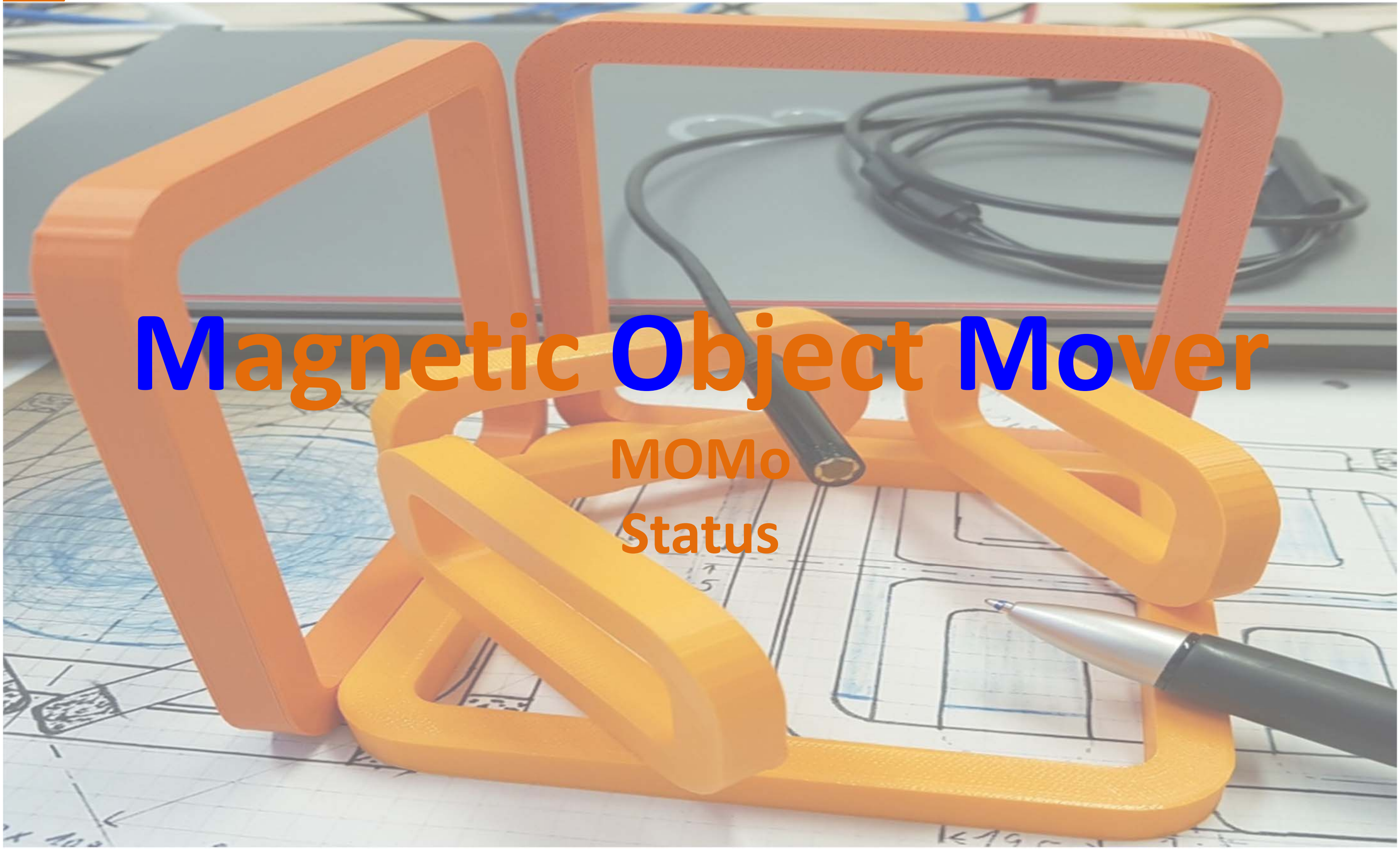
Magnetic Object Mover

MOMo

Status



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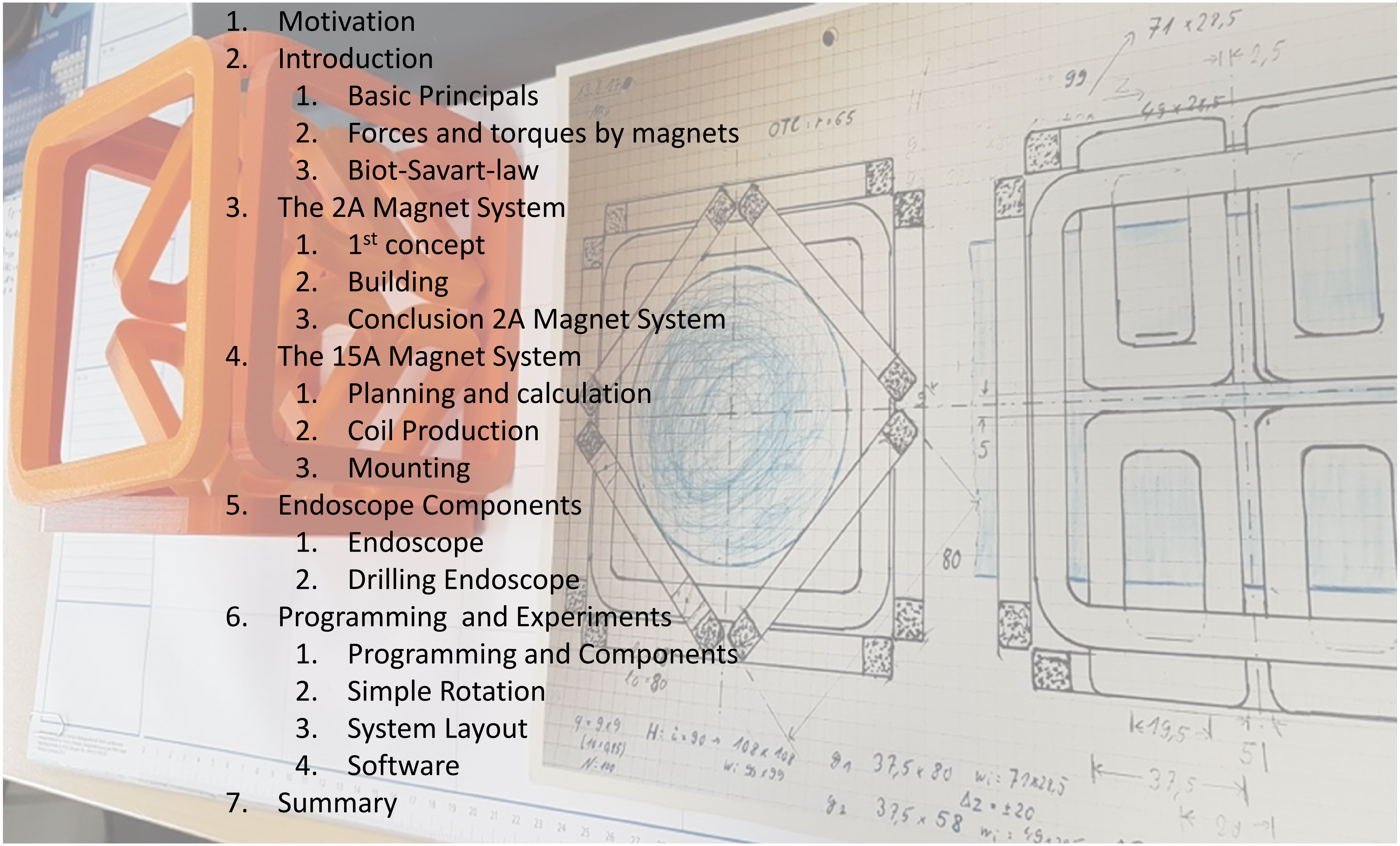


(1) Motivation

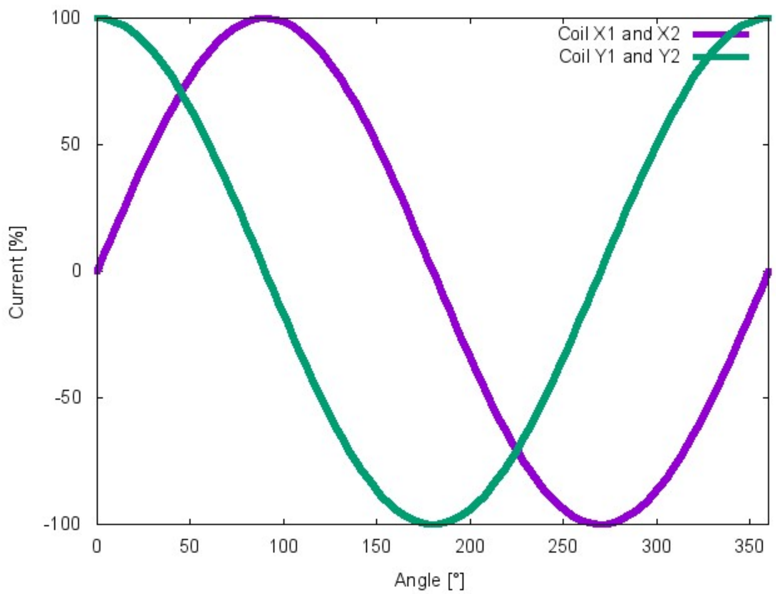
Experiments and Goals

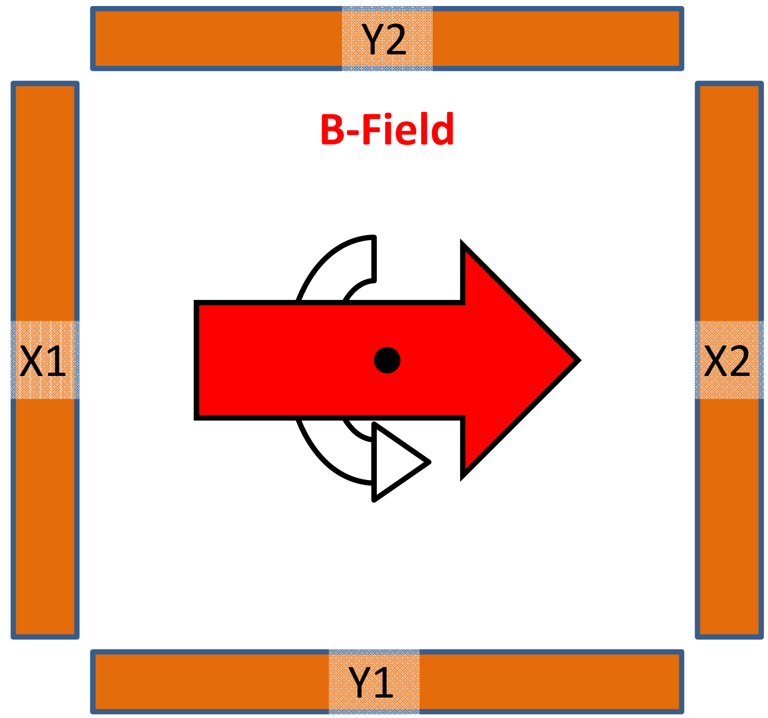
- Steering of “capsules” shown by Siemens Healthcare ~2010 in clinical studies
- Not shown: **Is a “drill” system feasible?**
- Idea: Work on a simple coil set to demonstrate “drill” systems
- Enabler: Today we have access to cheap USB Endoscopes (~20€), no need to get/ manufacture “capsules”

