Robotics
Intelligent sensors (part 3)

Tullio Facchinetti
<tullio.facchinetti@unipv.it>

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http://robot.unipv.it/toolleeo

Flow sensors

- a flow sensor detects the velocity or the flow rate of a fluid (gas or liquid)
- the flow rate is measured in m/s, m^3/s or kg/s

flow meter

provides as output a signal proportional to the measured velocity

Sensing technology

several different technologies are adopted for flow measurement:

- **pressure measurement** – based on Bernoulli's principle
- **magnetic flow meters** – evaluates the interference of the moving fluid on a magnetic field
- **vortex flow meters** – based on the rotation velocity of a fan
- **ultrasonic flow meters** – due to the Doppler effect, the frequency of an ultrasound changes depending on the velocity of the fluid traversing the sound wave path

Flow sensing through pressure measurement

the flow of fluids is measured by sensing the difference between the pressure within tubes having different cross-sectional size

the most widely used instruments are:

- **Venturi tube**: usually adopted to measure the flow of a liquid within a tube
- **Pitot tube**: usually used to measure the velocity of a gas (e.g., the air velocity in aerodynamics)

the physical principle is the bernoulli's principle

Basic assumptions

to simplify the analysis, the following assumptions are considered:

1. the fluid flows without creating vortexes (irrotational)
2. there is no friction between the fluid and the pipe
3. there is no heat exchange between fluid and pipe
4. the fluid can not be compressed (ρ is constant)

The Bernoulli's principle

under the considered assumptions, the Bernoulli's principle states that

$$P + \rho\frac{v^2}{2} + \rho g h = \text{constant}$$

- P : pressure in one point
- v : velocity of the fluid
- ρ the density of the fluid
- h : the height of the point
- g : the gravity acceleration

NOTE: the Bernoulli's equation can be obtained from Navier-Stokes's differential equations in case of an ideal fluid

The Bernoulli's principle

considering the fluid flowing in a pipe, the Bernoulli's principle can be applied to 2 different points of the pipe

$$P_1 + \rho_1 \frac{v_1^2}{2} + \rho_1 g h_1 = P_2 + \rho_2 \frac{v_2^2}{2} + \rho_2 g h_2$$

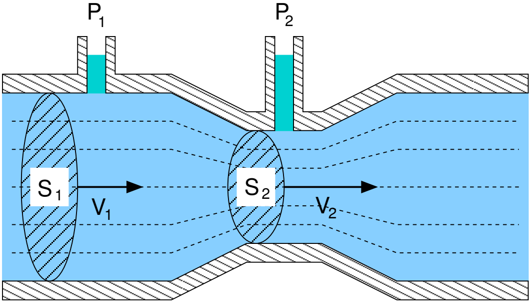
assuming that

1. the fluid is the same ($\rho_1 = \rho_2 = \rho$)
2. the pipe is horizontally oriented ($h_1 = h_2 = h$)

the above equation can be simplified as

$$\frac{P_1 - P_2}{\rho} = \frac{v_2^2 - v_1^2}{2}$$

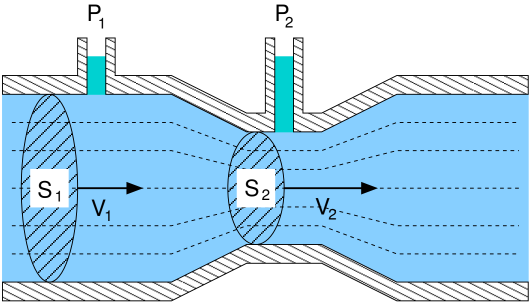
Venturi tube



being Q the flow, it holds $Q = Q_1 = Q_2$, where

- $Q_1 = S_1 v_1$ is related to the cross-section S_1
- $Q_2 = S_2 v_2$ is related to the cross-section S_2

Venturi tube



$$Q = \frac{S_2}{\sqrt{1-(S_2/S_1)^2}}\sqrt{\frac{2(P_1-P_2)}{\rho}}$$

Venturi tube

example of Venturi tube

section of a Venturi tube installed on a pipe

Pitot tube

the working principle of the Pitot tube is based on the concept of **total pressure**

