Shape Memory Alloy Test bench Presentation

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Teaching material on Virtuale

The goal

- **Steps to develop a control algorithm:**

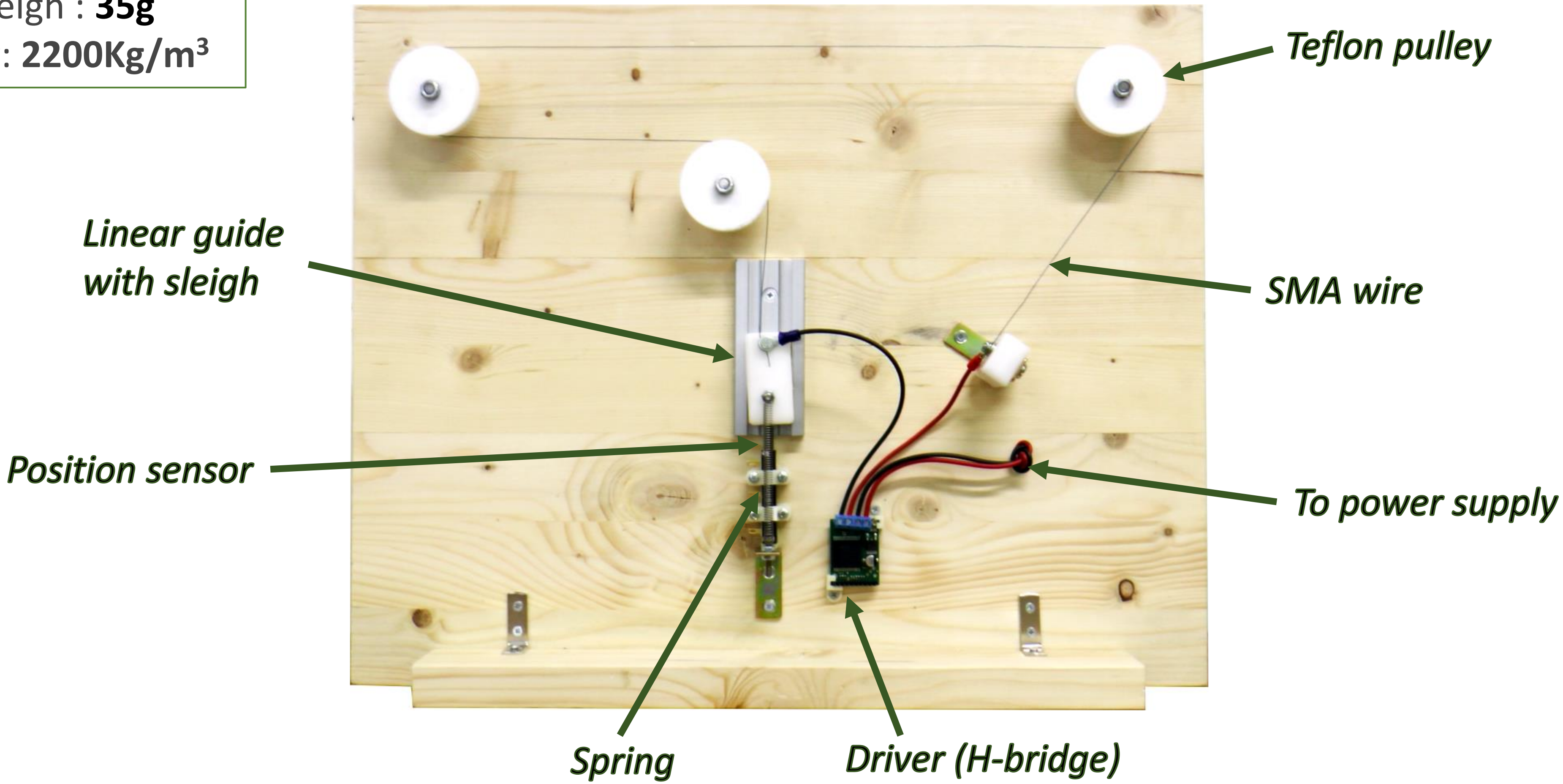
1) Create a model of the system
   - To be used to design the control algorithm.
   - It must be accurate to reproduce the behaviors of the system that affect the controller performance.
   - Accurate but not too accurate, to reduce computational complexity.

2) Define a control algorithm according to specifications.

3) Test the algorithm on the physical plant
   - Adjust parameters if necessary

The Test bench

Note:
Mass of the sleigh : **35g**
Teflon Density: **2200Kg/m^3**



- **SMA wire**

  - Useful papers:

    [1] Dutta SM, GhorbelFH. *Differential hysteresis modeling of a shape memory alloy wire actuator*. IEEE/ASME Transactions on Mechatronics. 2005 Apr; 10(2): 189-97.

