SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA
FACULTY OF MECHANICAL ENGINEERING

MagnetoShield: Prototype of a Low-Cost Magnetic Levitation Device for Control Education

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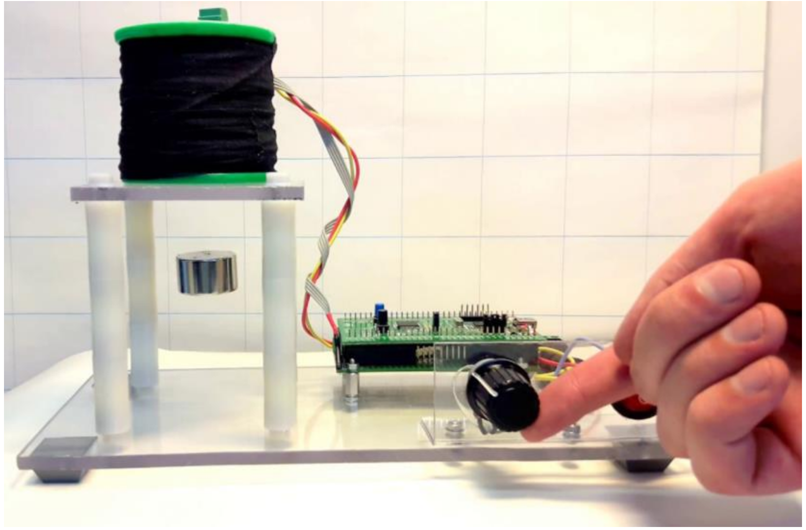
Institute of Automation, Measurement and Applied Informatics

Motivation: Commercial laboratory devices

- Teaching control engineering and mechatronics requires laboratory tools – "trainers" – for hands-on experience.
- Commercial tools are expensive, large, complicated and cannot be taken home by students.
- Many require closed-source software (e.g. MATLAB, LabView), and accessories (amplifiers, control PC, etc.)
- Implementation on microcontroller units (MCU) is under-represented

Motivation: Improvised laboratory devices

One of a kind improvised designs that are local to a laboratory or a small research team.



Pro:

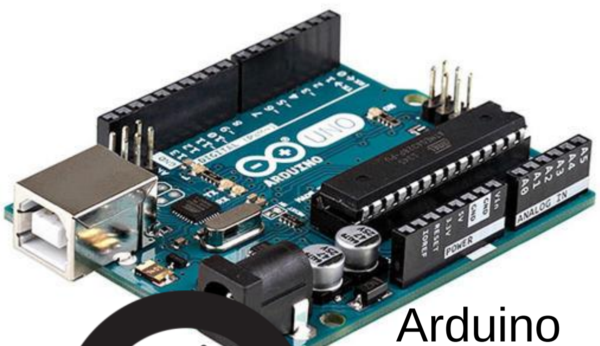
- Cheap!

Contra:

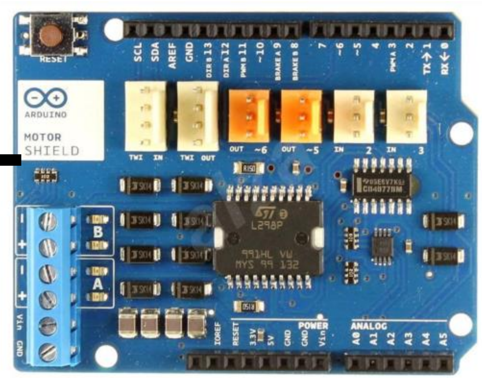
- Fragile, sensitive setups
- Not very well documented
- Cannot create teaching materials across several universities as an open course

Motivation: Arduino, a universal platform to build on

- Cheap
- Open source
- Easy to buy
- Standardized
- Free integrated development environment (IDE)
- Great community and abundance of learning materials
- Easy hardware expansion through so- called Shields


Arduino

+


Shield (Motor control)

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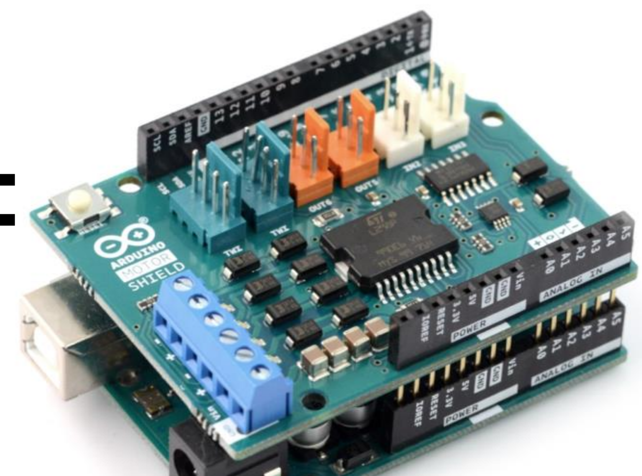