(2.1) Introduction of Basic Principals

Magnet System

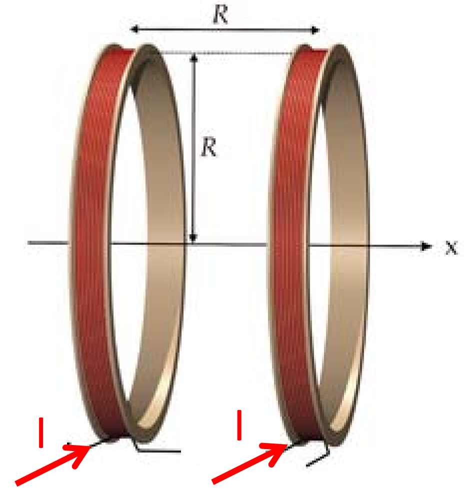
- This device will rotate as a synchro-motor if the outer coils generate a sinusoidal field.
- Apply magnetical force to an object instead of a rotor
- Rotation of the magnetic field
- 4 Helmholtz Coil System are used as stator





(2.2) Intermezzo: “Helmholtz coils”

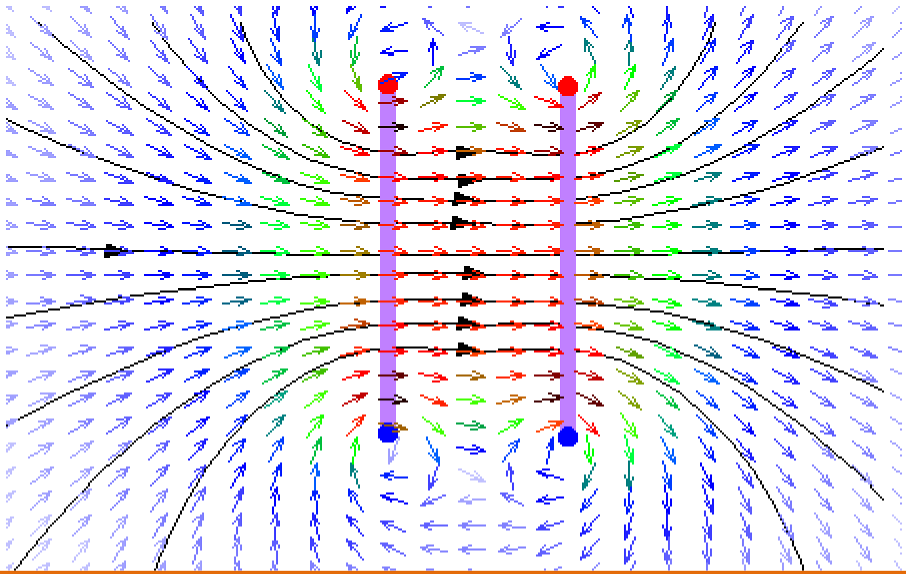
- Classical physics demonstrators
- Well known
- Current direction in coils: parallel
- Provide homogenous fields on axis
- No need for numerics: Can be understood analytically



$$B = B_x = \frac{\mu_0}{2} \frac{8(I_1 N_1 + I_2 N_2)}{\sqrt{125} R}$$

- Field: proportional I*N/R !

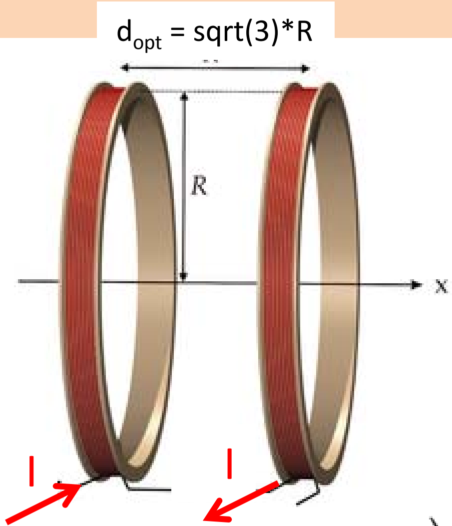
R [mm], I [A]: **B[mT] = 0,9 * 2* I * N / R**



Simulated field lines of a Helmholtz coil

Literature: German Wikipedia, Keyword “Helmholtz –Spule”, visited on 22.06.2018

(2.3) Intermezzo: “Anti Helmholtz” or “Maxwell” coils



- Helmholtz setup
- Coil-coil distance different
- Current direction in coils: anti-parallel
- Provide linear gradient
- No need for numerics: Can be understood analytically

- Gradient: proportional I*N/R² !

$$B(x) = \frac{\mu_0 \cdot N \cdot I \cdot R^2}{2} \left(\frac{1}{\left(R^2 + \left(x + \frac{a}{2}\right)^2\right)^{\frac{3}{2}}} - \frac{1}{\left(R^2 + \left(x - \frac{a}{2}\right)^2\right)^{\frac{3}{2}}} \right)$$

$$\frac{dB}{dx} = \sqrt{\frac{6912}{16807}} \cdot \frac{\mu_0 \cdot N \cdot I}{R^2} \approx 0{,}6413 \cdot \frac{\mu_0 \cdot N \cdot I}{R^2}$$

R [mm], I [A]: **g[mT/m] = 0,641 * I * N / R²**

Simulated field lines of a Helmholtz coil

Literature: German Wikipedia, Keyword “Helmholtz –Spule”, visited on 22.06.2018

(2.4) Forces and torques by magnets

In a homogenous magnetic field, a permanent magnet, represented by its magnetic moment experiences a Torque:

$$\vec{T} = \vec{m} \times \vec{B}$$

Thus a magnetic moment will be aligned to have $\vec{m}$ parallel to $\vec{B}$.

If fields are not homogenous, the magnet experiences a force proportional to the gradient of the field:

$$\vec{F} = (\nabla \vec{B}) \cdot \vec{m} = \begin{pmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_y}{\partial x} & \frac{\partial B_z}{\partial x} \\ \frac{\partial B_x}{\partial y} & \frac{\partial B_y}{\partial y} & \frac{\partial B_z}{\partial y} \\ \frac{\partial B_x}{\partial z} & \frac{\partial B_y}{\partial z} & \frac{\partial B_z}{\partial z} \end{pmatrix} \cdot \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}$$

If the field is homogenous, no forces do occur. In practice it is very difficult to realize perfect homogenous field over larger volumes. Thus forces due to inhomogeneity do always occur.

=> Magnet system:

Generates Torque $\vec{T}$ and Force $\vec{F}$ vectors

Physics (Maxwell's law):
Only 5 elements of the gradient matrix are independent
=> Use 8 parameters to describe a coil system at a specific point ($\vec{r}$)and time (t):

$$\begin{pmatrix} T_x(t) \\ T_y(t) \\ T_z(t) \\ F_x(t) \\ F_y(t) \\ F_z(t) \end{pmatrix} = U(m_x(t), m_y(t), m_z(t)) \cdot \begin{pmatrix} B_x(r,t) \\ B_y(r,t) \\ B_z(r,t) \\ \frac{\partial B_x(r,t)}{\partial x} \\ \frac{\partial B_y(r,t)}{\partial x} \\ \frac{\partial B_z(r,t)}{\partial x} \\ \frac{\partial B_z(r,t)}{\partial y} \\ \frac{\partial B_y(r,t)}{\partial y} \end{pmatrix}$$

The above vector formulation allows to compute the torque/force vector as a function of the orientation of m.
Each single coil contributes 8 parameters, depending on its geometry and applied current.