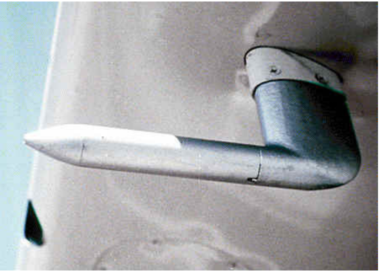
$$P_{tot}(x, y, z, t) = P_{st}(x, y, z, t) + \frac{1}{2}\rho|v|^2$$

- $P_{tot}(x, y, z, t)$ is the **total pressure**
- $P_{st}(x, y, z, t)$ is the **static pressure**
- $\frac{1}{2}\rho\|v\|^2$ is the **dynamic pressure**

all pressures refer to the same point at the same time

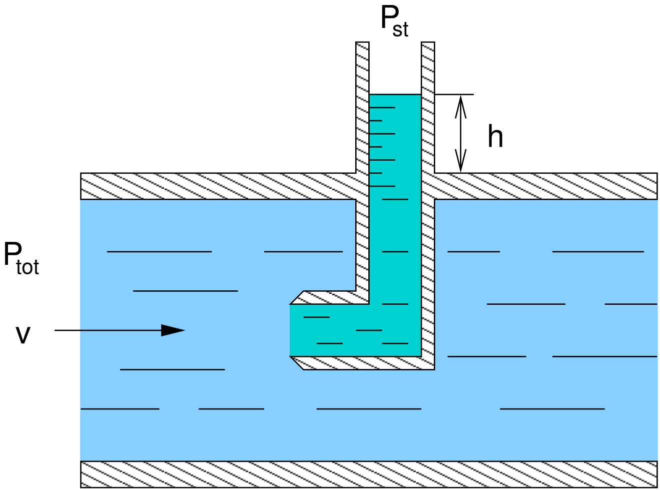
Pitot tube

example of Pitot tube



Pitot tube installed on a airplane

Pitot tube



Pitot tube

the velocity v can be calculated considering that:

- P_{tot} is measured on the main tube using a manometer
- $P_{st} = \rho g h$ is measured on the vertical tube (measuring h)

once P_{tot} and P_{st} are known, the velocity v is calculated using the formula

$$v = \sqrt{\frac{2(P_{tot} - P_{st})}{\rho}}$$

some considerations:

- P_{tot} and P_{st} should be measured in the same point, but this does not happen (approximation)
- the Pitot tube is built to limit the perturbation on the flow, allowing to approximate the ideal condition where P_{tot} and P_{st} are measured in the same point
- possible perturbations introduced by the external tube affect the linearity of the sensor
- a look up table can be obtained during the calibration by putting the Pitot into a fluid with known ρ and v, and measuring the corresponding P_{tot} and P_{st} pressures

Temperature and heat

temperature

a physical quantity related to the kinetic energy of molecules, representing the potential of the heat flow

heat

it is energy; its flow is due to two sub-systems being at different temperatures

Ideal gas law

in case of gases, the temperature is related to other physical quantities by the **ideal gas law**:

$$PV = nRT$$

- P: gas pressure
- V: gas volume
- n: amount of molecules [moles]
- R: universal gas constant
- T: absolute temperature [kelvin]

Thermal flow

the thermal flow is due to the following physical effects:

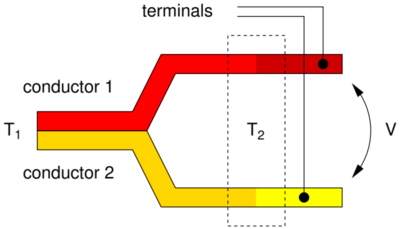
- **thermal conduction**: the heat flows between two adjacent static solids or fluids, or between two parts of the same body or fluid
- **thermal convection**: is due to the motion of a fluid, which produces a thermal exchange between adjacent regions and may lead to changes in density and pressure
- **thermal radiation**: it takes place by the emission, propagation and absorption of electromagnetic waves; can take place at high distances and does not require any transmission medium

Thermoelectric effects

thermal sensors can leverage one of the following thermoelectric effects:

- **Seebeck effect**: the most widely leveraged effect, it produces a voltage between two adjacent conductors having different temperatures
- **Peltier effect**: it generates a thermal emission or absorption when an input voltage is provided
- **Thomson effect**: produces an (often negligible) electric current in two regions of the same conductor having different temperatures