Motivation: New tools for mechatronics education

AutomationShield
Control Systems Engineering Education
www.automationshield.com

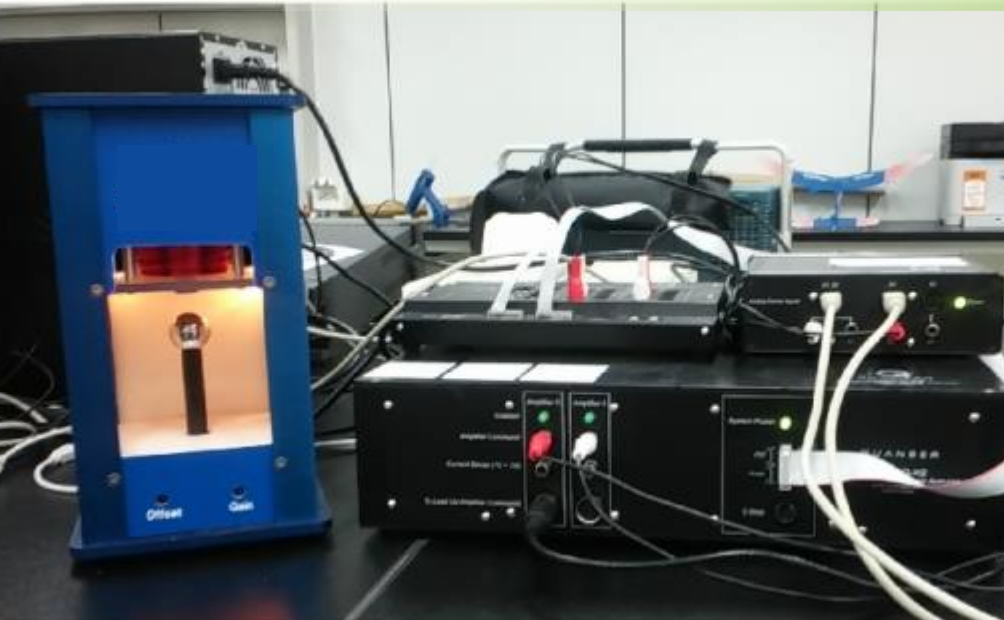
Create novel tools for control engineering education, implementing a lab experiment on a single Arduino expansion Shield, essentially a tiny mechatronics laboratory in the palm of your hand that is

- Cheap
- Open source
- Possible to build at home even by beginners (DIY)
- Standardized
- Free software library compatible with the Arduino IDE

Motivation: Commercial magnetic levitation devices

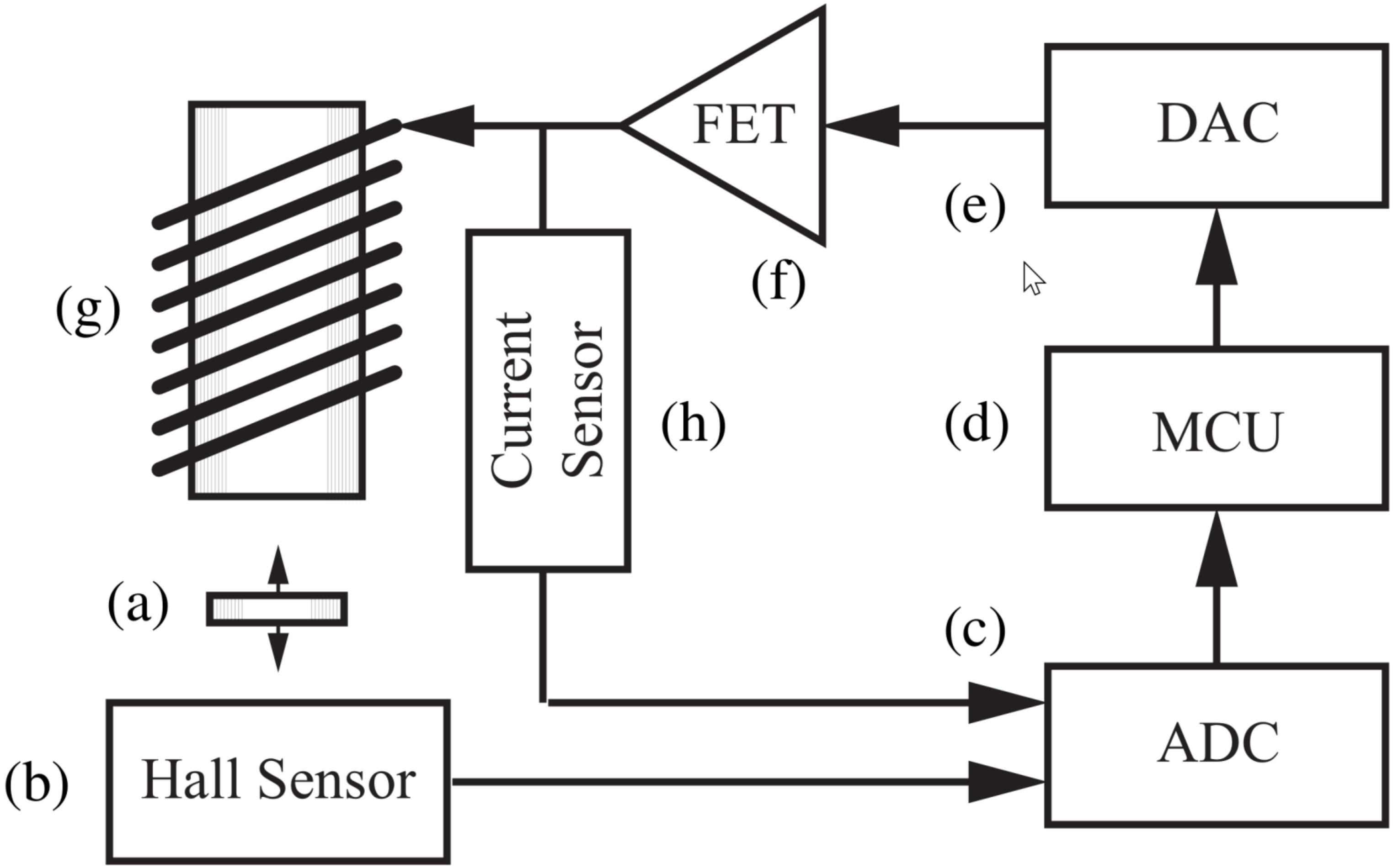
~25000 EUR

Motivation: Commercial MLD: large, expensive...

