. J. Isaksson, K. H. Johansson, S.-I. Niculescu, S. Olaru, E. Serra, S. Tennina and U. Tiberi, ”Wireless Ventilation Control for Large-Scale Systems: the Mining Industrial Case”, International Journal of Robust and Nonlinear Control, vol. 20 (2), pp. 226 - 251, Jan. 2010. `http://www.gipsa-lab.grenoble-inp.fr/~e.witrant/papers/09_IJRNC_r23.pdf`
- F. Castillo Buenaventura, E. W., C. Prieur and L. Dugard, ”Dynamic Boundary Stabilization of Hyperbolic Systems”, Proc. of the 51st IEEE Conference on Decision and Control, Maui, Hawaii, December 10-13, 2012. `http://www.gipsa-lab.grenoble-inp.fr/~e.witrant/papers/13_cdc_castillo.pdf`

UFR de Physique

MINING VENTILATION CONTROL

Lesson 7: Application of wireless sensors to mining ventilation

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Universidad Pedagógica y Tecnológica de Colombia, Sogamoso, April 4, 2013

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Background

- Typical existing ventilation control systems are either poor or non existing, a continuous monitoring of air quality is absent, and the only communication capability is simply voice over walky-talkie
- The amount of air pumped in the rooms is manually controlled in open-loop, and ventilation energy can be optimized while guaranteeing operators safety
- Reference works: [Fischione, Pomante, Santucci et al., 2008, W. et al. 2009]

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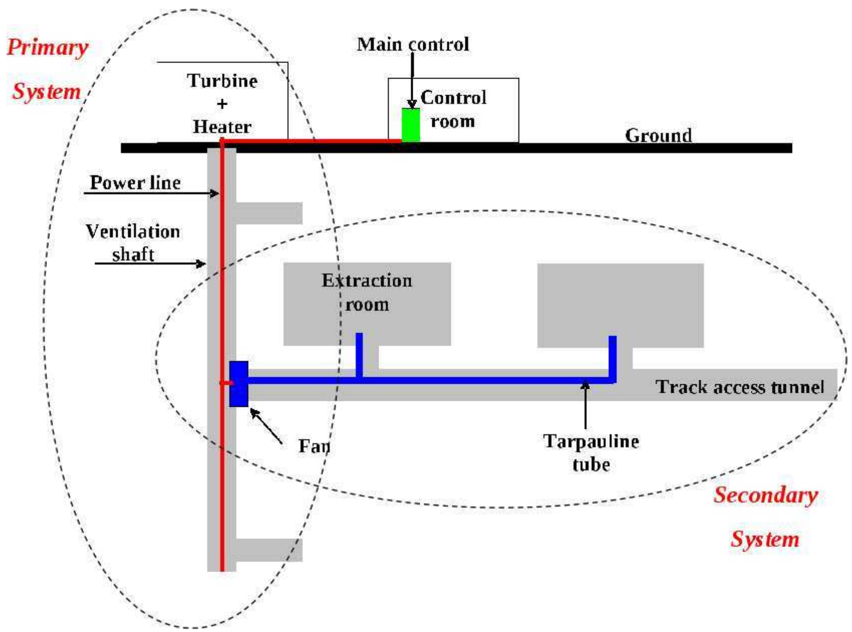
Mine topology



Motivation & Goals

- Advanced communication architectures for distributed sensing/actuation leads a mining operating site to become an interconnected system
- Advanced control strategies allow to save energy and improve safety
- Provide advanced services

Wireless sensing and communication architecture:

- Design space exploration keeping into account present and future needs able to increase safety and efficiency of the whole system
- Set of models and algorithms needed to validate the proposed approaches by means of simulations

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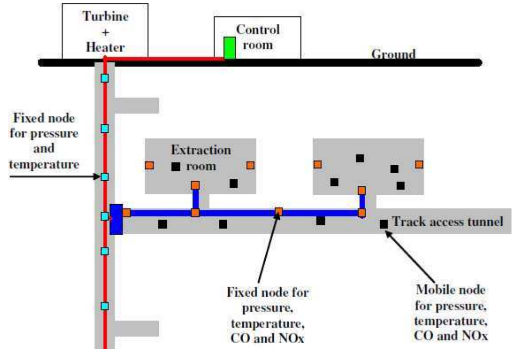
Communication Architecture

- The primary need for automation is sensing:
  - to obtain information about air pressure and temperature to apply a proper control strategy
  - for the secondary system, gas concentrations are also required
- Basic sensing infrastructure composed of:

- fixed wireless sensor nodes in the ventilation shaft, tunnels and extraction rooms
- mobile wireless sensors associated to entities working in the secondary system



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Communication Architecture (2)