(2.5) Introduction Biot-Savart-law

Recipe for steering a magnet in a coil system:

- Define Coil geometry
- Determine needed force/torque vector ($\overrightarrow{FT}$)
- Set position of interest (magnet position)
- Compute needed currents

Simple general formula:

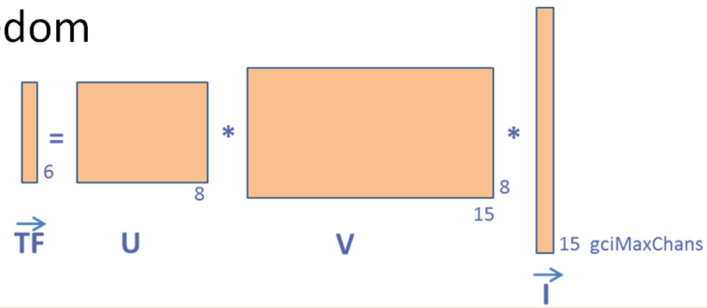
$$\overrightarrow{FT} = U \times V \times \vec{I}$$

$\vec{I}$: The vector of applied currents

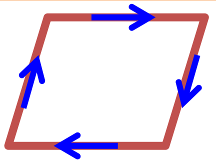
V: Matrix of field/gradient 8-vectors per coil

U: Matrix, describing the orientation of the magnet in global coordinate system

Physics: Need up-to 15 coils to have all degrees of freedom



V- Matrix:



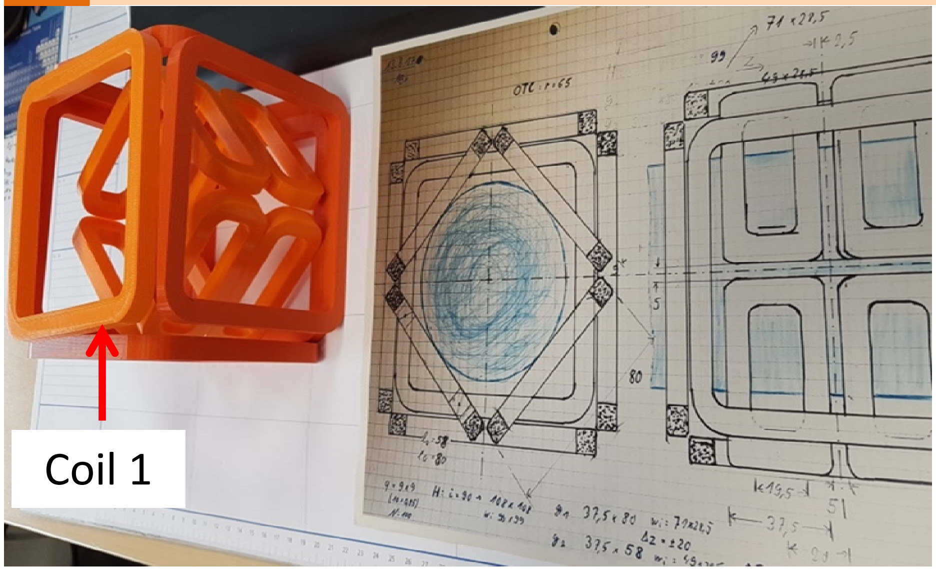
- Describe coils by wires
- Use Biot-Savart-law to compute field of each wire at the position of interest:

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0 I}{4\pi\sqrt{r_2^2 - p_2^2}} \frac{\mathbf{r}_2 \times \mathbf{r}_1}{|\mathbf{r}_2 \times \mathbf{r}_1|}\left(\frac{p_2}{r_2} + \frac{p_1}{r_1}\right)$$

- Differentiate numerically for the gradient-terms.
- V-Matrix at any given point is a constant property of the magnet system

=> Nasty theory, discussed after two more intuitive approaches on further examples

(3.1) 2A system, 1st concept



Geometry and printed coil dummies of a 1:8, 2A system (1)
Base: Rectangular Helmholtz-coils

Initial goals:

- Understand theory
- Validate geometry
- Measure (?) fields
- Focus: Gradients !

Example of a "V-Matrix":

Coil 1

	14box80 @ 2A			HxPos	HxNeg	HyDwn	HyUp	HzFro	HzBck	Gor-	Gor+	Gol-	Gol+	Gur-	Gur+	Gul-	Gul+	OTC
				Coil 1	Coil 2	Coil 3	Coil 4	Coil 5	Coil 6	Coil 7	Coil 8	Coil 9	Coil 10	Coil 11	Coil 12	Coil 13	Coil 14	Coil15
B_x	0,000	mT	B_x	40,2145	-40,2145	0,0000	0,0000	0,0000	0,0000	11,9308	11,9308	11,9308	11,9308	11,9308	11,9308	11,9308	11,9308	0,0000
B_y	0,000	mT	B_y	0,0000	0,0000	40,2145	-40,2145	0,0000	0,0000	-11,9308	-11,9308	11,9308	11,9308	11,9308	11,9308	-11,9308	-11,9308	0,0000
B_z	1,609	mT	B_z	0,0000	0,0000	0,0000	0,0000	40,2145	-40,2145	11,9872	-11,9872	-11,9872	11,9872	11,9872	-11,9872	-11,9872	11,9872	0,0000
$\partial B_x/\partial x$	43,483	mT/m	Bx x	1087,0811	1087,0811	-543,4901	-543,4901	-543,4901	-543,4901	-118,9665	-118,9665	118,9665	118,9665	-118,9665	-118,9665	118,9665	118,9665	0,0000
$\partial B_y/\partial x$	0,000	mT/m	By x	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	446,2799	446,2799	446,2799	446,2799	-446,2799	-446,2799	-446,2799	-446,2799	0,0000
$\partial B_z/\partial x$	0,000	mT/m	Bz x	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	-498,9944	498,9944	-498,9944	498,9944	-498,9944	498,9944	-498,9944	498,9944	0,0000
$\partial B_y/\partial y$	-21,740	mT/m	By y	-543,4901	-543,4901	1087,0811	1087,0811	-543,4901	-543,4901	-118,9665	-118,9665	118,9665	118,9665	-118,9665	-118,9665	118,9665	118,9665	0,0000
$\partial B_z/\partial y$	0,000	mT/m	By z	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	498,9944	-498,9944	-498,9944	498,9944	-498,9944	498,9944	498,9944	-498,9944	0,0000
$\partial B_z/\partial z$	-21,744	mT/m	$\partial B_z/\partial z$	-543,5909	-543,5909	-543,5909	-543,5909	1086,9802	1086,9802	237,9330	237,9330	-237,9330	-237,9330	237,9330	237,9330	-237,9330	-237,9330	0,0000
			I [A]	2,0	2,0	0,0	0,0	2,0	-2,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

(3.2) 2A system, 1^{st} concept

	14box80 @ 2A			HxPos	HxNeg	HyDwn	HyUp	HzFro	HzBck	Gor-	Gor+	Gol-	Gol+	Gur-	Gur+	Gul-	Gul+	OTC
				Coil 1	Coil 2	Coil 3	Coil 4	Coil 5	Coil 6	Coil 7	Coil 8	Coil 9	Coil 10	Coil 11	Coil 12	Coil 13	Coil 14	Coil15
B_x	0,000	mT	B_x	40,2145	-40,2145	0,0000	0,0000	0,0000	0,0000	11,9308	11,9308	11,9308	11,9308	11,9308	11,9308	11,9308	11,9308	0,0000
B_y	0,000	mT	B_y	0,0000	0,0000	40,2145	-40,2145	0,0000	0,0000	-11,9308	-11,9308	11,9308	11,9308	11,9308	11,9308	-11,9308	-11,9308	0,0000
B_z	1,609	mT	B_z	0,0000	0,0000	0,0000	0,0000	40,2145	-40,2145	11,9872	-11,9872	-11,9872	11,9872	11,9872	-11,9872	-11,9872	11,9872	0,0000
$\partial B_x/\partial x$	43,483	mT/m	Bx x	1087,0811	1087,0811	-543,4901	-543,4901	-543,4901	-543,4901	-118,9665	-118,9665	118,9665	118,9665	-118,9665	-118,9665	118,9665	118,9665	0,0000
$\partial B_y/\partial x$	0,000	mT/m	By x	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	446,2799	446,2799	446,2799	446,2799	-446,2799	-446,2799	-446,2799	-446,2799	0,0000
$\partial B_z/\partial x$	0,000	mT/m	Bz x	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	-498,9944	498,9944	-498,9944	498,9944	-498,9944	498,9944	-498,9944	498,9944	0,0000
$\partial B_y/\partial y$	-21,740	mT/m	By y	-543,4901	-543,4901	1087,0811	1087,0811	-543,4901	-543,4901	-118,9665	-118,9665	118,9665	118,9665	-118,9665	-118,9665	118,9665	118,9665	0,0000
$\partial B_z/\partial y$	0,000	mT/m	By z	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	498,9944	-498,9944	-498,9944	498,9944	-498,9944	498,9944	498,9944	-498,9944	0,0000
$\partial B_z/\partial z$	**-21,744**	mT/m	$\partial B_z/\partial z$	-543,5909	-543,5909	-543,5909	-543,5909	1086,9802	1086,9802	237,9330	237,9330	-237,9330	-237,9330	237,9330	237,9330	-237,9330	-237,9330	0,0000
			I [A]	2,0	2,0	0,0	0,0	2,0	-2,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

6 HeHo coils **8 gradient coils**

Units of V-matrix: mT/100A field and mT/m/100A for gradients

(Attention: Large values are per 100A: 40mT/100A*2A=~0,8mT) Example gives gradient in x and field in Z

Multiply matrix with current vector to get field and gradients

First 6 coils: Helmholtz coils (HeHo's)

Hx: Field in x-direction

Hy: Field in y-direction

Hz: Field in z-direction

Using only the 6 HeHo's

- Arbitrary field (strength and direction) possible
- Only gradients (forces) along Coordinate axis possible ($\partial B_x/\partial x$, $\partial B_y/\partial y$, $\partial B_z/\partial z$)
- No mixed-term gradients possible (physics)
- Only 2 independent gradients possible
  $\partial B_z/\partial z = -\partial B_x/\partial x - \partial B_y/\partial y$

(3.3) 2A system, planning and basic data

- System derived from 14-coils plan
- Realize only the 6 HeHo's
- Stick to 2A (have 2A current drivers, which can be controlled easily)
- Max field: 1,6 mT

- Experimental result: Rotor sticks often, follows badly the sinusoidal field.

- Drill: $\vec{m}$ ~ 0,17 N m / T
- => T = 0,000255 N m
- Gradients: g ~ 40mT/m

Scaling:

A full-size system should have ~600 open bore.

A 80mm system is ~1/8 in size.