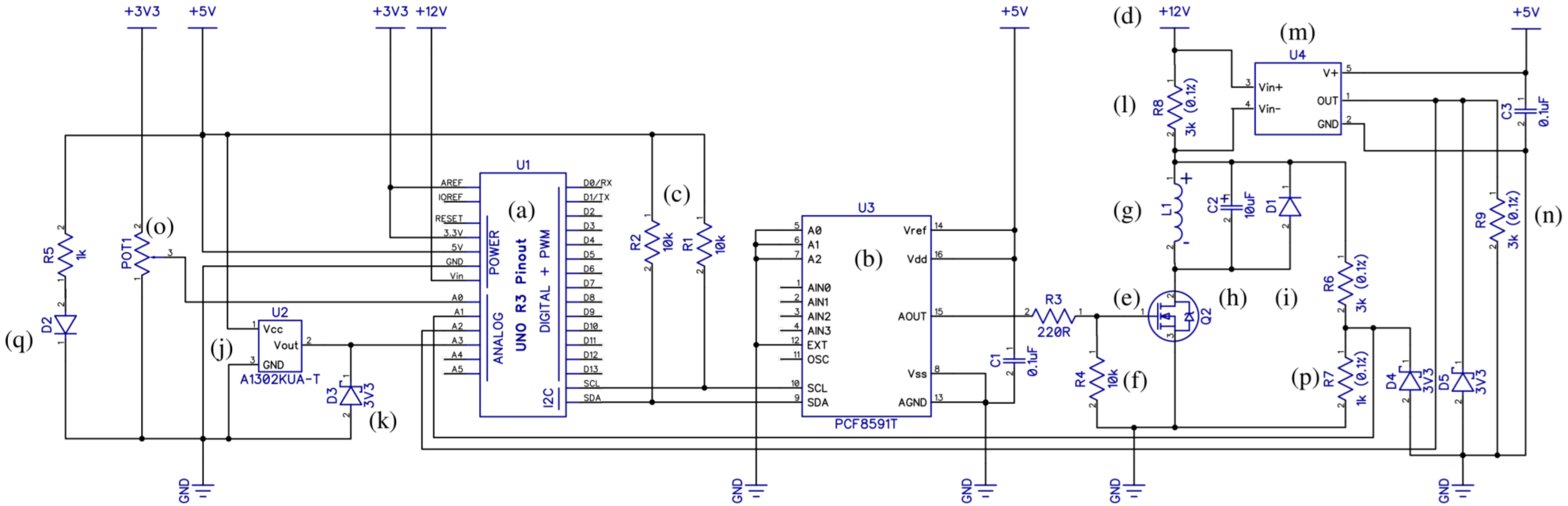


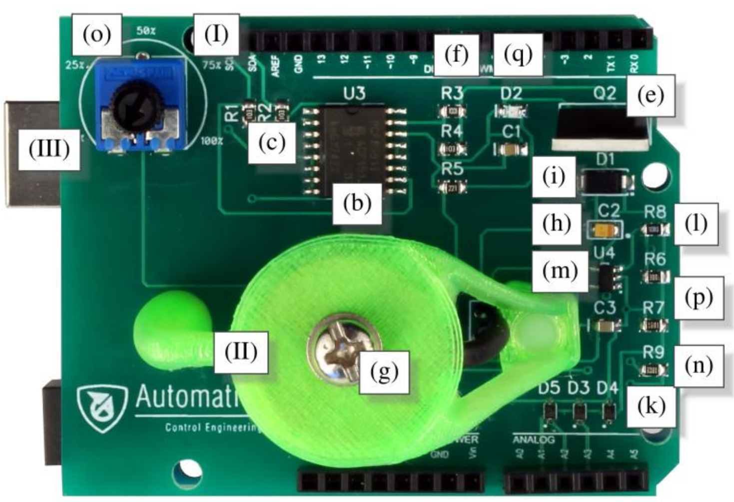
Introducing the MagnetoShield

MagnetoShield: Basic functionality

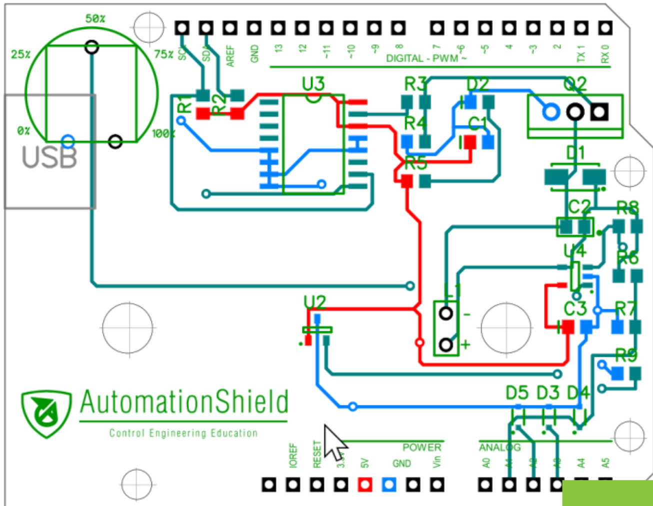


MagnetoShield: Electronics

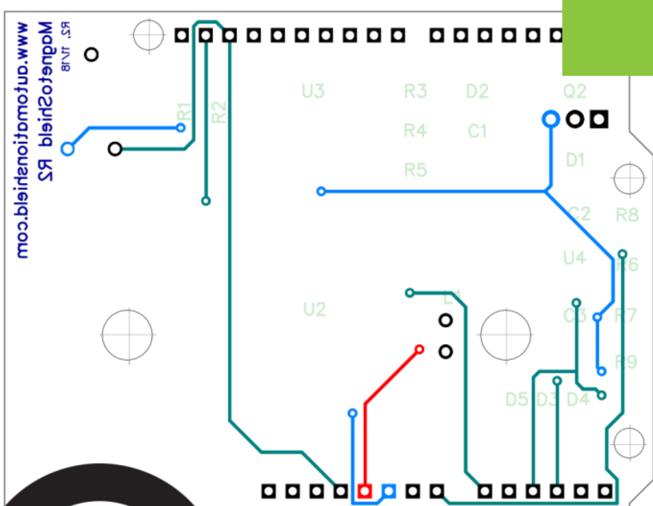




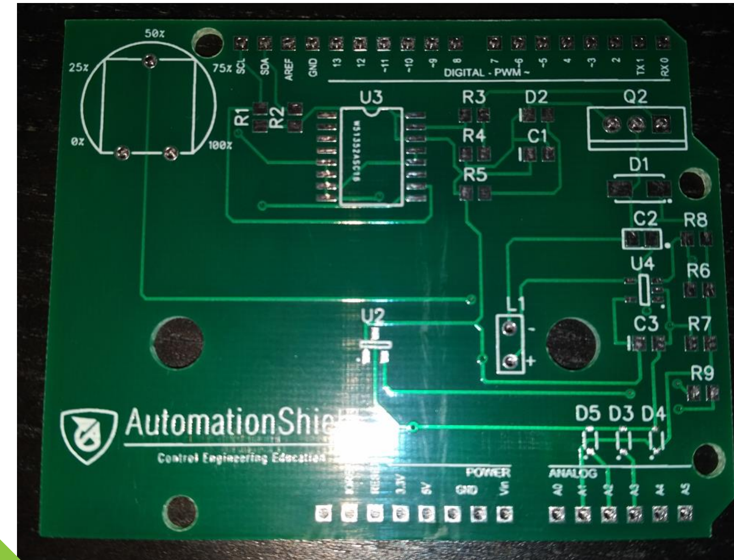
MagnetoShield: Open-source hardware

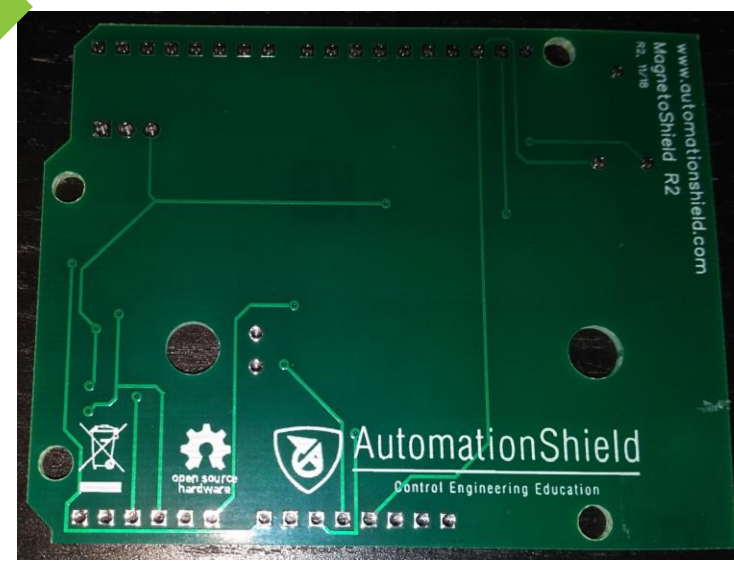


(a) Top layer.



(b) Bottom layer.





MagnetoShield: Approximate price is <10 EUR!

Name	Part no., value.	Designator	Mark	Pcs.	Price	Total
3D print	5.7 g ϕ=1.75 mm PETG filament, bright green, at 240°C (90°C bed)	-	-	1	0.18	0.18
Capacitor	0805, ceramic, 0.1 μF (e.g. KEMET C0805C104K3RACTU, 25 V)	C1,C3	-	2	0.13	0.26
Capacitor	0805, tantalum, 10 μF (e.g. AVX TAJR106M010RNJ, 10 V)	C2	(h)	1	0.10	0.10
Enclosure top	clear acrylic; e.g. h=2 mm, stamped to the outer diameter of the tube	-	-	1	0.05	0.05
Current sensor	Texas Instruments INA169	U4	(m)	1	1.07	1.07
DAC	NXP Semiconductors PCF8591T	U3	(b)	1	0.79	0.79
Diode	DO214AC (e.g. Vishay Semiconductor BYG20J, 1.5 A, 600 V)	D1	(i)	1	0.15	0.15
Hall sensor	Allegro Microsystems A1302ELHLT-T	U2	(j)	1	0.71	0.71