- The sensing network has to be complemented by a communication network portion, which is in charge of delivering information over longer ranges, up to controllers and actuators
- Different opportunities can be considered, i.e.
  - Uniform radio network
  - Hybrid wired-wireless architecture
  - Extended mobile wireless architecture

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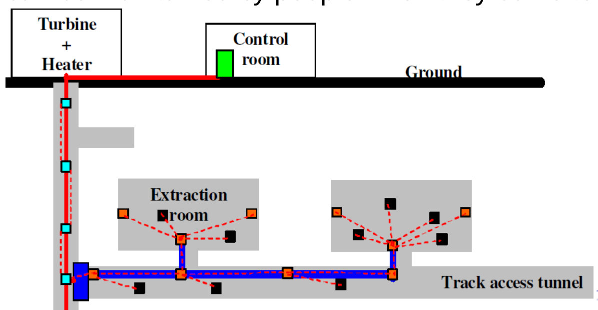
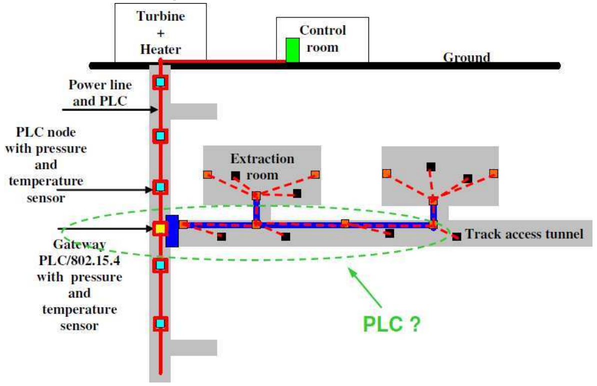
Uniform radio network

- One radio technology (e.g. 802.15.4) is adopted in the system: interaction with the existing infrastructure is minimal
- Topology variation induces an impact in scalability of solutions, since a larger size implies larger number of hops, longer delays and larger traffic to be supported by relaying nodes
  - the nodes deployed on portions of tunnels where electrical cabling is absent should be battery powered
  - mobile nodes is not subjected to energy issues, since they can be maintained by people when they come to ground



Hybrid wired-wireless architecture

- Since the system foresees the presence of some cabling it is interesting to consider Power Line Communication devices for setting up the network
  - provide a wired backbone along the power line to connect the Control Room with an 802.15.4 WSN
  - could be very useful for relay nodes
- A proper PLC/802.15.4 Gateway is needed: acts also as a sink node for the patches described before



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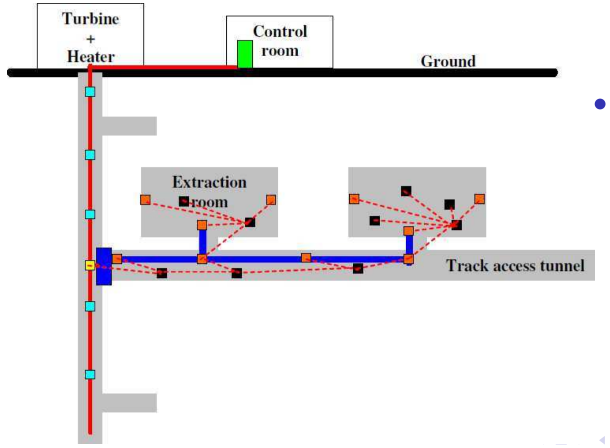
Extended mobile wireless architecture

The basic setup depicted so far can be enhanced by further exploiting the mobile entities:

- An interesting evolution exploits hand-helds and on-truck nodes to build a dynamic wireless backbone
- Such a network would help to make energy constraints on some lower tier wireless sensor nodes less stringent



- Moreover, the introduction of a 802.11 network would provide a larger bandwidth support for introducing advanced services

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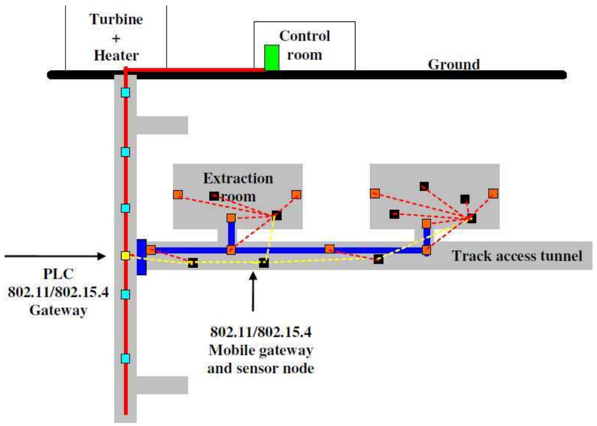
Extended mobile wireless architecture with mobile gateway