Seebeck effect: the thermocouple



- it is made by two joint conductors
- the junction is said **hot junction**
- the temperature T_1 to be measured is applied to the hot junction
- the temperature T_2 is associated to the cold junction **cold junction** (the terminal block)
- when $T_1 \neq T_2$ a voltage V is generated on the cold junction

The thermocouple

The thermocouple

in a thermocouple, the relationship between temperature and electric voltage on the cold junction is given by

$$\Delta V = A_1(T_1 - T_2) + A_2(T_1^2 - T_2^2) + \ldots + A_n(T_1^n - T_2^n)$$

where:

- $A_1 \ldots A_n$ are constant depending on the material
- T_1 and T_2 are the temperatures on the hot and cold junctions, respectively
- the relationship is non-linear

The thermocouple

- there are some materials whose high order terms are negligible
- in that case, the relationship becomes linear

$$\Delta V = A_1(T_1 - T_2)$$

if T_2 is known, by measuring the voltage ΔV it is possible to determine the desired temperature T_1

unfortunately, in normal working conditions, the temperature T_2 is not known

The law of successive temperatures

- let V_{12} be the Seebeck voltage when the two temperatures are T_1 and T_2
- let V_{23} be the Seebeck voltage when the two temperatures are T_2 and T_3
- let V_{13} be the Seebeck voltage when the two temperature are T_1 and T_3

the following relationship holds:

$$V_{13} = V_{12} + V_{23}$$

it is called **Law of successive temperatures**

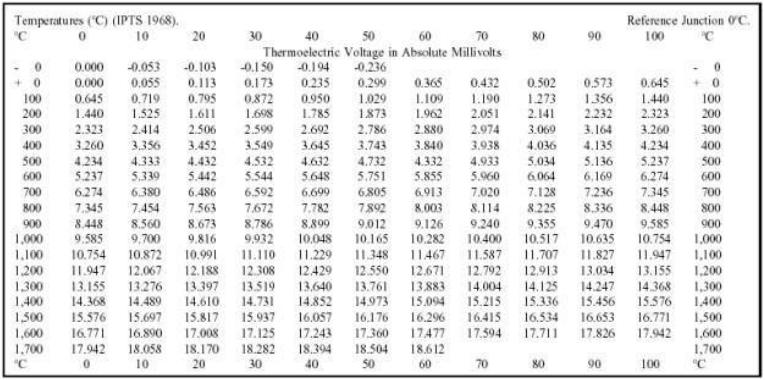
The law of successive temperatures

$$V_{(T_1,T_0)} = V_{(T_1,T_r)} + V_{(T_r,T_0)}$$

- T_0 : manufacturing calibration temperature; usually $T_0 = 0^\circ C$
- T_r : temperature of the cold junction during the measurement (known)
- T_1 : temperature to measure (unknown)
- $V_{(T_r,T_0)}$: measured voltage at temperature $T_r - T_0$ (this parameter is provided by the manufacturer)
- $V_{(T_1,T_r)}$: measured voltage during the sensing
- $V_{(T_1,T_0)}$: calculated value from the law of successive temperatures

the relationship between V and T at the temperature T_0 is provided by the manufacturer, therefore from $V_{(T_1,T_0)}$ it is possible to obtain T_1

The law of successive temperatures



Temperatures (°C) (IPTS 1968). Reference Junction 0°C.