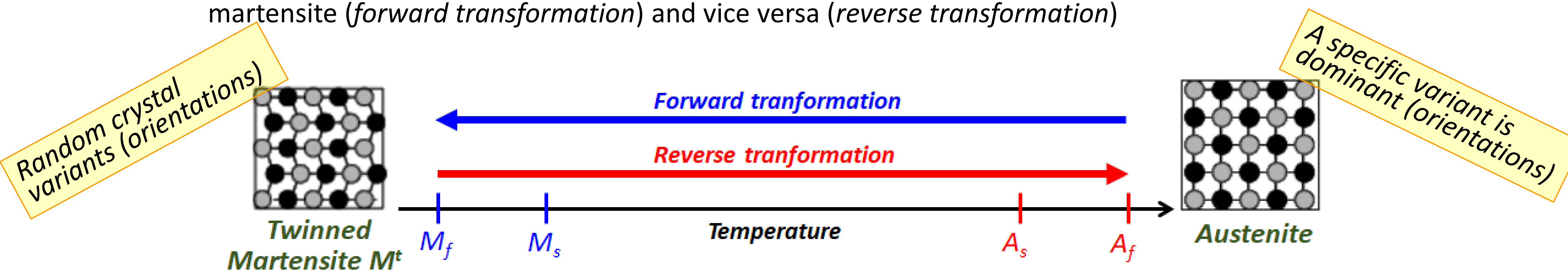
    [2] Romano R., Tannuri EA. *Modeling, Control and experimental validation of a novel actuator based on shape memory alloys*. Mechatronics. 2009 Oct 1; 19(7): 1169-77.

  - SMAs are alloys with the ability to recover their shape when the temperature is increased.
  - NiTi alloy was discovered by W.J. Buehler and F. Wang in 1959 at the Naval Ordinance Laboratory (NOL) → NiTiNOL.

• Austenite – Martensite transformation

- SMAs have two phases:
  - **Austenite (A)**: high temperature, cubic crystal structure, <u>elastic</u> behavior.
  - **Martensite (M)**: low temperature, tetragonal crystal structure, <u>plastic</u> behavior.

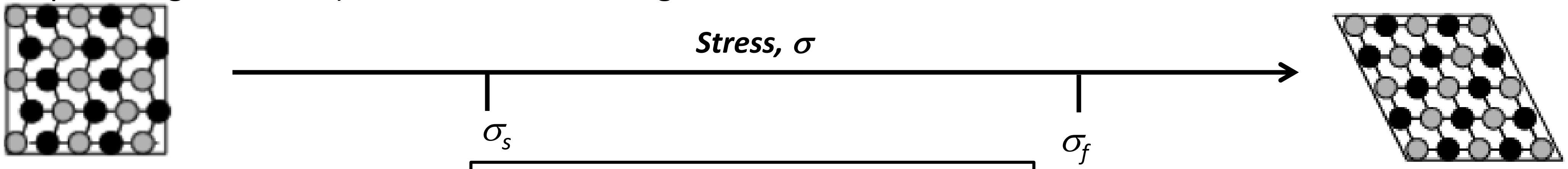
- The unique behavior of SMAs consists in the reversible phase transformation from austenite to martensite (*forward transformation*) and vice versa (*reverse transformation*)



- The A-M transformations are characterized by the martensite fraction R_m which is the volume fraction of M phase present in the SMA at any instant.

• Martensite phase: twinned or detwinned

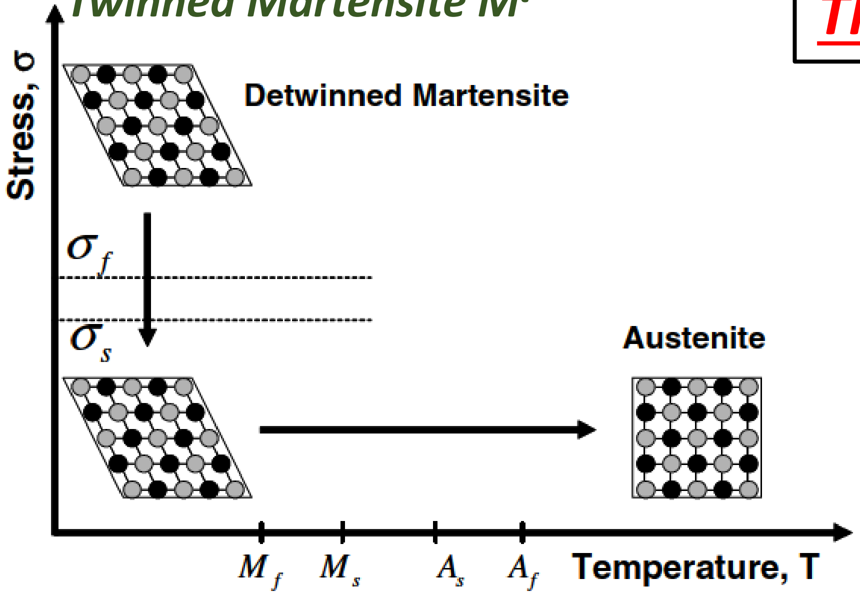
- During martensitic phase, if a load is applied to the material it is possible to detwin it (a macroscopic shape change is visible). The deformed configuration is retained when the load is released.