Header	6x1, female, 2.54 mm pitch	-	-	1	0.07	0.07
Header	8x1, female, 2.54 mm pitch	-	-	2	0.10	0.20
Header	10x1, female, 2.54 mm pitch	-	-	1	0.10	0.10
LED	0805, red	D2	(q)	1	0.16	0.16
Magnet	NdFeB, disc, ϕ=8 mm, h=2 mm, N38	-	-	1	0.09	0.09
MOSFET	IRF520	Q2	(e)	1	0.22	0.22
PCB	2 layer, FR4, 1.6 mm thick	-	-	1	0.23	0.23
Pot	10 k, 250 mW (e.g. ACP CA14NV12,5-10KA2020)	POT1	(o)	1	0.10	0.10
Resistor	10 kΩ, 0805	R1,R2,R4	(c),(f)	3	0.01	0.03
Resistor	3 kΩ, 0805, 0.1%, 0.125 W (e.g. Viking AR05BTCW3001)	R6, R9	(n),(p)	2	0.35	0.71
Resistor	1 kΩ, 0805, 0.1%, 0.125 W (e.g. Viking AR05BTCW1001)	R7	(p,q)	1	0.08	0.16
Resistor	220 Ω, 0805	R3	(f)	1	0.01	0.01
O-Ring	rubber, M12, h=1 mm, e.g. ϕ=18 mm (outer),	-	-	1	0.03	0.03
Screws	polyamid, M3x8	-	-	2	0.01	0.03
Shaft	ACP CA9MA9005			1	0.12	0.12
Shunt	10 Ω, 0805, 0.1%, 0.1 W (e.g. ROYAL OHM TC0525B0100T5)	R8	(l)	1	0.47	0.47
Solenoid	ELE-P20/15, ϕ=20 mm, h=15 mm, 12/24 V, 25 N	L1	(g)	1	2.67	2.67
Enclosure tube	clear, Plexiglas XT, h=8 mm, ϕ=10 mm (inner), ϕ=12 mm (outer)	-	-	1	0.03	0.03
Zener diode	3.3V, SOD323 (e.g. NEXPERIA BZX384-C3V3.115)	D3–D5	(k)	3	0.02	0.06
					Total:	**$8.79**