Thermoelectric Voltage in Absolute Millivolts

°C	0	10	20	30	40	50	60	70	80	90	100	°C
- 0	0.000	-0.053	-0.103	-0.150	-0.194	-0.236						- 0
+ 0	0.000	0.055	0.113	0.173	0.235	0.299	0.365	0.432	0.502	0.573	0.645	+ 0
100	0.645	0.719	0.795	0.872	0.950	1.029	1.109	1.190	1.273	1.356	1.440	100
200	1.440	1.525	1.611	1.698	1.785	1.873	1.962	2.051	2.141	2.232	2.323	200
300	2.323	2.414	2.506	2.599	2.692	2.786	2.880	2.974	3.069	3.164	3.260	300
400	3.260	3.356	3.452	3.549	3.645	3.743	3.840	3.938	4.036	4.135	4.234	400
500	4.234	4.333	4.432	4.532	4.632	4.732	4.332	4.933	5.034	5.136	5.237	500
600	5.237	5.339	5.442	5.544	5.648	5.751	5.855	5.960	6.064	6.169	6.274	600
700	6.274	6.380	6.486	6.592	6.699	6.805	6.913	7.020	7.128	7.236	7.345	700
800	7.345	7.454	7.563	7.672	7.782	7.892	8.003	8.114	8.225	8.336	8.448	800
900	8.448	8.560	8.673	8.786	8.899	9.012	9.126	9.240	9.355	9.470	9.585	900
1,000	9.585	9.700	9.816	9.932	10.048	10.165	10.282	10.400	10.517	10.635	10.754	1,000
1,100	10.754	10.872	10.991	11.110	11.229	11.348	11.467	11.587	11.707	11.827	11.947	1,100
1,200	11.947	12.067	12.188	12.308	12.429	12.550	12.671	12.792	12.913	13.034	13.155	1,200
1,300	13.155	13.276	13.397	13.519	13.640	13.761	13.883	14.004	14.125	14.247	14.368	1,300
1,400	14.368	14.489	14.610	14.731	14.852	14.973	15.094	15.215	15.336	15.456	15.576	1,400
1,500	15.576	15.697	15.817	15.937	16.057	16.176	16.296	16.415	16.534	16.653	16.771	1,500
1,600	16.771	16.890	17.008	17.125	17.243	17.360	17.477	17.594	17.711	17.826	17.942	1,600
1,700	17.942	18.058	18.170	18.282	18.394	18.504	18.612					1,700
°C	0	10	20	30	40	50	60	70	80	90	100	°C

Example of thermocouple temperature-vs-voltage table

Numerical example

- suppose that in a given situation $T_r = 100^\circ C$ and T_1 is the unknown temperature to measure
- $V_{(T_r, T_0)} = 0.033\text{mV}$ when $T_r = 100^\circ C$ (from tables provided by the manufacturer, being $T_0 = 0^\circ C$)
- the sampled output voltage is $V_{(T_1, T_r)} = 1.759\text{mV}$
- using the law of successive temperatures: $V_{(T_1, T_0)} = 1.759 + 0.033 = 1.792\text{mV}$
- from the manufacturer table, being $T_0 = 0^\circ C$ and $V_{(T_1, T_0)} = 1.792\text{mV}$, it holds $T_1 = 600^\circ C$

the problem is to keep $T_r = 100^\circ C$
(or another known value)

The thermocouple: example of compensation

it is possible to maintain the cold junction at a known temperature with one of following methods:

- liquefying ice
- boiling water
- thermal generation using some thermoelectric effect
- measuring the temperature of the cold junction with a thermistor

another method encompasses the following steps:

- to bring the hot junction to a known temperature
- to measure the voltage
- to obtain the temperature of the cold junction using the law of successive temperatures

The thermocouple: pro

- no moving parts (long lifetime)
- passive transducer
- wide sensing range, usually from $-200^\circ C \div 2750^\circ C$
- relatively fast response time (seconds)
- good repeatability and accuracy $(0.1^\circ C \div 4^\circ C)$
- low cost

The thermocouple: cons

- low sensitivity ($\sim 50 \mu V/^{\circ}C$); the measured value can be confused with the noise; filtering, shielding and adequate A/D conversion can limit (but not eliminate) the problem
- the accuracy, typically $> 0.5^{\circ}C$, may not be enough in certain applications
- requires a temperature reference value, although modern components generate the reference electrically
- the transfer function is not linear, although the manufacturer provides a calibration table specific for each device

Thermo-resistive effect

the thermo-resistive effect is based on the variation of resistance of a material when the temperature changes

there are two distinct technologies:

1. **resistance thermometers**, or resistance temperature detectors (RTDs), use some metals such as copper, nickel or platinum as transducers
2. **thermistors** use semiconductors made ceramics, metals (copper, iron, cobalt or manganese) or newer material

PTC sensors: Positive Temperature Coefficient

the resistance increases with the temperature, and viceversa

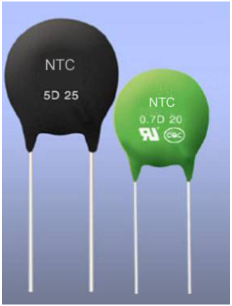
NTC sensors: Negative Temperature Coefficient

the resistance decreases with the temperature, and viceversa

sensing ranges of NTC sensors (Carel)