Fields in HeHo's: Scale 1/r => Same fields in center: ~12,5% current

Gradients in HeHo's: Scale $1/r^2$ => Same gradients in center: ~1,6% current

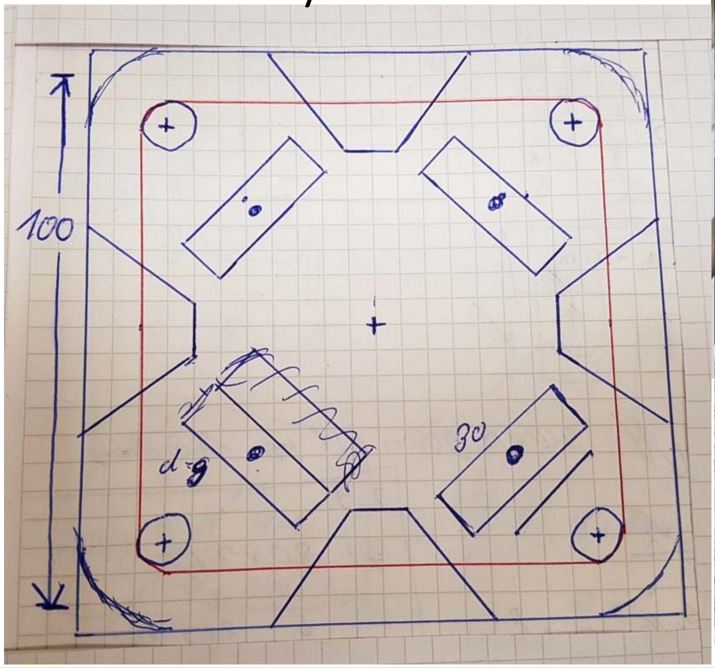
Assume for a full size system 100A => 12,5A for fields and 1,6A for gradients !

2A: No chance to "drill" since this needs field

(3.4) First 2A Magnet System

First 2A Magnet System
- Self bonding wire (Backlackdraht)
- Wire: Ø0,85 mm, 100 windings
- Mid of coil: 100mm x 100mm
- 9mm x 9mm coil cross section

Mechanical layout coils-winder

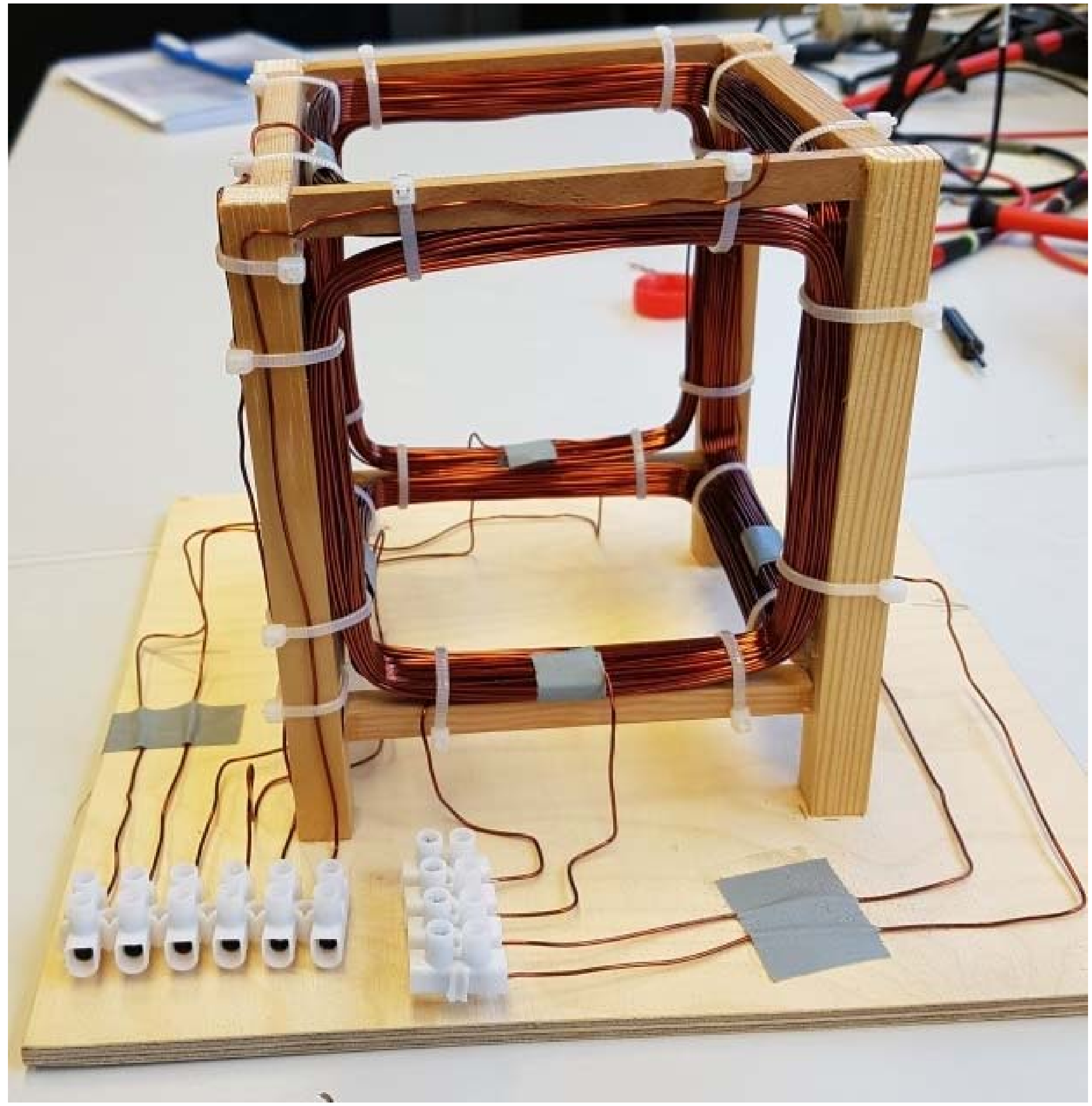


(3.5) Conclusion 2A Magnet System

6 Coil 2A Magnet System
- 6 Helmholtz Coils
- To control the coil current a PLC was used
- Maximal current 2A (due to the thermal load)
- 1,5 .. 1,6mT (lower than V-matrix due to imperfections)

→ Rotor sticks frequently
→ Torque too low

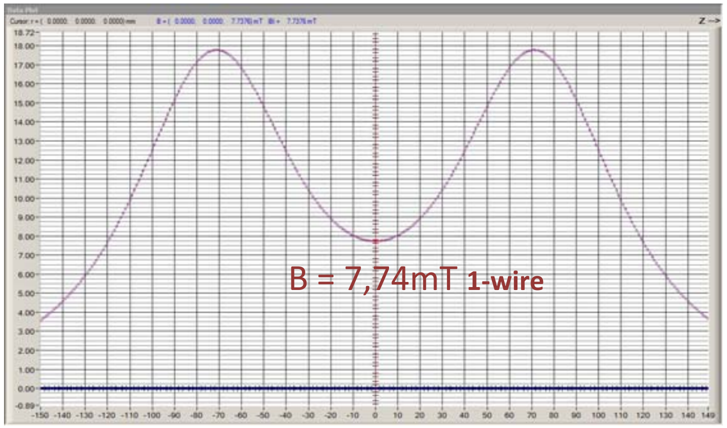
→ Build 15A version

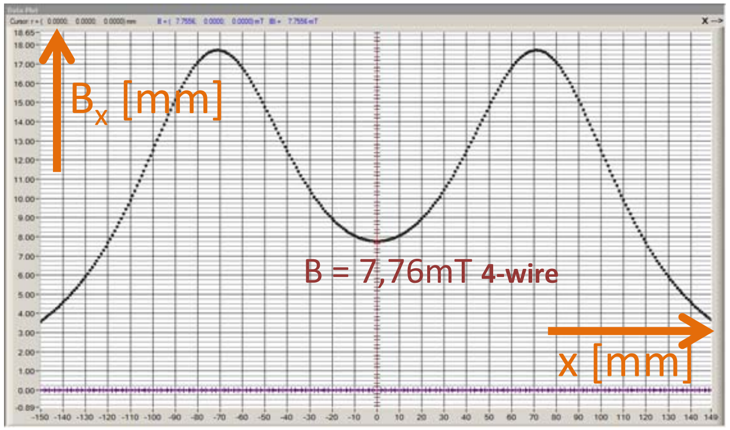


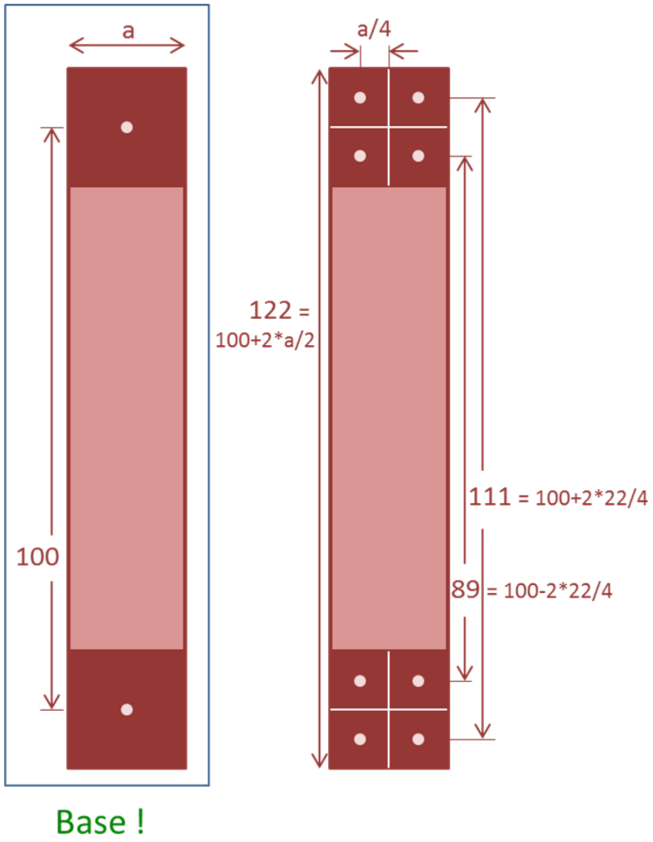
(4.1) 15A Coil planning and calculation

Coil planning:

- Goal: 100mm x 100mm "filament" in computation
- 15A wire (~2mm diameter), 100 windings => 20x200 Cu "Thick => is one filament justified?
- Compare computation with 1 and 4 filaments => marginal difference, one is OK