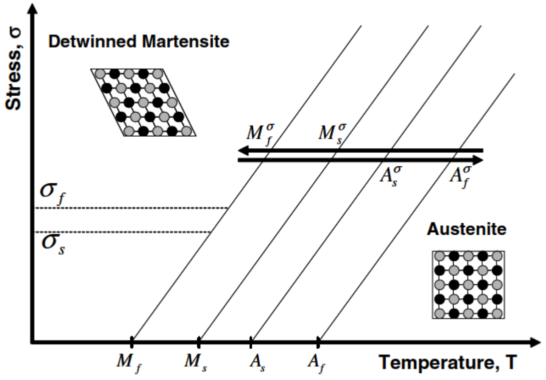


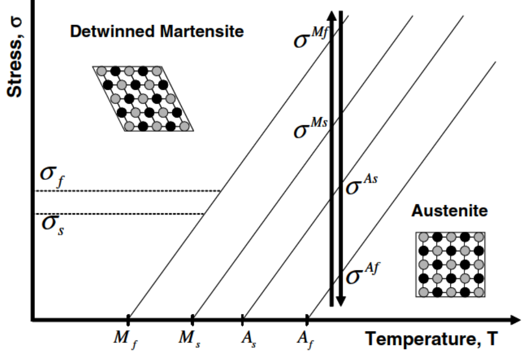
Twinned Martensite M^t

The Shape Memory Effect

Detwinned Martensite M^d

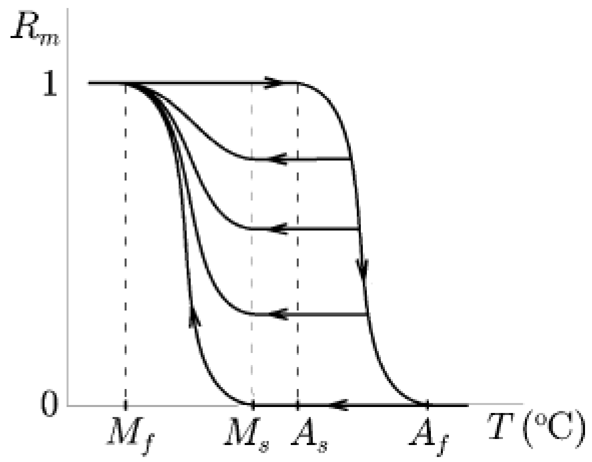






• Austenite – Martensite transformation

- The A-M transformation exhibits temperature hysteresis behavior (major and minor loops).



- R_m martensite fraction.

- How to model the hysteresis?
  Idea: the derivative of the R_m-T curve is a gaussian function (important mean value and variance).
  - For more details see:
    [1], section III
    [2], section 3.2

- The Shape Memory Effect for our applications

  - The wire is heated and the temperature is above A_s → austenite phase, the wire remember its original short length and has an elastic behavior.

Current to heat the wire

  - The wire is cooled and the temperature is below M_s → martensite phase, the wire presents plastic behavior.

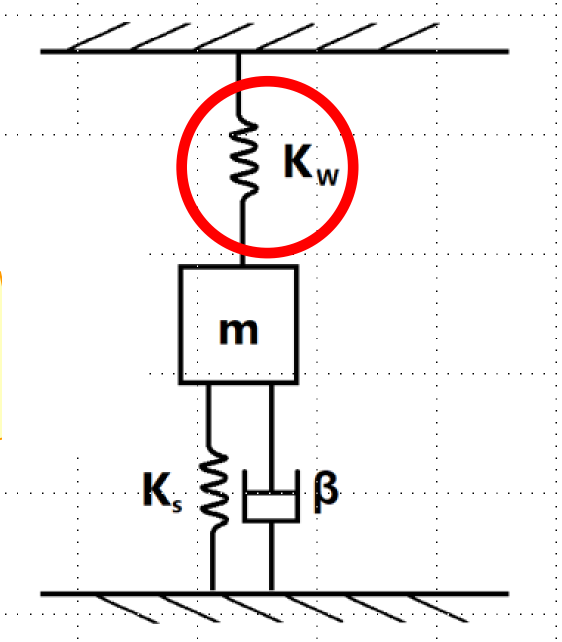
  - A mechanical load is applied to the material to obtain the detwinned martensite and stretch the wire.

Spring force + sleigh weight to generate the mechanical load.

SMA

- **SMA wire model:**
    - Thermal part: input: voltage/power/current; output: $T, \dot{T}$ (see [1] section II and [2] section 3.1).
    - Hysteresis part: input $T, \dot{T}$; output R_m (see [1] section III and [2] section 3.2).
    - Mechanical part: it's important to model properly the elastic/plastic behaviour of the wire according to its phase (see [1] section IV and [2] section 3.3).