- $[-50, +50]^\circ C$ in a liquid
- $[-50, +105]^\circ C$ in air

NTC sensors



example of NTC resistance thermometer
(thermistor)

Resistance thermometer

let's consider the following equation:

$$\rho(T) = \rho_0[1 + \alpha(T - T_0)]$$

- T is the temperature to measure [K]
- T_0 is the reference temperature [K] (usually $0^\circ C$ or $25^\circ C$)
- $\rho(T)$ is the resistivity at temperature T
- ρ_0 is the resistivity at temperature T_0
- α is a constant related to the material

from the relationship $R = \rho(L/S)$ the resistance is

$$R(T) = R_0[1 + \alpha(T - T_0)]$$

the β equation is

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{\beta} \ln\left(\frac{R}{R_0}\right)$$

where

- R is the resistance at temperature T [kelvin]
- R_0 is the resistance at temperature T_0 [kelvin]
- β is a coefficient related to the material

- non-linear relationship between temperature and resistance
- simplified version of the Steinhart-Hart equation

Thermistors: the β equation

it is possible to obtain R as follows:

$$R = R_0 e^{\beta(1/T - 1/T_0)}$$

that can be expressed as

$$R = r_\infty e^{\beta/T}$$

$$r_\infty = \lim_{T \to \infty} R = R_0 e^{-\beta/T_0}$$

Thermistors: numerical example

known parameters:

- resistance equal to $10k\Omega \pm 1\%$ at the temperature of $25^\circ C$
- coefficient $\beta = 3435$ Kelvin
- desired sensing range of $[-3, 60]^\circ C$

derived values:

$$r_\infty \to [98.2, 100.2] m\Omega$$

$$R(-3^\circ C) = \begin{cases} 32.676 k\Omega, & \text{if } r_\infty = 98.2 \\ 33.336 k\Omega, & \text{if } r_\infty = 100.2 \end{cases}$$

$$R(60^\circ C) = \begin{cases} 2.951 k\Omega, & \text{if } r_\infty = 98.2 \\ 3.010 k\Omega, & \text{if } r_\infty = 100.2 \end{cases}$$

RTDs vs thermistors

- while the temperature coefficient of thermistors is negative, the one of RTDs is positive
- it is possible to dope a semiconductor to obtain a positive coefficient
- the transfer function (temperature-to-voltage) of a thermistor is non-linear
- the sensitivity of thermistors is – typically – an order of magnitude greater than RTDs
- thermistors have a smaller sensing range

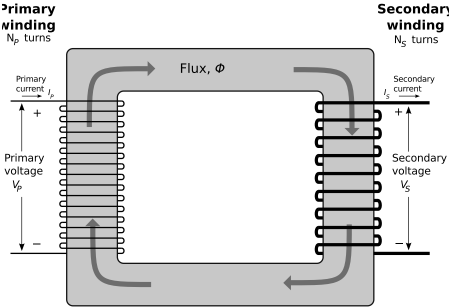
Electric current measurement

current sensors allow to measure the electric current without a direct connection between the electric circuit and the measuring instrument

depending on the type of insertion on the circuit, some options are available:

- current transformers (CT)
- current clamps
- Hall effect current transducers

Current transformers



(source: Wikipedia)

- based on the working principle of the transformer
- the primary coil is the circuit under sensing
- the secondary coil is coupled with the measurement device

Current transformers (CT)

- an alternate current flows in the conductor, generating a variable induced magnetic flow
- when the flow is chained to another circuit, a voltage is generated on this latter
- the voltage induced from the primary to the secondary coil generates an electric current on the secondary coil that is proportional to the one on the primary coil
- the ratio between the two currents is equal to the ratio of the number of coils on the primary and secondary coil

Current transformers

pros

- the sensor is (typically) passive
- small size
- immune to disturbs
- high dynamic range

cons

- can only measure alternate currents
- requires to cut the wires of the circuit under measurement

Current clamps

- same working principle of the CT
- there are coils around a core U-shaped body
- the missing part of the magnetic circuit is made by a bar that closes the upper part
- the bar is made by ferromagnetic material
- the sensor can be opened to insert the electric wire