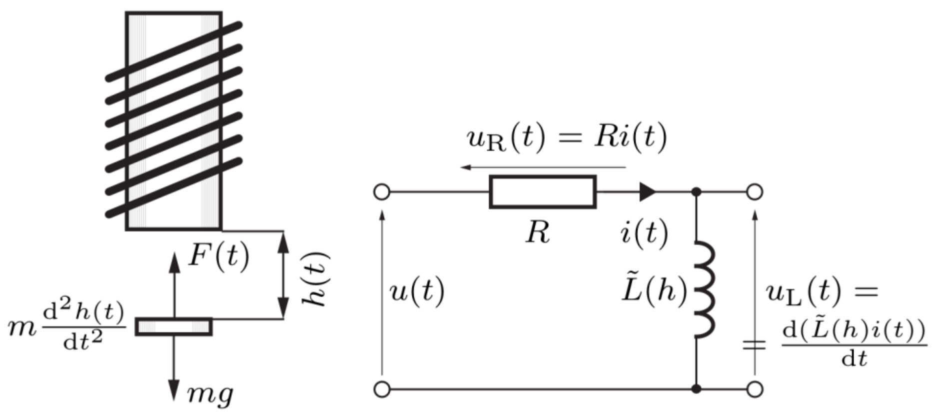
MagnetoShield: Programmer's interface

All simplified and included within the "AutomationShield" library for the free Arduino IDE:

- Calibrate height reading
```
MagnetoShield.calibration();
```
- Read object height to *y*
```
y=MagnetoShield.sensorRead();
```
- Send a certain voltage *u* to solenoid
```
MagnetoShield.actuatorWrite(u);
```
- Read current in solenoid to *i*
```
i=MagnetoShield.auxReadCurrent();
```
- Read external reference *r*
```
r=MagnetoShield.referenceRead();
```

MagnetoShield: Modeling

Symbol	Description	Unit
$h(t)$	Instantaneous distance from solenoid	m
m	Mass of the magnet	kg
$i(t)$	Instantaneous solenoid current	A
K	Magnetic force constant	$\mathrm{Nm^2A^{-2}}$
L	Solenoid inductance	H
R	Solenoid resistance	Ω
$u(t)$	Instantaneous solenoid voltage	V
F	Magnetic force	N
$B(t)$	Instantaneous magnetic flux density	G
N	Number of turns on the solenoid	-
A	Active cross sectional area of the solenoid	$\mathrm{m^2}$
μ	Permeability of air	$\mathrm{NA^{-2}}$
μ_0	Vacuum permeability	$\mathrm{NA^{-2}}$
g	Gravitational acceleration	$\mathrm{m\,s^{-2}}$



(a) Mechanical. (b) Electrical.

Dynamics:

$$\frac{\mathrm{d}^2h(t)}{\mathrm{d}t^2} = g - \frac{K}{m}\frac{i(t)^2}{h(t)^2},$$
$$\frac{\mathrm{d}i(t)}{\mathrm{d}t} = \frac{2K}{L}\frac{i(t)}{h(t)^2}\frac{\mathrm{d}h(t)}{\mathrm{d}t} - \frac{R}{L}i(t) + \frac{1}{L}u(t)$$

Transfer function:

$$G(s) = \frac{\Delta H(s)}{\Delta U(s)} = \frac{-\left(\frac{2Ki_0}{mLh_0^2}\right)}{\left(s^2 - \left(\frac{2Ki_0^2}{mh_0^3}\right)\right)\left(s + \frac{R}{L}\right) + \left(\frac{4K^2i_0^2}{mLh_0^4}\right)s}$$

State-space representation:

$$\dot{x}_1(t) = x_2(t),$$
$$\dot{x}_2(t) = g - \frac{K}{m}\frac{x_3(t)^2}{x_1(t)^2},$$
$$\dot{x}_3(t) = \frac{2K}{L}\frac{x_2(t)x_3(t)}{x_1(t)^2} - \frac{1}{L}Rx_3(t) + \frac{1}{L}u(t)$$