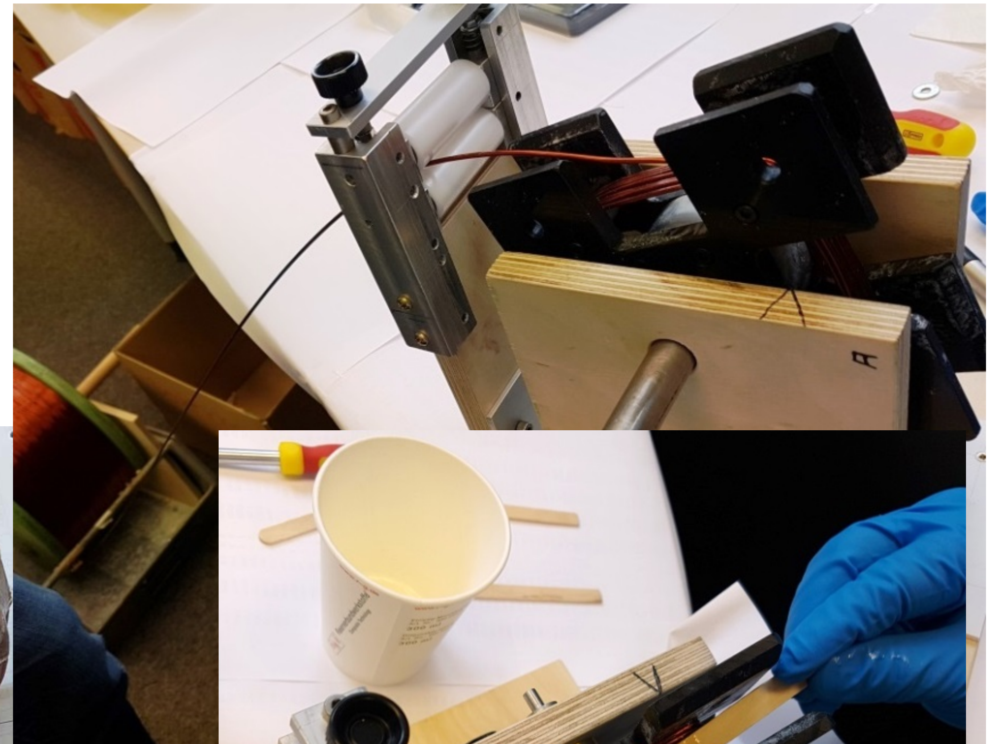


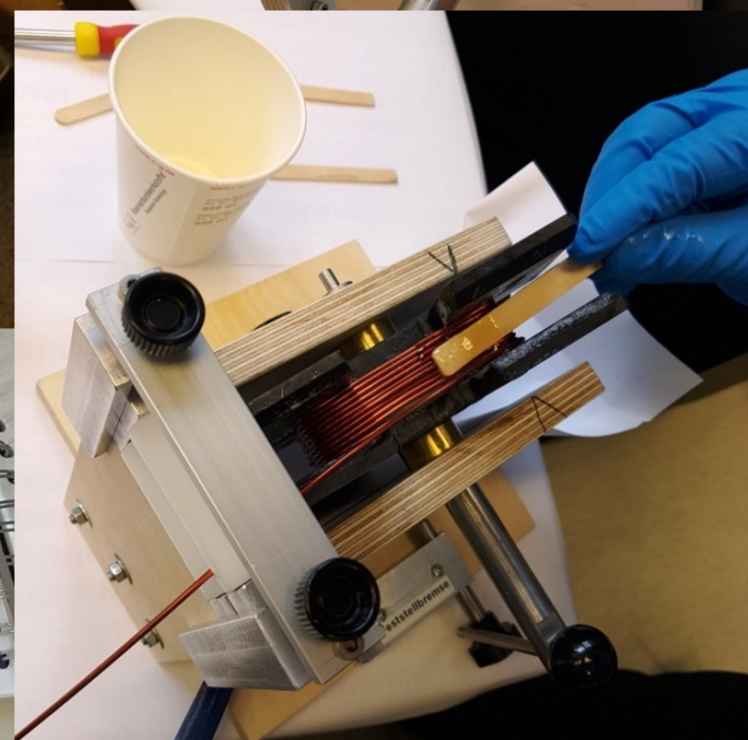


(4.2) 15A Coil Production

Step 1 - Manufacturing

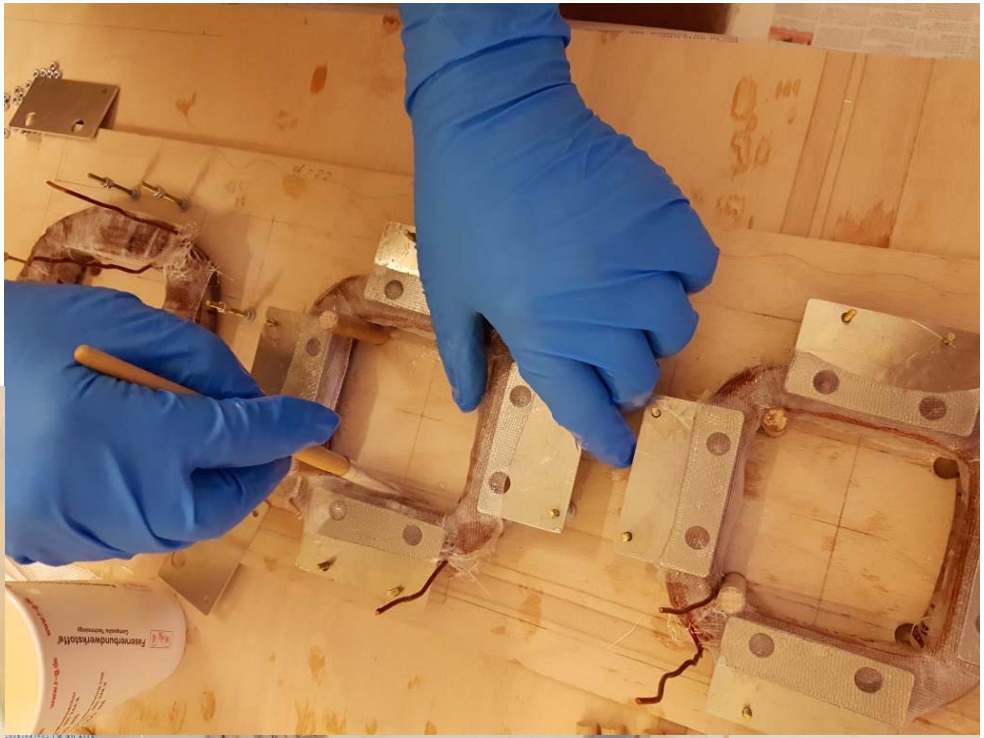
- 15A Copper Wire Coils have to be glued, to maintain their shape after production
- During production the 2mm diameter copper wire has to be bended and fixated
- Drying process needs roughly 24h





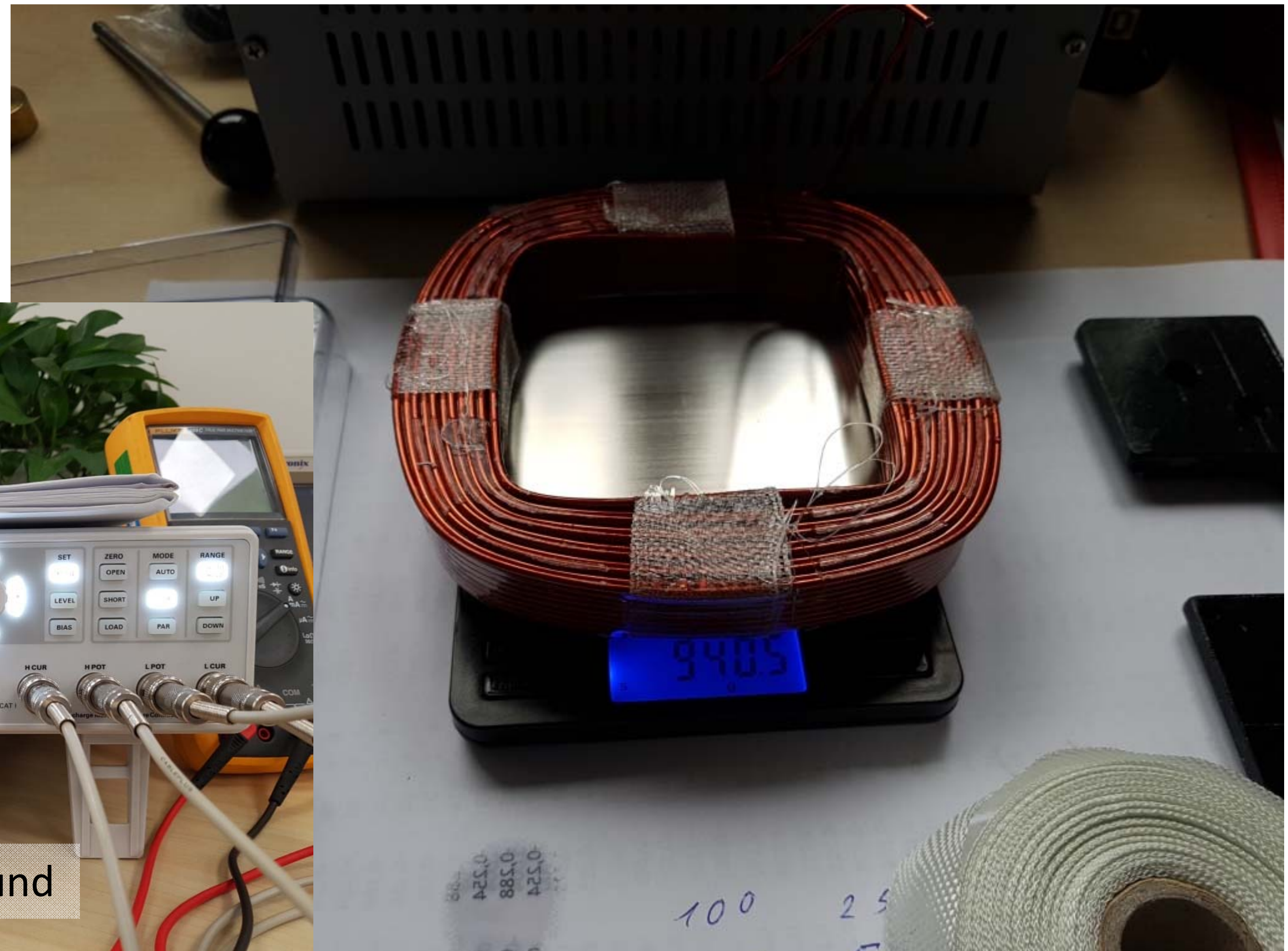
(4.4) 15A Coil Production

Step 2 – Final Steps
- Wrap Coils with fiberglass fabric
- Placing frame components
- Glue both components with coil
- Drying process needs roughly 24h again