Current clamps

pros

- wires do not require operations (cut or unmounting)
- easy and quick install

cons

- higher manufacturing complexity
- more expensive w.r.t. a CT

Hall effect sensors

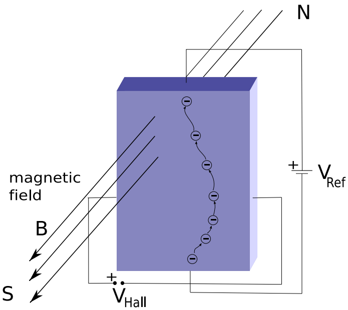
Hall effect

is the generation of a voltage difference (the Hall voltage) across an electrical conductor, transverse to an electric current in the conductor and a magnetic field perpendicular to the current

source: Wikipedia

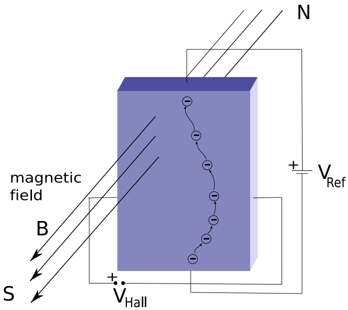
- the sensor is – in practice – a voltage generator based on the Hall effect
- the output depends from the magnetic flux generated by the electromotive force (e.m.f.)

Hall effect sensors



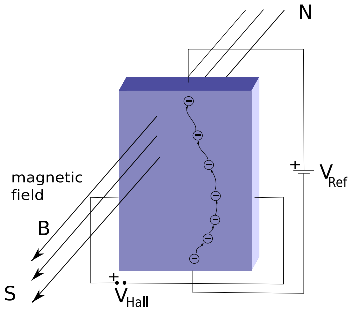
- the electric current *I* flows in an omogeneous conductor
- if no external magnetic inductive fields are present, the charges are distributed evenly

Hall effect sensors



- if there is an external magnetic inductive field, the distribution of charges is non-even on the two plates
- therefore, a voltage (the Hall voltage) is generated between the two plates

Hall effect sensors



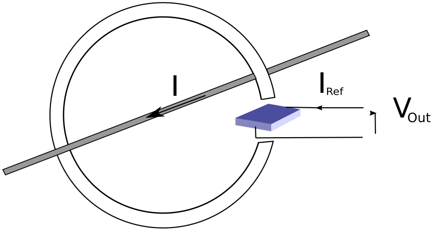
- the Hall voltage is proportional to *I* and to the modulus of the magnetic field *B*
- the effect is more evident in semiconductors

Hall effect sensors

there are two types of sensors:

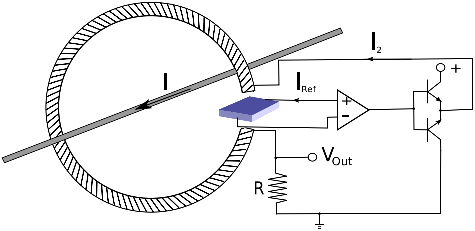
- **open-loop**: they directly measure the Hall voltage
- **closed-loop**: a feedback loop is used to compensate (nullify) the Hall voltage, and the required current is measured

Hall effect sensors: open-loop configuration



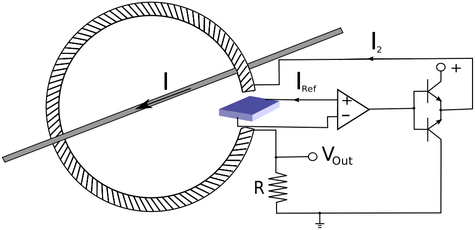
- a torus made by ferromagnetic material conveys and concentrates the magnetic field in the iron body
- the Hall transducer is inserted in the iron body
- an operational amplifier increases the output voltage
- there are integrated circuits including the transducer and the required circuitry

Hall effect sensors: closed-loop configuration



- Hall effect sensors have linear behavior for a low magnetic flux
- it is required to make the sensor working close to a null magnetic flux
- around the torus there is a coil made by *N* coils
- the versus of the coil is in opposition to the magnetic field generated by *I*

Hall effect sensors: closed-loop configuration



- the circuit is driven by an amplifier
- the input voltage V is generated from the Hall effect by the reference current I_{Ref} and the magnetic field imposed to the torus
- if the two magnetic fields compensate each other, i.e. $|I| = |I_2|\, N$, the voltage V mesured at the Hall transducer is null, and $V_{Out} = RI_2 = RI/N$