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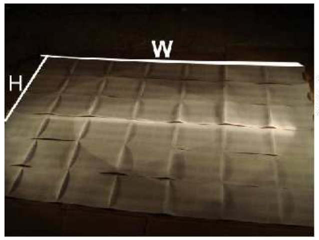
Models, Algorithms and Tools

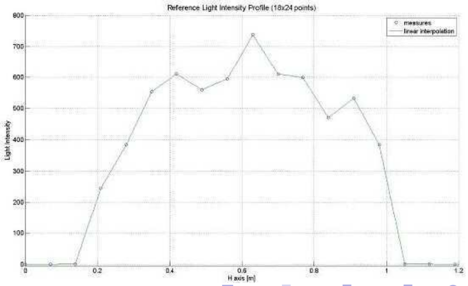
Different approaches by means of simulations have been developed as a set of models and algorithms related to the main features of the system:

- Distributed Estimation by Wireless Sensors
- Latency/Energy Models in Multi-hop WSN

Distributed Estimation by Wireless Sensors

- Objective: use a set of distributed measurements to obtain an estimate of the air quality
- These approaches are in contrast to the traditional ones with sensors that provide raw data to a fusion center
- Results have been achieved for a movable grid of sensors and some experimental results have been obtained in lab facilities with light sensing elements
- A practical example: reconscruction of a known profile (of light) by means of a network of MICAz nodes





Latency/Energy Models in Multi-hop WSN

Considering the uniform radio network architecture the wireless network can be interpreted as a clustered network:

- deal with network delay for closed-loop analysis and with energy consumption concerns for network lifetime with limited maintenance

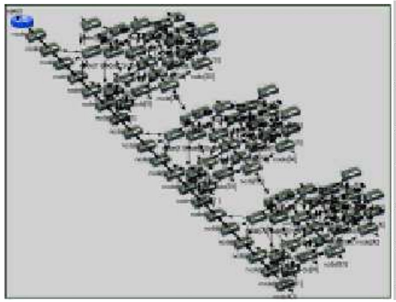
→ high level model for end-to-end delay that can be further refined introducing some topological details

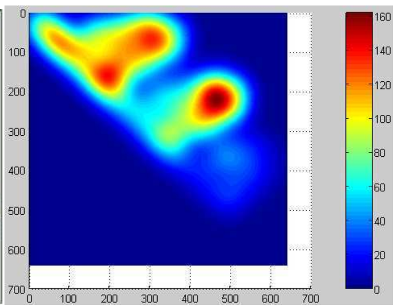
→ model for the energy spent in the Transmission / Reception / Idle states and during the transitions

- need a framework to support energy/performance analysis of control algorithms by means of discrete event network simulators

Latency/Energy Models in Multi-hop WSN (2)

- 2 discrete event simulator have been setup (OMNeT++, DESYRE) to evidence energy depletion and latency:



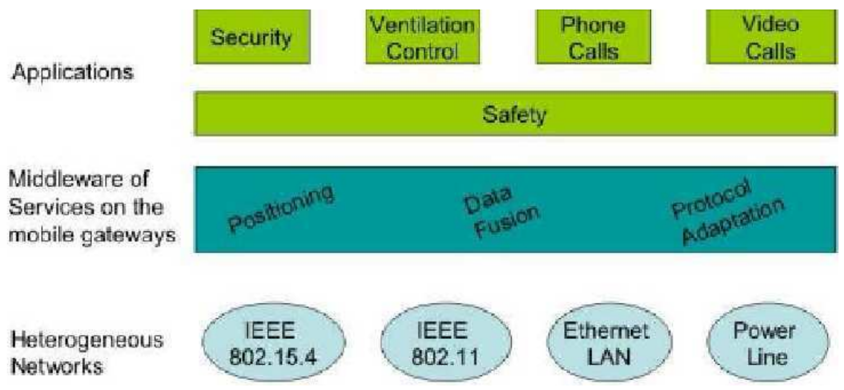


Advanced Services

The presence of mobile nodes in the system leads to consider other services

- A localization service is of particular interest and it would be limited, at a first instance, to provide the tunnel/room coordinates
- A perspective view is to deploy a localization services that allows to track the position within the whole mining area
- Other advanced services require the extended architecture (e.g. 802.11), e.g. IP-based voice/video service

A longer term view



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- Architecture definition and algorithms design for a WSN in the mining scenario
- Need analysis of network architectures of increasing complexity, with the goal of supporting distributed estimation and fulfilling reliability and latency requirements for a ventilation control application

Feedback control principles
E. Witrant
Background
Goals
Communication Architecture
Uniform radio network
Hybrid wired-wireless architecture
Extended mobile wireless architecture
Models, Algorithms and Tools
Distributed Estimation by Wireless Sensors
Latency/Energy Models in Multi-hop WSN
Advanced Services
Conclusions

Reference

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