(4.3) 15A Coil – Technical Data

Technical Data of our 15A Coils
- 940 g copper
- 100 windings
- L = 1,118mH
- R = 220 mOhm
- Bore diameter 80x80



Test of “CoilZero”, 440g, round

(4.5) New 15A Magnetic System

New Magnetic System
- 6x940 g copper coils
- Preliminary setup without frame

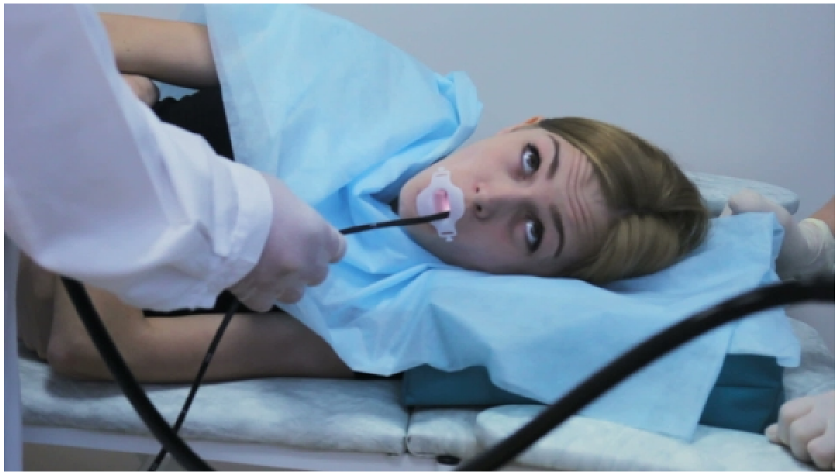
→ Frame currently under construction
→ Will be finished soon

(5.1) Endoscope

Endoscope

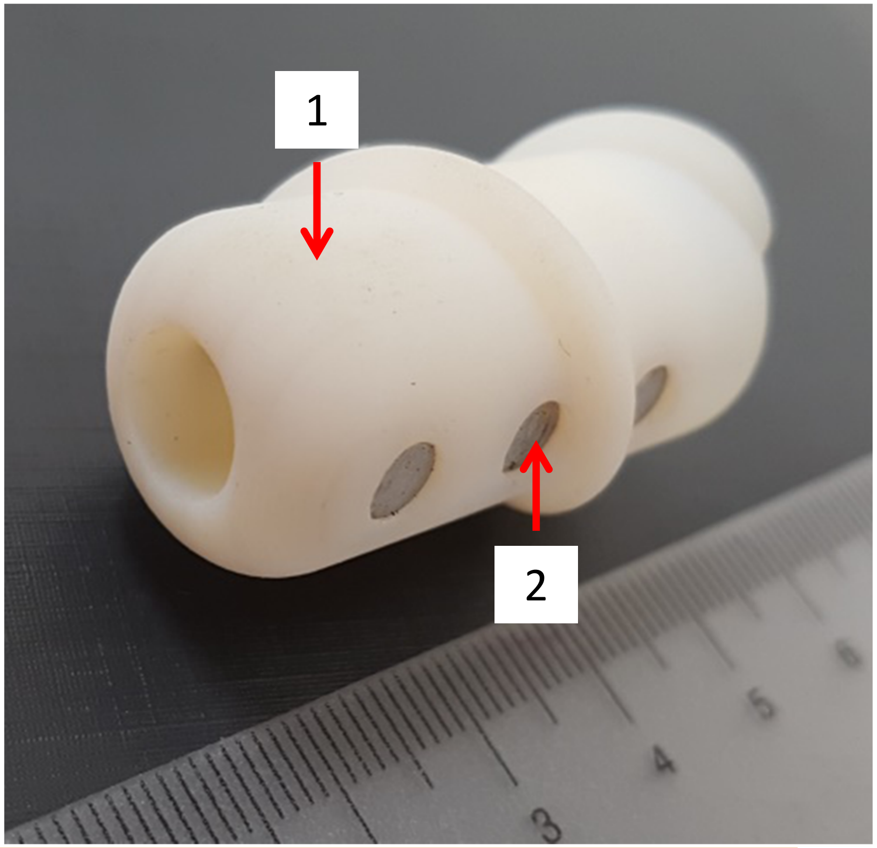
- Medical Endoscopes base on two characteristics:
  1. Optical camera system taken from an arbitrary point inside a patient
  2. Move the camera to such points by mechanical manipulating of a physical connection between it and patients exterior
- Very inconvenient for patients - Although a great improvement over eventual alternative procedures, the application of especially gastro-entrolocigal endoscopies and colonoscopies is reported still as highly inconvenient for patients

The ability to mechanically operate in vivo and/or remove samples to the exterior is considered an important but nevertheless optional implementation detail of currently marketed endoscopes. For our experiments we don't take it into consideration for the time being.



(5.2) Rotor

Rotor
- An magnetical object aligns itself with the homogenous but time variant B-field
- The Magnetic Axis of the rotor needs to be orthogonal to the intended rotational axis
- 3D printed rotor head (1) to house magnets in a defined position
- Standard Neodymium Magnet (2): NdFeB
- Axial magnetized round Magnets
- Standard commercially available Magnet price: 2 – 5 EURO



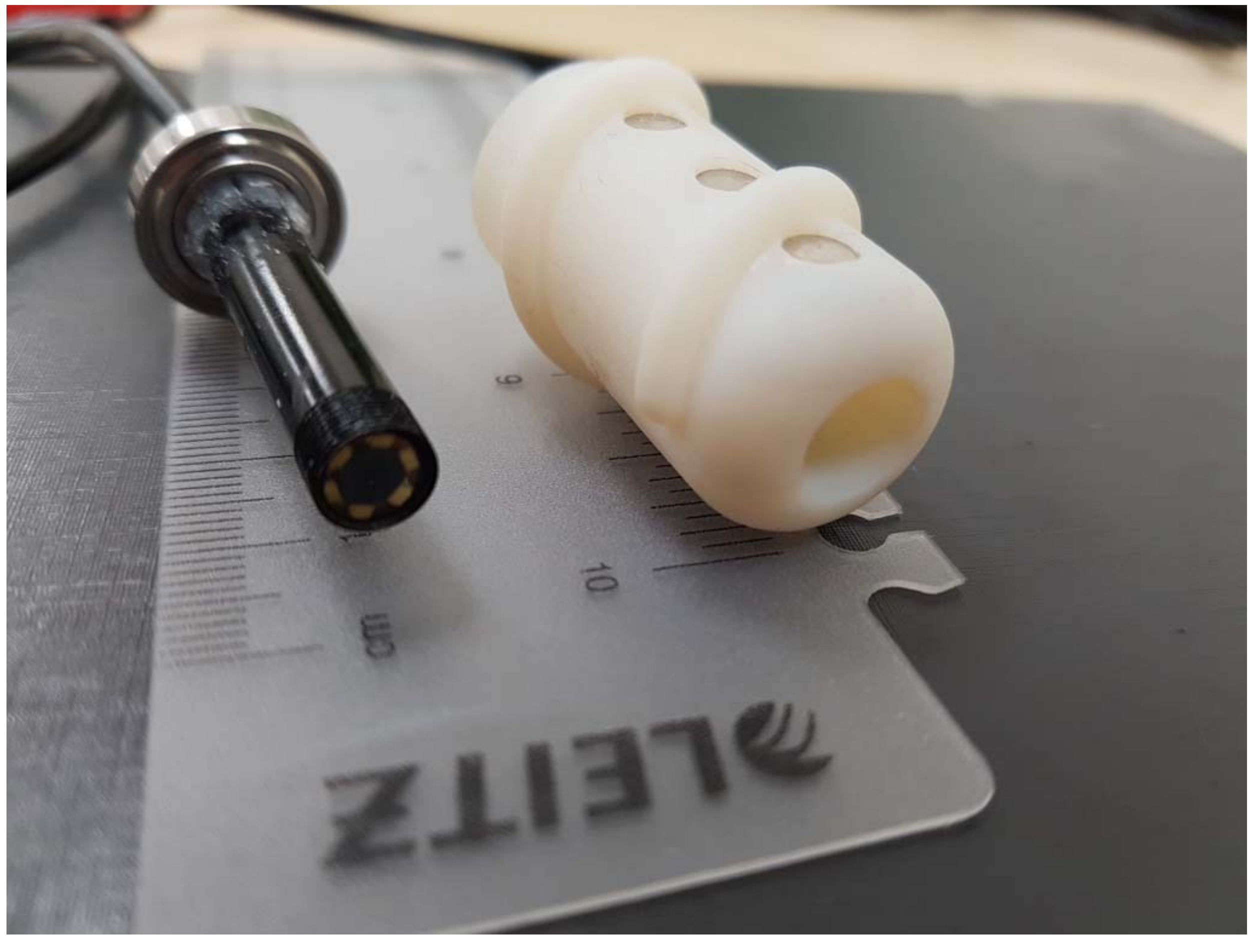
(5.2) Rotor + Endoscope = Drilling Endoscope

Drilling Endoscope

- Magnetic field rotates
- Rotor head follows the field
- Works like a propeller producing propulsion

- Bearing between Rotor and Endoscope

- Standard USB-Endoscope
- Light can be controlled with the integrated LEDs
- USB – Universal connection
- OS independent
- Resolution: VGA
- Price: 10 – 15 EURO