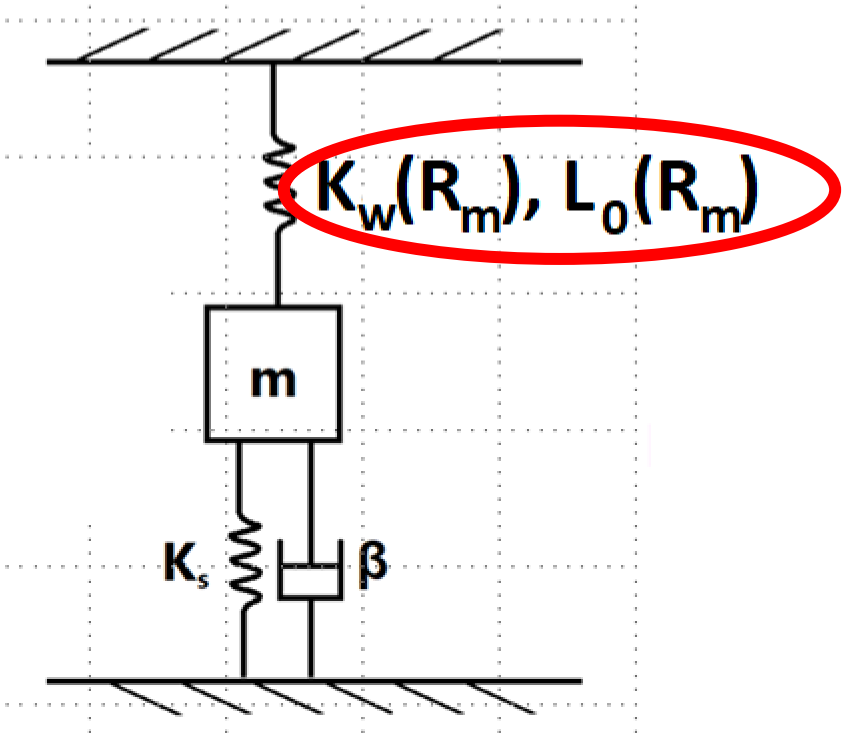
Adjust the model parameters in order to obtain a simulative behaviour similar to the one of your the test bench.



- **SMA wire control:**
    - PI, PID

You can't control the cooling phase.

- **Mechanical model:**
  - We can model the wire as a spring with variable stiffness and variable rest length. Both the stiffness and the rest length depends on R_m.



The Test bench

- SMA wire
  - Name: *Flexinol®* , Dynalloy, Inc.
  - Length: about 1m
  - Datasheet:
    - http://www.dynalloy.com/pdfs/TCF1140.pdf

Diameter: **0,5mm** (0.02in)
Wire type: **HT 90 *C** (high temperature)
Resistance: **4.3 ohm/m**

	LT	HT
As (°C)	**68**	**88**
Af (°C)	**78**	**98**
Ms (°C)	**52**	**72**
Mf (°C)	**42**	**62**

Fusion Temperature: **1.300°C**

The Test bench

- **SMA wire**

Phase	MARTENSITE	AUSTENITE
Electrical resistivity (µΩcm)	**76**	82
Young module	**28-40**	**75-83**
Magnetic susceptibility (µemu/g)	**2,5**	**3,8**
Thermal conductivity (W/cm°C)	**0,08**	**0,18**
Thermal expansion coefficient (1/°C)	**6.6e-6**	**11e-6**

Current for 1s contraction	**4000 mA**
Poisson ratio	**0.33**
Density	**6,45 g/cm3**
Specific heat	**0,2 cal/g°C**
Latent Heat of Transformation	**24,2 Joule/g**
Suggested max return force	**560 Mpa**(about 43 ton per inch^2)
Suggested return force	**187 Mpa** (about 13 ton per inch^2)
Suggested deformation force	**35 Mpa** (about 2,5 ton per inch^2)
Ultimate Tensile Strength (Mpa)	**1.000** (about 71 ton per nch^2)
Work	**1 Joule/g**
Suggested deformation	**3-5%**

The Test bench

- Spring
  - Datasheet: http://it.rs-online.com/ product code: **0821453**

Material: **Stainless steel**
Free Length: **37.7mm**
Max Length: **116.10mm**
External diameter: **5.5mm**
Wire diameter: **0.5mm**
Initial stress: **6.50N**
Elastic constant: **0.07N/mm**

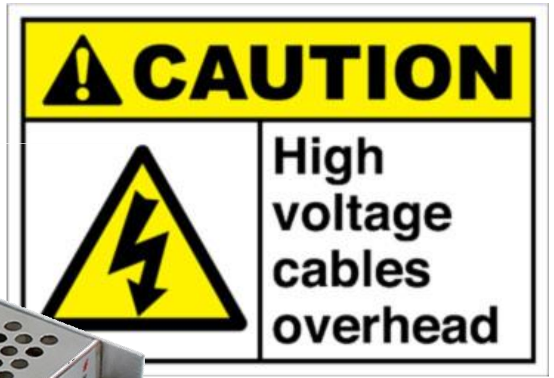
  - Force equation:

