

AToM – Antenna Toolbox for Matlab

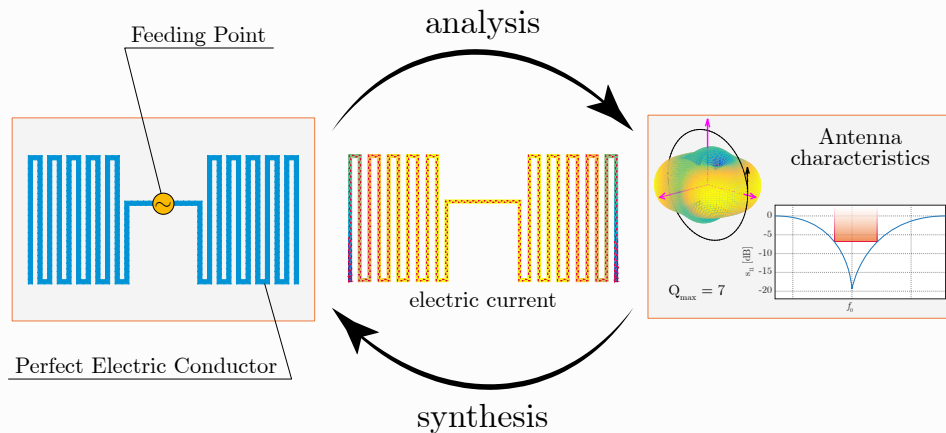
“Antenna Source Concept – the new Approach to Antenna Design”

Miloslav Čapek

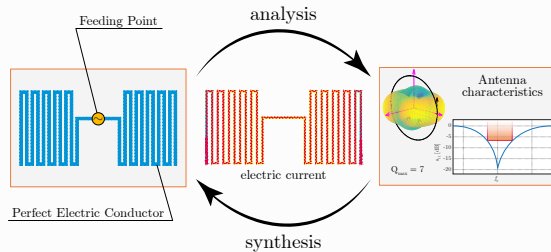
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CEM User Group Meeting
Lund
November 17, 2016

- 1 Analysis \times Synthesis
- 2 Source Concept
 - What is the Source Concept?
 - Seeking for Optimal Antennas
- 3 Taking Advantage of Source Concept
 - Modal Decomposition
 - Spatial Decomposition
 - Optimization
 - Fundamental Bounds
 - Post-processing
- 4 AToM Project
- 5 AToM Architecture
- 6 Integration into CEM One (ESI Group)



Antenna analysis × antenna synthesis.



Antenna analysis × antenna synthesis.

Synthesis

- ▶ not developed in contemporary EM simulators,
- ▶ is a challenge,
- ▶ cannot be (probably?) completely done.

Definition of Source Concept



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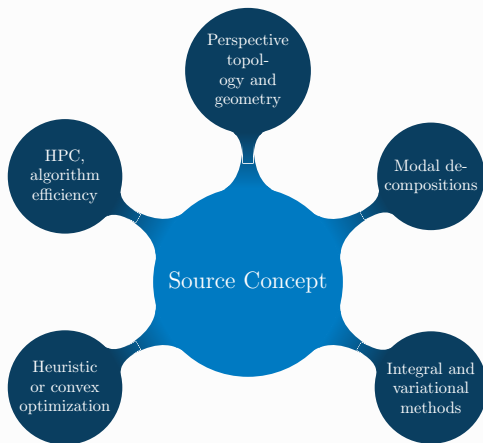
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- ▶ It is a mixture of powerful techniques, both analytical and numerical, together with the idea that the electromagnetic current can be substituted into any expression relevant to small antenna design.
- ▶ The ultimate goal presents the ability to manipulate with the currents completely freely.

Source Concept

What is it?



Sketch of main fields of the source concept.

Source concept...

- ▶ represents a radiator Ω completely by a **source currents** \mathcal{J} and \mathcal{M} ,
- ▶ infers all parameters from a **source current**, i.e. $\mathcal{L}(\mathcal{J}, \mathcal{M})$.