(6.1) MOMo Programming

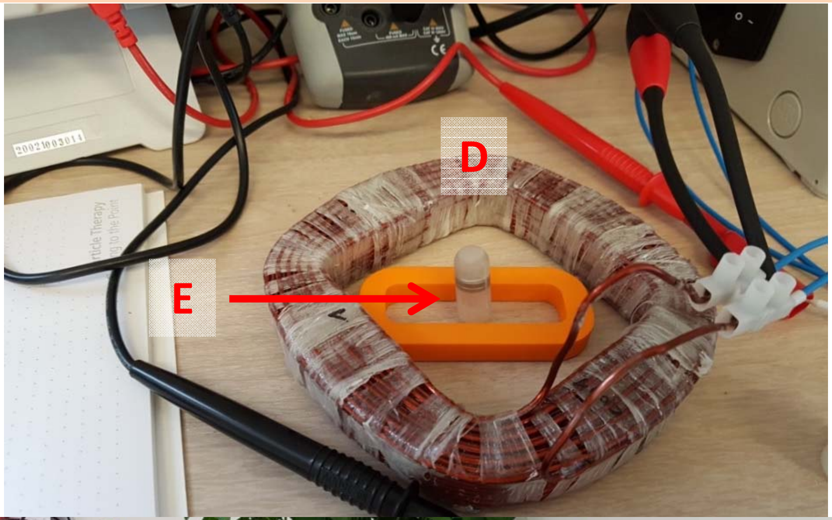
Tapas programming

- Communication between the TAPAS boards via SPI
- Piggy-pack on motorware
- Controlled by one raspy
- Control loop

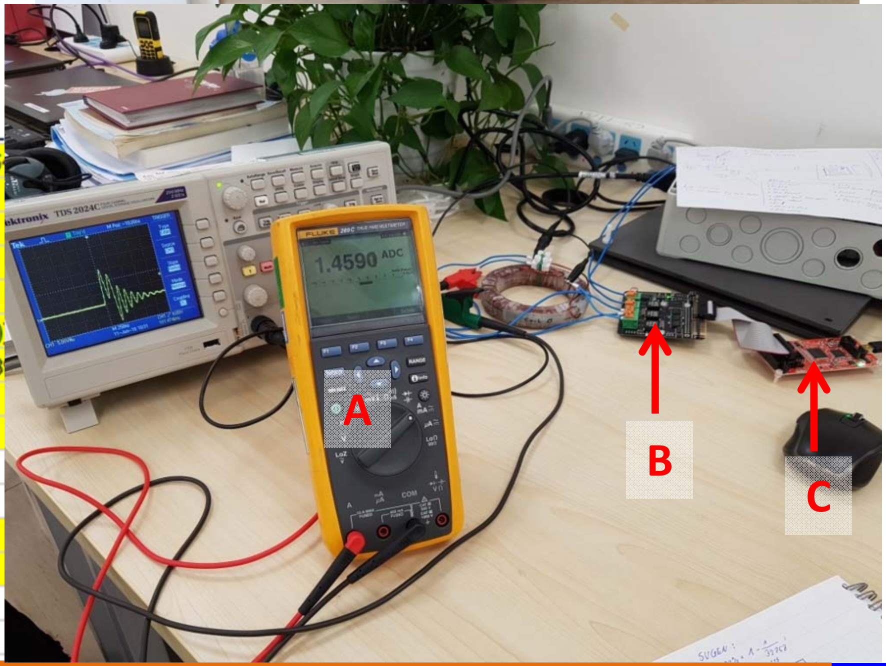
- DC-BUS Current, Voltage Board temp. Error Status, Digital IN

(6.2) MOMo Components

MOMo Components
- A) Fluke Multimeter – Current measurement
- B) Tapas Boards providing controlled current
- C) TAPAS Programmer
- D) Coil (here: „CoilZero“, 440g)
- E) Magnet used as probe



gAdcData	struct _HAL_AdcData_t_	{I={value=[350746,53020,285
I	struct _MATH_vec3_	{value=[358903,36706,4078]}
value	long[3]	[350746,32628,-8157]
(x)= [0]	long	0.022364676 (Q-Value(24))
(x)= [1]	long	0.002430915833 (Q-Value(24))
(x)= [2]	long	0.0004861950874 (Q-Value(24)
V	struct _MATH_vec3_	{value=[314389,311607,31438
value	long[3]	[314389,311607,311607]
(x)= [0]	long	0.01873904467 (Q-Value(24))
(x)= [1]	long	0.01873904467 (Q-Value(24))
(x)= [2]	long	0.01857322454 (Q-Value(24))
(x)= dcBus	long	0.2391304374 (Q-Value(24))
(x)= I_dcBus	long	0.5121996403 (Q-Value(24))
(x)= TempSensor	long	28.22023344 (Q-Value(24))
AnalogIn	long[6]	[0,0,0,0,0...]

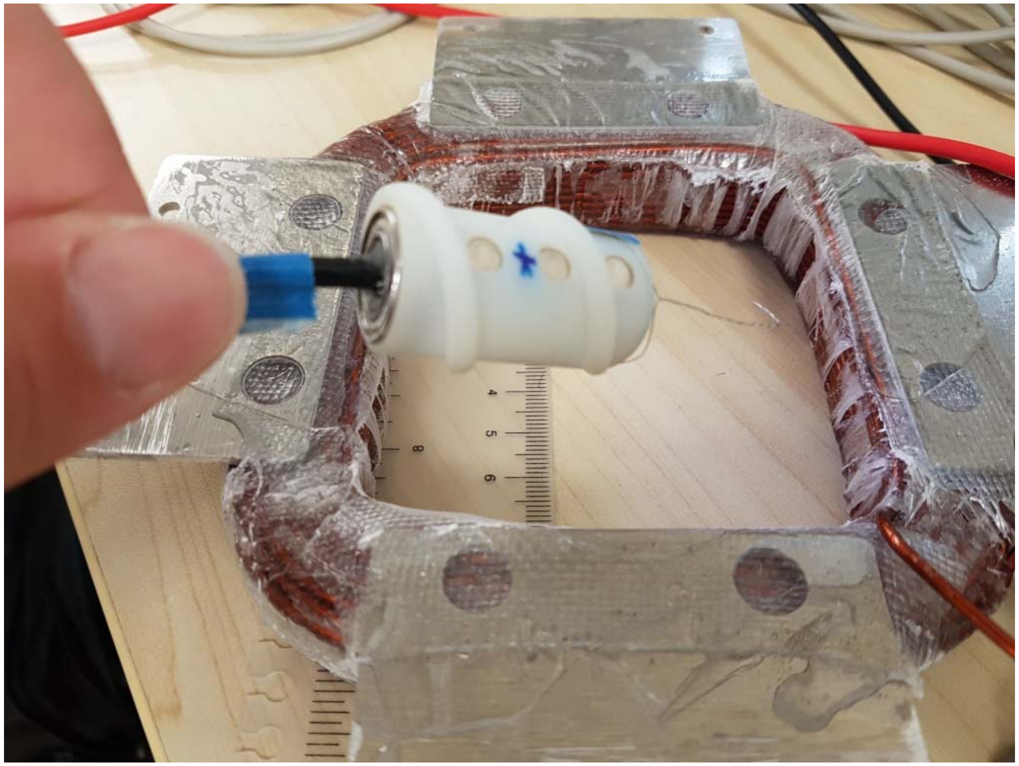


(6.3) MOMo Simple Rotation

- With one coil the magnetic field is inverted
- „Drilling“ Endoscope turns (speed and angle can’t be controlled with one coil.

- TAPAS H-bridge is used to invert coil current

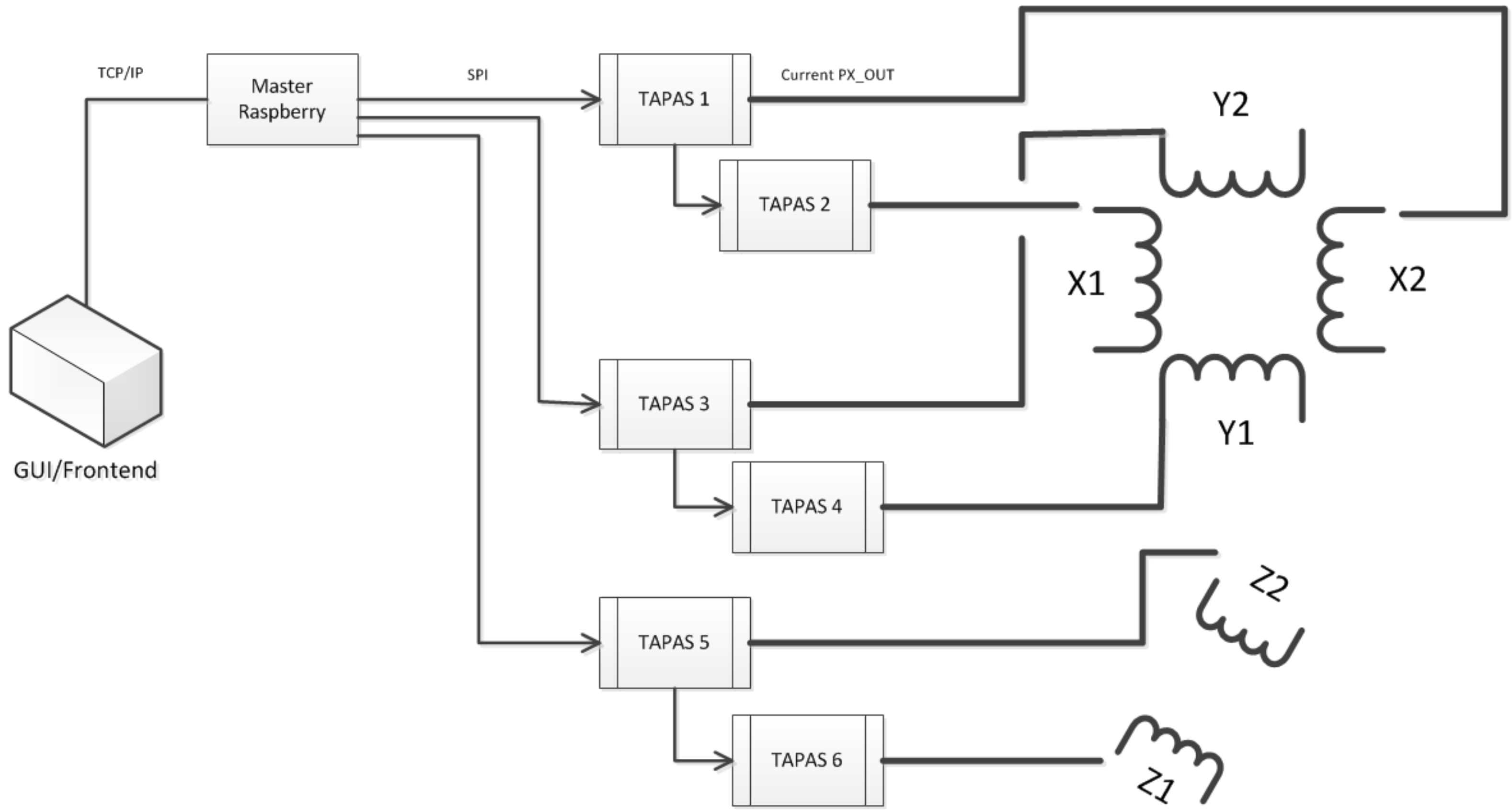
→ See video: 20180624_075317



(6.4) MOMo Layout

MOMo Layout

- A Raspberry Pi acting as SPI master to multiple TAPAS slaves.
- Each TAPAS slave act itself as master for more TAPAS slaves as desired.
- Each TAPAS controls current output to only one coil (as of now).