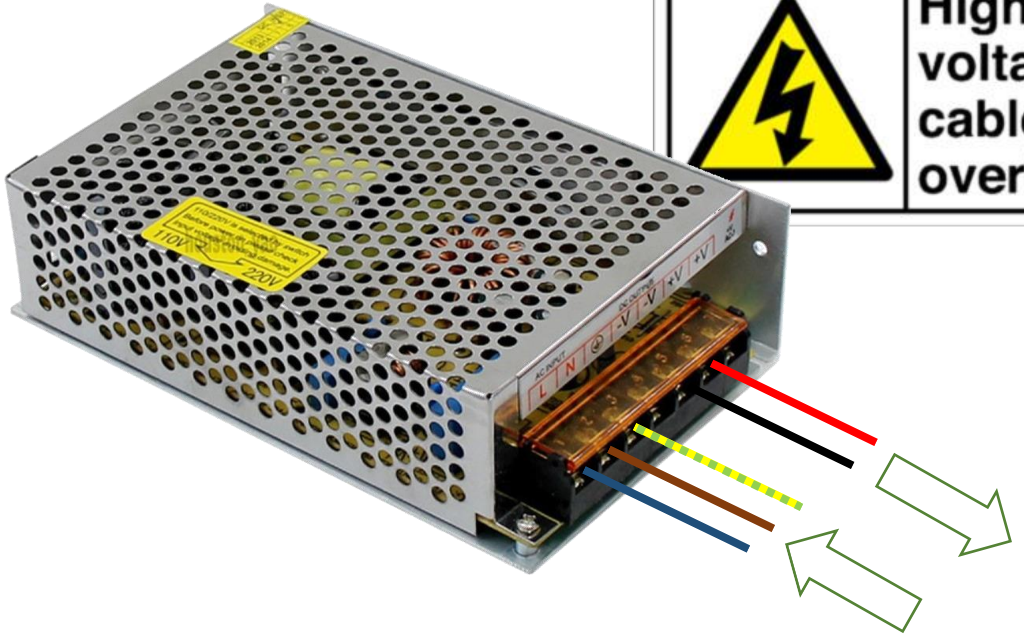
$$F_{EL} = F_{INIT} + K \cdot \Delta x$$

The Test bench

- Power supply
  - It converts 220V AC to 24V DC

Power: **240W**
Dimension**: 200x110x50mm**
Input voltage AC: **100/240V**
Output voltage DC: **24V**
Output current: **10A**
IP code: **IP20**
Material: **Alluminum**



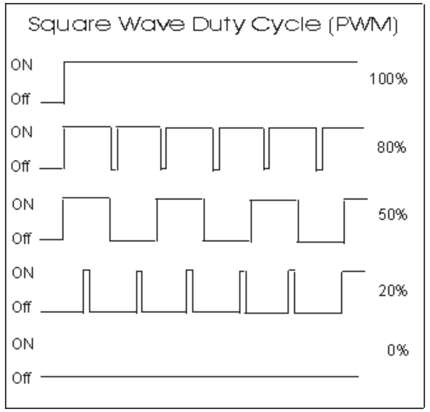


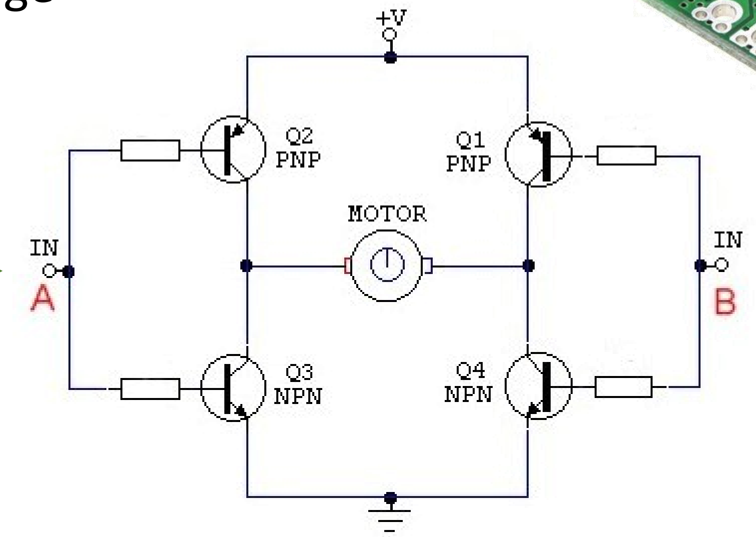
- How to control the current provided to the wire?

The Test bench

- **Driver**
  - Name: VNH5019® , ST Microelectronics.
  - Full bridge motor driver that implements a H-bridge

*The **duty** is a percent of the maximum voltage (24V in this case)*

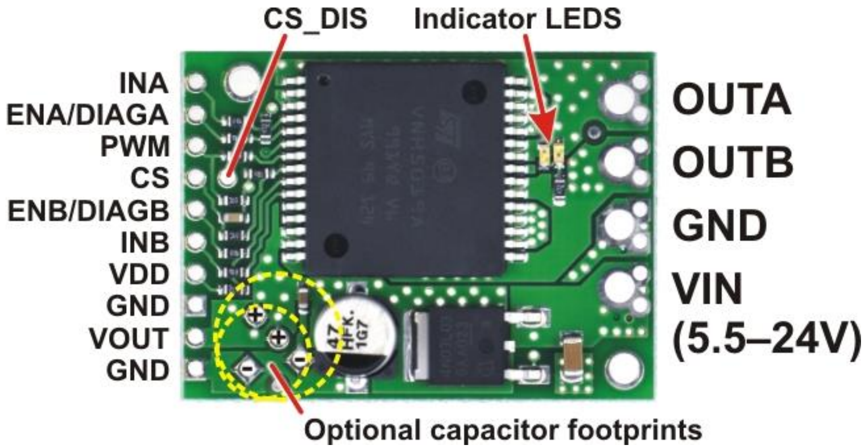




  - Datasheet and useful link:
    - http://www.st.com/en/automotive-analog-and-power/vnh5019a-e.html
    - https://www.pololu.com/product/1451
    - http://www.st.com/content/ccc/resource/technical/document/data_brief/3b/bf/c3/13/d5/b2/4c/b0/DM00101248.pdf/files/DM00101248.pdf/jcr:content/translations/en.DM00101248.pdf