MagnetoShield: Examples for DAQ and identification

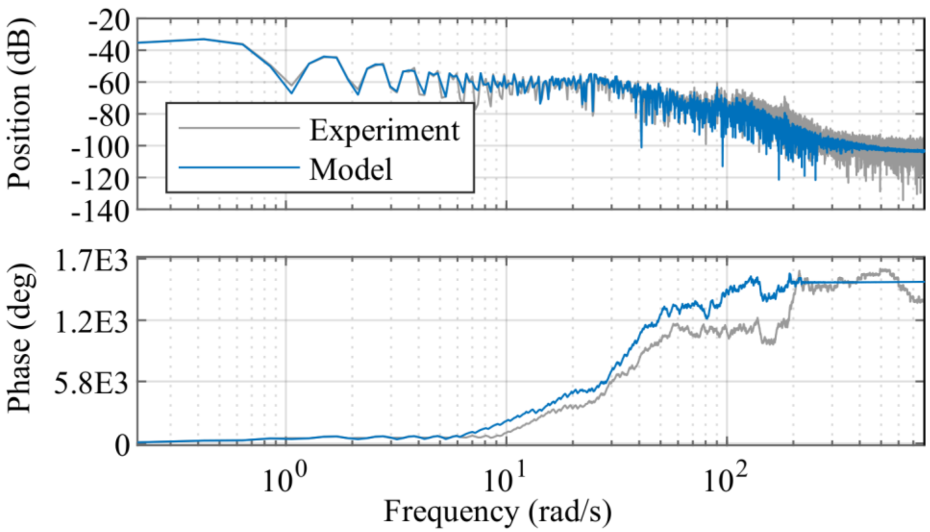
System identification experiment for data collection, and parameter estimation using the MATLAB System Identification Toolbox.

```
      step();                              // Algorithm step
      enable=false;                        // Then disable until next interrupt
    }
  }

  void stepEnable(){                       // This is the ISR
    if(enable){                            // If step still running
    realTimeViolation=true;                // RT has been violated
    while(1);                              // Stop
    }                                      // Else
    enable=true;                           // change flag and run step
  }

  // A single algoritm step
  void step(){

  // Experiment control
  if (i>sizeof(R)/sizeof(R[0])){           // If finished
    MagnetoShield.actuatorWrite(0);        // Turn off magnet
    while(1);                              // and do nothing
  }
  else if (k % (T*i) == 0){                // else for each section
    r = R[i];                              // set reference
    i++;                                   // increment section counter
  }

  w=wBias-(float)random(0,wP)/100.0;       // [V] Input noise
  y = MagnetoShield.sensorRead();          // [mm] Sensor Read
  I = MagnetoShield.auxReadCurrent();      // [mA] Current read
  u =          (r-y),0.0,12.0,0.0,5.0)+w;       // [V] PID + noise
     omationSh     nstrainFloat(u,0,12);
     etoShie   actuat   te(u);             // Actuate
```

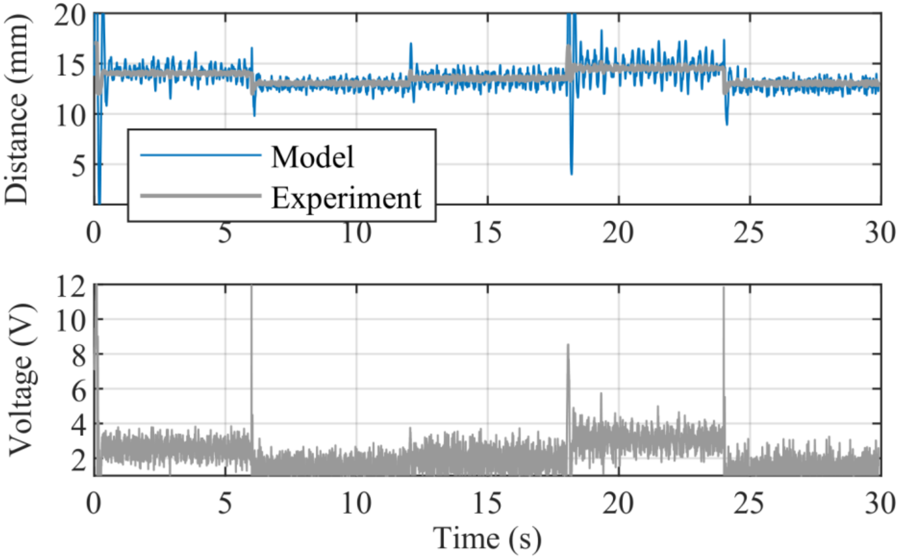
```
beta=2*(Km/m)*u0/y0^2;                     % Linearized parameter guess
gamma=2*Km*mean(i)/(L*y0^2);               % Linearized parameter guess
delta=R/L;                                 % Parameter guess
epsilon=1/L;                               % Parameter guess

%% Construct model
if fixedInductance==1                      % Magnet inductance L fixed
    A=[0       1    0;
       alpha   0    -beta
       0       0    -delta];

elseif  fixedInductance==0                 % Magnet inductance L(y) distance dependent

    A=[0       1        0;                 % Dybamic matrix initial guess
       alpha   0        -beta
       0       gamma    -delta];
end

B=[0; 0; epsilon];                         % Input matrix
C=[1 0 0;                                  % Output matrix
   0 0 1];                                 % Distance and current measured
D=[0; 0];                                  % No feed-through
K = zeros(3,2);                            % Disturbance
x0=[h0; dh0; i0];                          % Initial condition
disp('Initial guess:')
sys=idss(A,B,C,D,K,x0,0)                   % Construct state-space representation
```

MagnetoShield: Identification (TF) - Results

$$G(s) = \frac{\Delta H(s)}{\Delta U(s)} = \frac{-3033}{s^3 + 829.7s^2 + 1126s - 4.52\text{E}5}$$



(a) Frequency domain comparison.



(b) Closed-loop simulation.