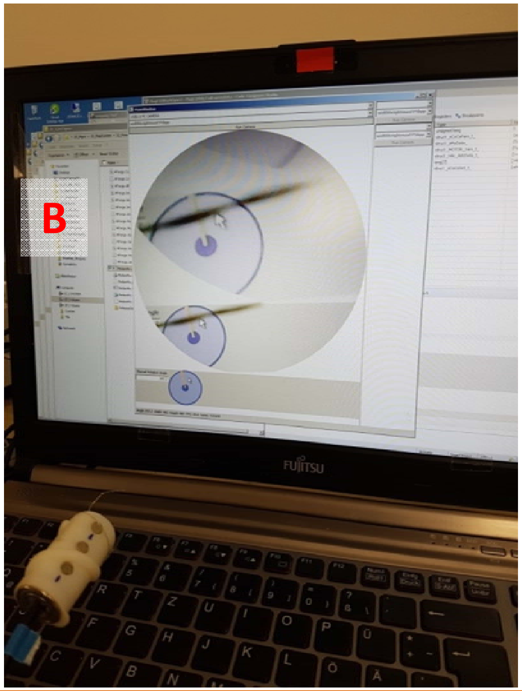
(6.5) MOMo Software

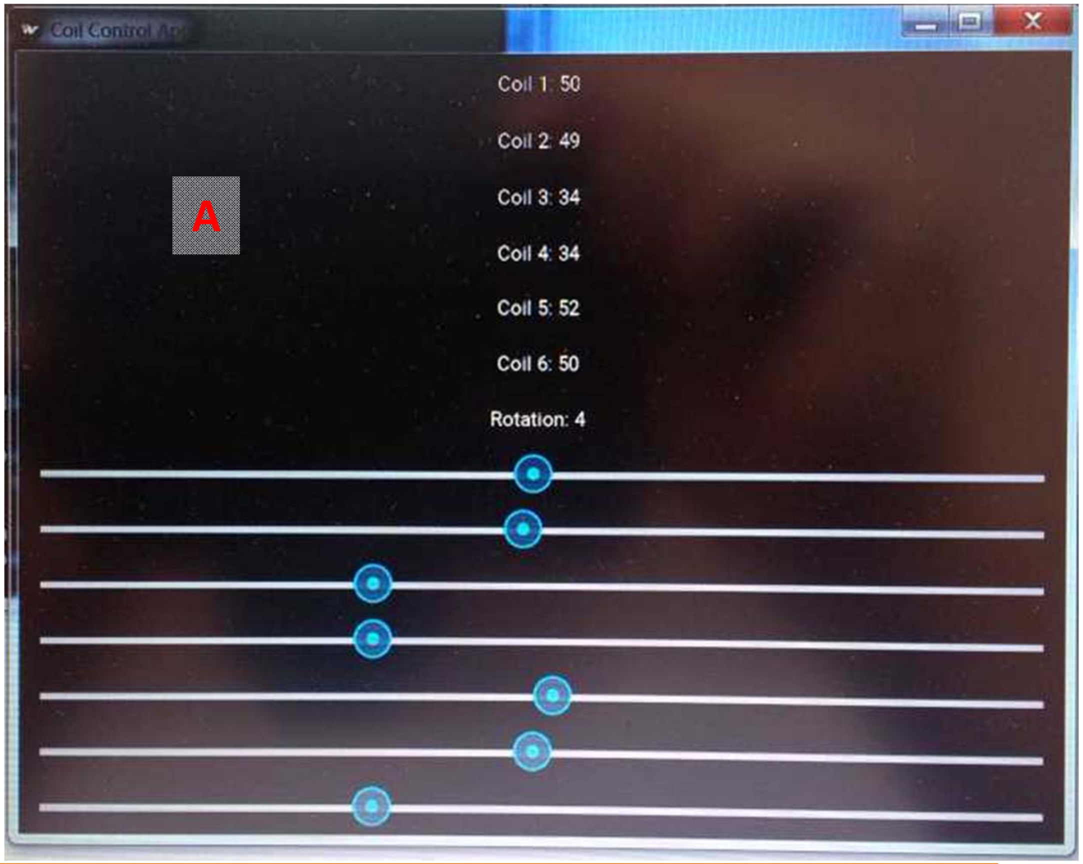
MOMo – Tkinker GUI

- Control of each TAPAS Board with sliders in a Python Tkinker GUI (A)
- One can set the current or rotate the B field

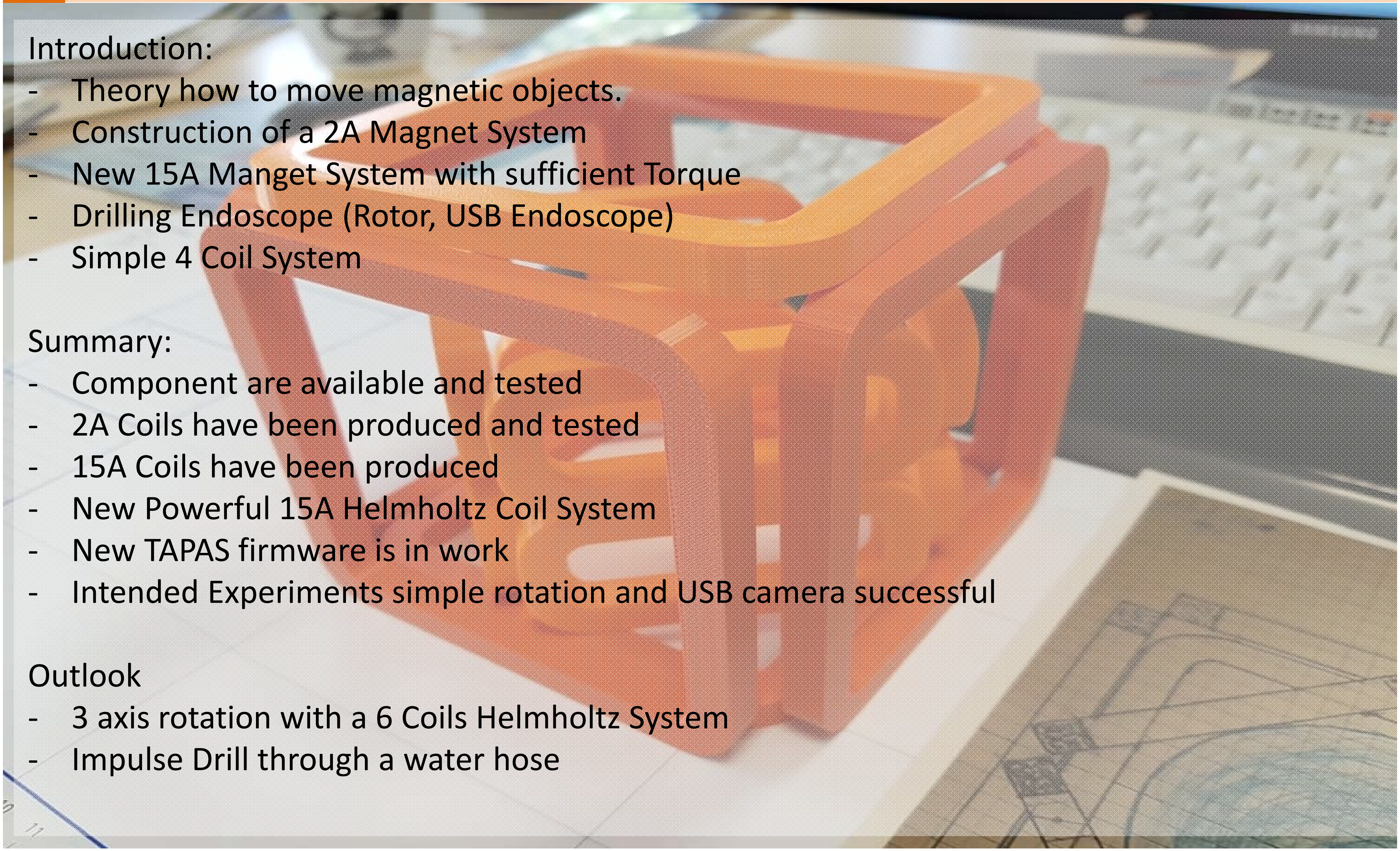
USB-Endoscope

- Read-out via Windows driver (B)





(7.1) Summary



Introduction:
- Theory how to move magnetic objects.
- Construction of a 2A Magnet System
- New 15A Manget System with sufficient Torque
- Drilling Endoscope (Rotor, USB Endoscope)
- Simple 4 Coil System

Summary:
- Component are available and tested
- 2A Coils have been produced and tested
- 15A Coils have been produced
- New Powerful 15A Helmholtz Coil System
- New TAPAS firmware is in work
- Intended Experiments simple rotation and USB camera successful

Outlook
- 3 axis rotation with a 6 Coils Helmholtz System
- Impulse Drill through a water hose

Thank you for your attention!

- Dr. Martin Bräuer
- Dr. Asim Araz
- Klaus Hörcher
- Andreas Henne