The Test bench

- **Driver**
  - Configuration used:



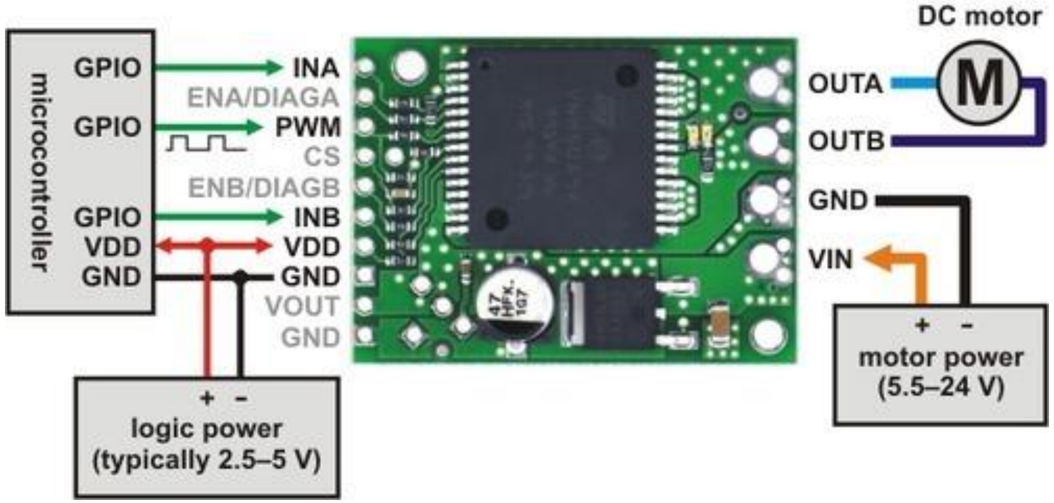
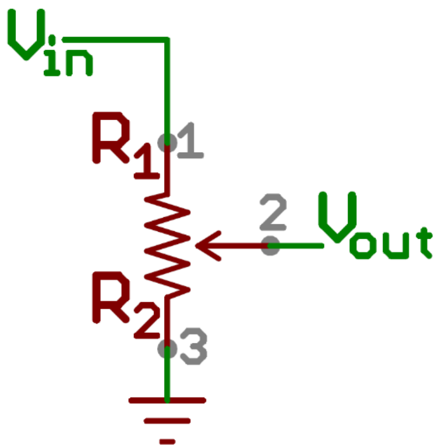


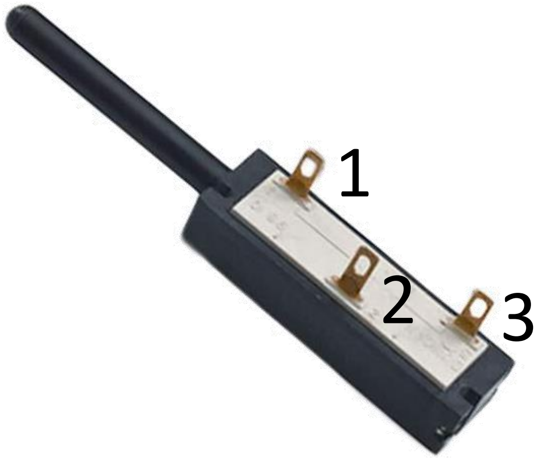
Table 12. Truth table in normal operating conditions

IN_A	IN_B	$DIAG_A/EN_A$	$DIAG_B/EN_B$	OUT_A	OUT_B	CS ($V_{CSD} = 0$ V)	Operating mode
1	1	1	1	H	H	High imp.	Brake to V_{CC}
1	0	1	1	H	L	$I_{SENSE} = I_{OUT}/K$	Clockwise (CW)
0	1	1	1	L	H	$I_{SENSE} = I_{OUT}/K$	Counterclockwise (CCW)
0	0	1	1	L	L	High imp.	Brake to GND

- Position sensor
  - Name 9615R5.1KL2.0, BEI Sensors
  - Spring-return linear-position sensor designed for space-limited and harsh operating environment based on the voltage divider circuit idea.

Active travel: **39.6mm (1.5inches)**
Dimension**: 98.3x16.1x12.7mm**
Resistance: **5.10 KOhm**
Sealing: **IP40**
Material: **Plastic**