MagnetoShield: Identification (SS) - Results

$$\Delta\dot{\mathbf{x}}(t) = \begin{bmatrix} 0 & 1 & 0 \\ \alpha & 0 & -\beta \\ 0 & \gamma & -\delta \end{bmatrix} \Delta\mathbf{x}(t) + \begin{bmatrix} 0 \\ 0 \\ \epsilon \end{bmatrix} \Delta u(t)$$

TABLE III
INITIAL GUESS AND ESTIMATE OF VARIOUS MODEL PARAMETERS

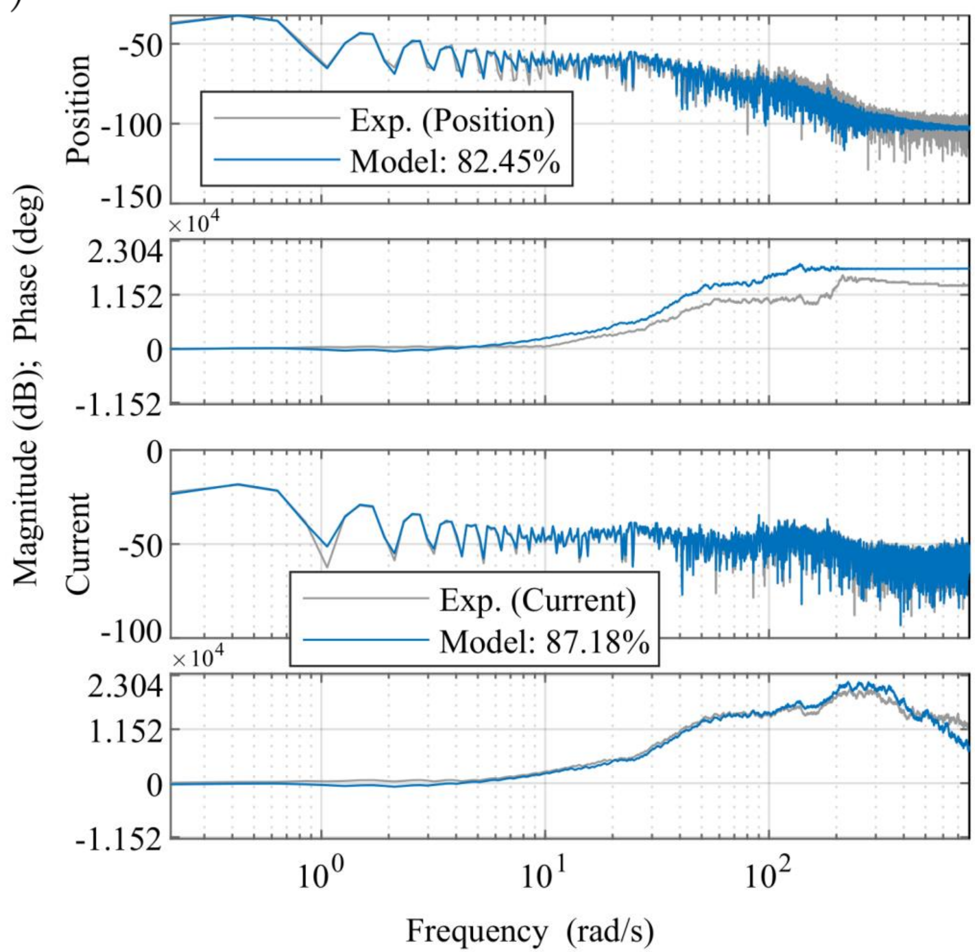
Symbol	Measured or initialized	Identified	Unit
m	7.60E−04	-	kg
K	2E−6, 5E−3	1.6E−6, 4.9E−5	$\mathrm{Nm^2A^{-2}}$
L	0.239	0.175	H
R	198	236	Ω
α	6300	1853	$\mathrm{Nm^{-2}}$
β	46.4	365.1	$\mathrm{NAm^{-1}}$
γ	7.24E−04	2.537	$\mathrm{NA^{-1}H^{-1}}$
δ	829.7	1345	$\Omega\ \mathrm{H^{-1}}$
η	4.184	5.71	$\mathrm{H^{-1}}$

where

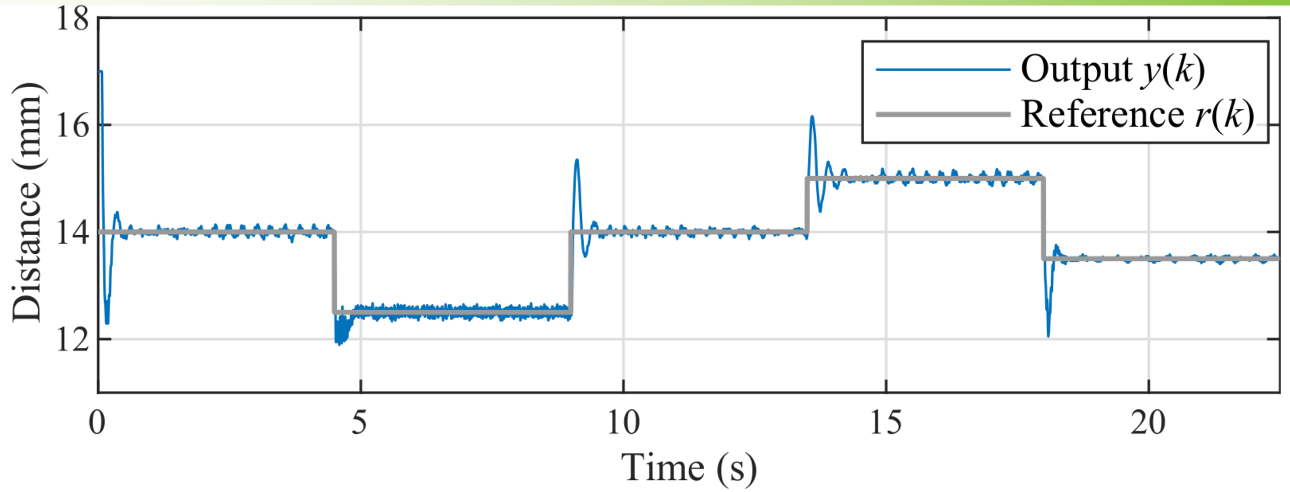
$$\alpha = \frac{2K}{m}\frac{x^2_{3(0)}(t)}{x^3_{1(0)}(t)}, \qquad \beta = \frac{2K}{m}\frac{x_{3(0)}(t)}{x^2_{1(0)}(t)},$$