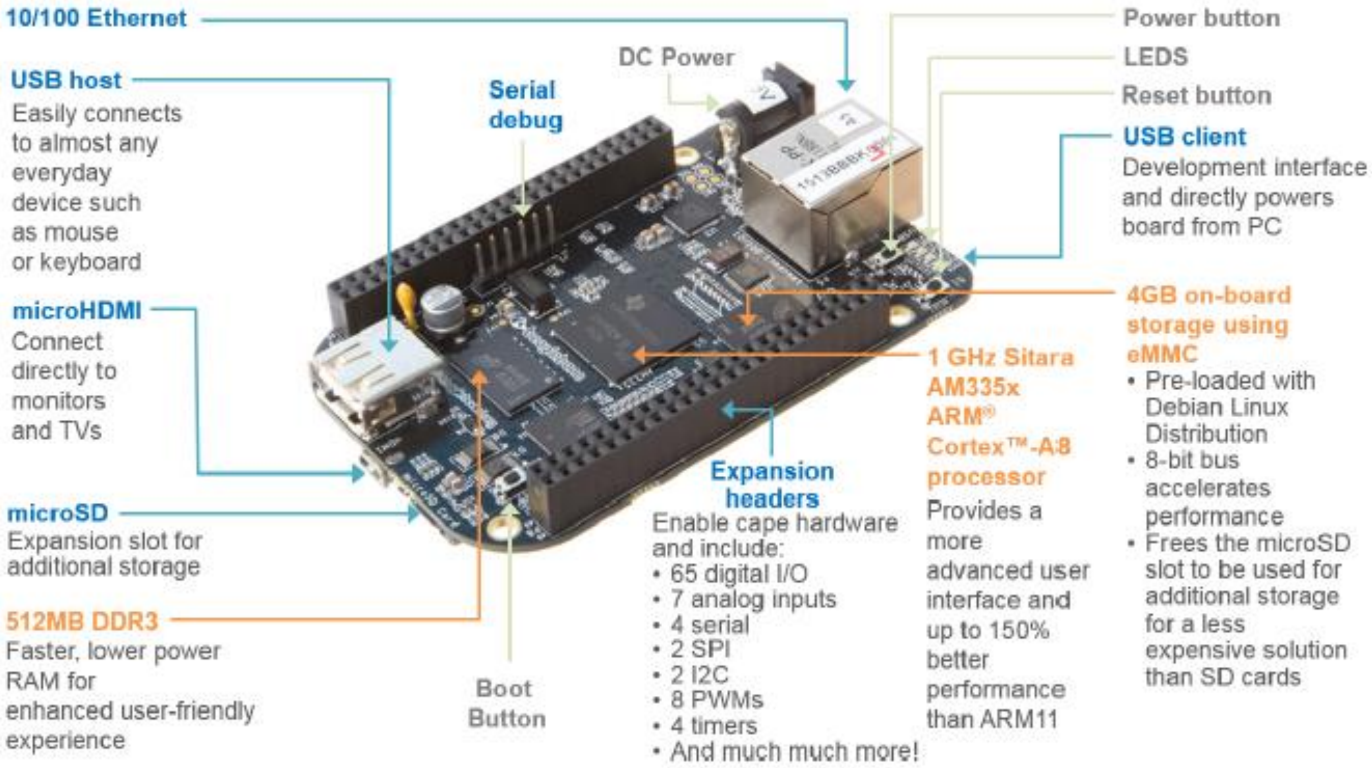


- Datasheet:
  - http://ecatalog.beisensors.com/viewitems/linear-position-sensors/linear-position-sensor-9600-series-compact-spri?#

The Test bench

- Control board
  - Name: Beaglebone Black

  - It is a low-cost development platform with a default Linux based OS



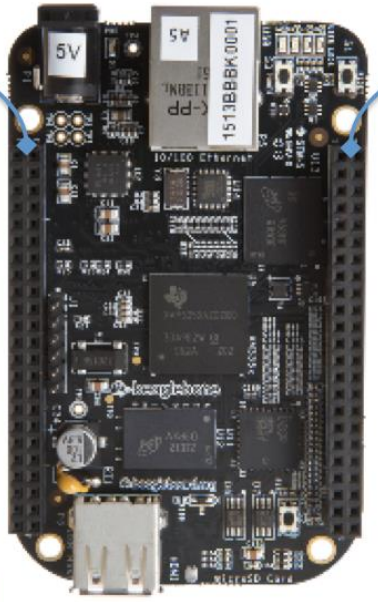
  - Datasheet:
    - https://beagleboard.org/black

The Test bench

- Control board
  - Pinout:

P9

DGND	1	2	DGND
VDD_3V3	3	4	VDD_3V3
VDD_5V	5	6	VDD_5V
SYS_5V	7	8	SYS_5V
PWR_BUT	9	10	SYS_RESETN
UART4_RXD	11	12	GPIO_60
UART4_TXD	13	14	EHRPWM1A
GPIO_48	15	16	EHRPWM1B
SPI0_CS0	17	18	SPI0_D1
I2C2_SCL	19	20	I2C2_SDA
SPI0_D0	21	22	SPI0_SCLK
GPIO_49	23	24	UART1_TXD
GPIO_117	25	26	UART1_RXD
GPIO_115	27	28	SPI1_CS0
SPI1_D0	29	30	GPIO_112
SPI1_SCLK	31	32	VDD_ADC
AIN4	33	34	GNDA_ADC
AIN6	35	36	AIN5
AIN2	37	38	AIN3
AIN0	39	40	AIN1
GPIO_20	41	42	ECAPPWM0
DGND	43	44	DGND
DGND	45	46	DGND

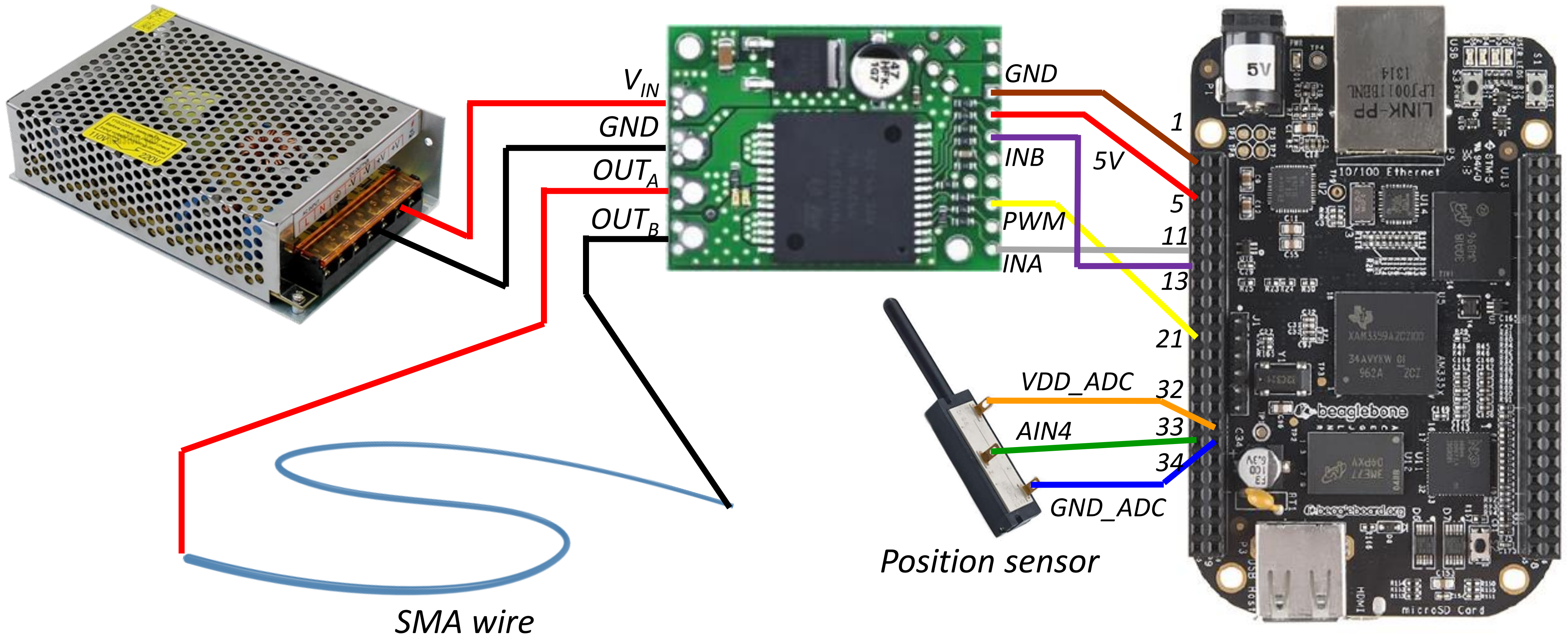


LEGEND
POWER/GROUND/RESET
AVAILABLE DIGITAL
AVAILABLE PWM
SHARED I2C BUS
RECONFIGURABLE DIGITAL
ANALOG INPUTS (1.8V)

P8

DGND	1	2	DGND
MMC1_DAT6	3	4	MMC1_DAT7
MMC1_DAT2	5	6	MMC1_DAT3
GPIO_66	7	8	GPIO_67
GPIO_69	9	10	GPIO_68
GPIO_45	11	12	GPIO_44
EHRPWM2B	13	14	GPIO_26
GPIO_47	15	16	GPIO_46
GPIO_27	17	18	GPIO_65
EHRPWM2A	19	20	MMC1_CMD
MMC1_CLK	21	22	MMC1_DAT5
MMC1_DAT4	23	24	MMC1_DAT1
MMC1_DAT0	25	26	GPIO_61
LCD_VSYNC	27	28	LCD_PCLK
LCD_HSYNC	29	30	LCD_AC_BIAS
LCD_DATA14	31	32	LCD_DATA15
LCD_DATA13	33	34	LCD_DATA11
LCD_DATA12	35	36	LCD_DATA10
LCD_DATA8	37	38	LCD_DATA9
LCD_DATA6	39	40	LCD_DATA7
LCD_DATA4	41	42	LCD_DATA5
LCD_DATA2	43	44	LCD_DATA3
LCD_DATA0	45	46	LCD_DATA1

- Final circuit



First steps

- Read the pdf guide «BBBConfiguration» to connect the Beaglebone to your Laptop and your Matlab.
- In this file you will find also the procedure to follow to take confidence with the physical plant.
- Read carefully the Important Notes!

Bibliography

- [1] Dutta SM, GhorbelFH. *Differential hysteresis modeling of a shape memory alloy wire actuator*. IEEE/ASME Transactions on Mechatronics. 2005 Apr; 10(2): 189-97.
- [2] Romano R., Tannuri EA. *Modeling, Control and experimental validation of a novel actuator based on shape memory alloys*. Mechatronics. 2009 Oct 1; 19(7): 1169-77.
- *Shape Memory Alloys*, Dimitris C. Lagoudas, Springer, 2008
- https://www.mathworks.com