$$\gamma = \frac{2Kx_{3(0)}(t)}{Lx^2_{1(0)}(t)}, \qquad \delta = \frac{1}{L}R,$$

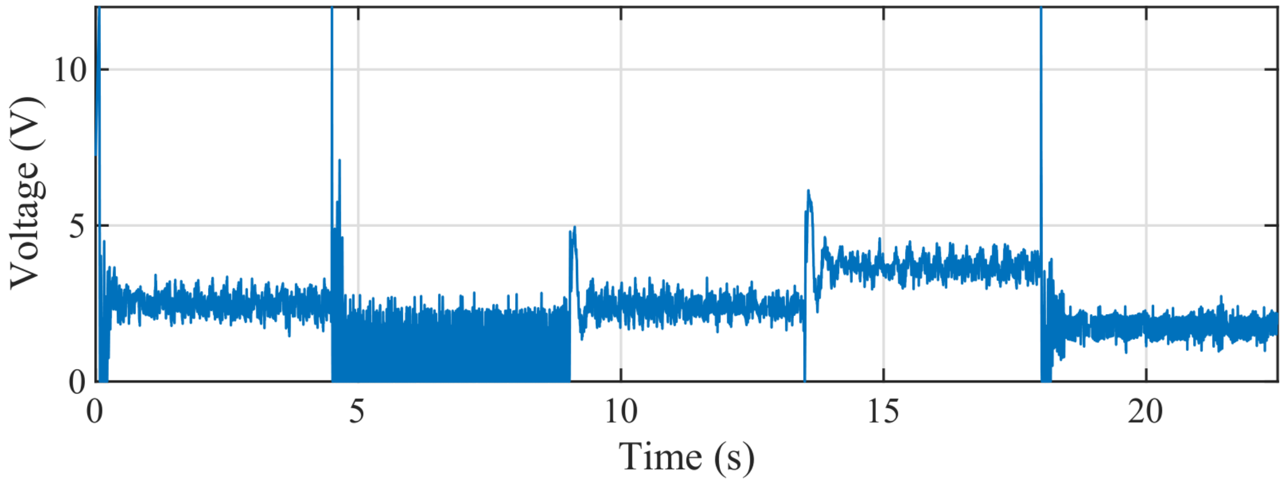
$$\epsilon = \frac{1}{L}.$$



MagnetoShield: Control example (PID) - Results

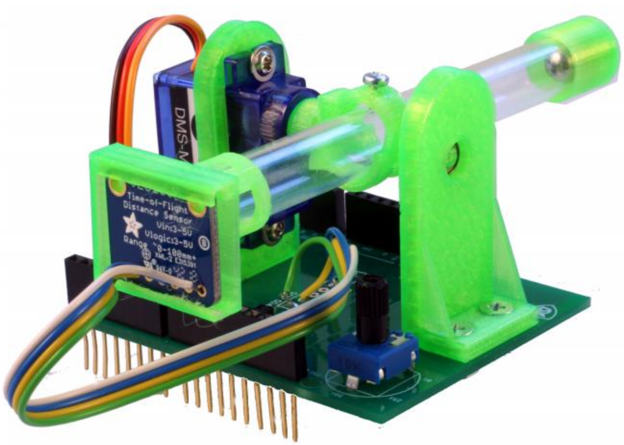


(a) Magnetic disc position.



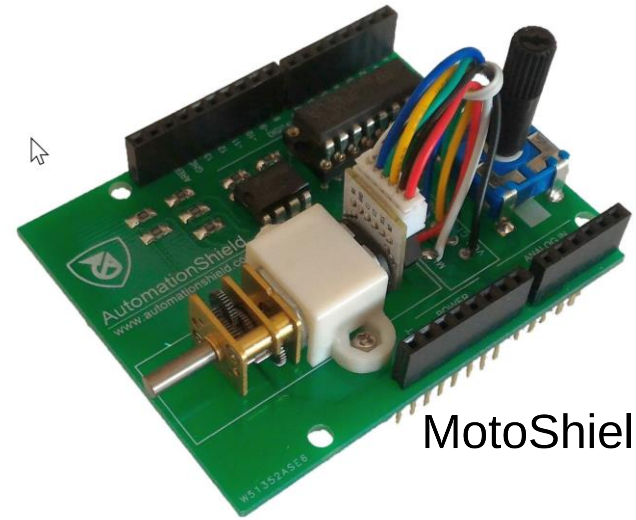
(b) Input voltage.

Other shields within our initiative



BOBShield (Ball On Beam)

FloatShield



MotoShield

LinkShield

OptoShield

HeatShield

The current pandemic situation…

“Take-home” laboratories would be highly desirable for many institutions at this unusual times…

(Several of my students have the “AutomationShield” devices currently at home and thus are a lot less worried about their thesis projects.)

Thank you for your attention!

Visit www.automationshield.com for more details

and please feel free to contact me any time via:

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researchgate.net/profile/Gergely_Takacs

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