Operators – Key Instruments of Source Concept



- ▶ all antenna parameters are expressed with operators (or functionals)

$$\mathbf{P} = \mathcal{L}(\mathcal{J}, \mathcal{M}) \quad (1)$$

- only their properties are important
- physics is imprinted in their structure
- can be represented in many different ways, e.g. $\langle \mathbf{r}, \mathcal{L}\mathbf{r}' \rangle$, $\langle \mathbf{f}_m, \mathcal{L}\mathbf{f}_n \rangle$, $\langle \mathbf{J}_p, \mathcal{L}\mathbf{J}_q \rangle$



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Example: EFIE \rightarrow impedance matrix (MoM with, e.g., RWG functions) \rightarrow characteristic basis (CM):

$$\text{Then: } \mathcal{Z} = \mathcal{R} + j\mathcal{X} = -j\omega \mathbf{n}_0 \times \left(\mathcal{A} + \frac{1}{k^2} \nabla \nabla \cdot \mathcal{A} \right), \quad \mathcal{A}(\star) = \frac{\mu}{4\pi} \int_{\Omega'} (\star) \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} d\Omega', \quad \mathbf{A}(\mathbf{r}) = \mathcal{A}\mathbf{J}(\mathbf{r}'),$$

$$\rightarrow \mathbf{Z} = \mathbf{R} + j\mathbf{X} = [\langle \mathbf{f}_m, \mathcal{Z}\mathbf{f}_n \rangle] = -\frac{jZ_0}{4\pi} \int_{\Omega} \int_{\Omega'} \left(k\mathbf{f}_m \cdot \mathbf{f}_n^* - \frac{1}{k} \nabla \cdot \mathbf{f}_m \nabla' \cdot \mathbf{f}_n^* \right) \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} d\Omega'.$$

$$\rightarrow (1 + j\lambda_p) \delta_{pq} = \mathbf{I}_p^H \mathbf{Z} \mathbf{I}_q, \quad \mathbf{X} \mathbf{I}_p = \lambda_p \mathbf{R} \mathbf{I}_p \quad \text{EFIE is diagonalized (all symbols have classical meaning).}$$

What operators we know?



- ▶ assume operators in their matrix forms, i.e. $\mathcal{L} \rightarrow \mathbf{L} \Rightarrow \mathcal{J} \rightarrow \mathbf{I}$
 - as far as meaningful, all algebraic operations are explicitly executable

$$\text{Impedance op. } P_r + 2j\omega (W_m - W_e) \rightarrow \frac{1}{2} \mathbf{I}^H \mathbf{Z} \mathbf{I}$$



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$$\text{Near-field op. } \mathbf{E}(\mathbf{r}) \rightarrow \mathbf{N}_e(\mathbf{r}) \mathbf{I}, \quad \mathbf{H}(\mathbf{r}) = \mathbf{N}_m(\mathbf{r}) \mathbf{I}$$

$$\text{Directivity op. } D_\ell(\mathbf{r}) \rightarrow \frac{4\pi \mathbf{I}^H \mathbf{F}_\ell^H(\mathbf{r}) \mathbf{F}_\ell(\mathbf{r}) \mathbf{I}}{Z_0 \mathbf{I}^H \mathbf{R} \mathbf{I}}$$



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$$\text{Resistance op. } P_L \rightarrow \frac{1}{2} \mathbf{I}^H \mathbf{\Sigma} \mathbf{I}$$

$$\text{Electric moment op. } \mathbf{p} \rightarrow \mathbf{P} \mathbf{I}$$

$$\text{Magnetic moment op. } \mathbf{m} \rightarrow \mathbf{M} \mathbf{I}$$



What are Operators Good For?

1. Determine lower/upper bounds,
2. estimate optimal trade-offs between various parameters,
3. find proper feeding networks,
4. understand underlying physics,
5. make material synthesis¹,
6. modify shape of source region¹.

¹This problem is far from to be solved.



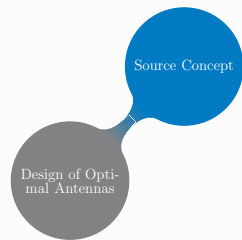
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Final goal is to design best antennas as possible.

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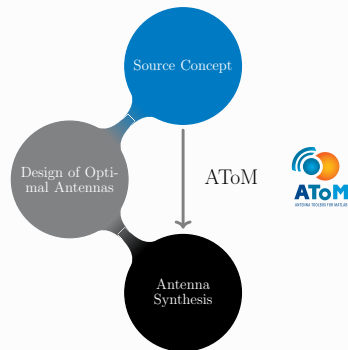
Design of Optimal Antennas



- ▶ The source concept was recently utilized for so-called optimal antenna design².
- ▶ To this purpose, it is beneficial to have a fast prototyping environment with partially open-source code.

²M. Gustafsson, D. Tayli, and M. Cismasu, "Physical bounds of antennas", in *Handbook of Antenna Technologies*, Z. N. Chen, Ed. 2015, pp. 1–32. doi: [10.1007/978-981-4560-75-7_18-1](https://doi.org/10.1007/978-981-4560-75-7_18-1)

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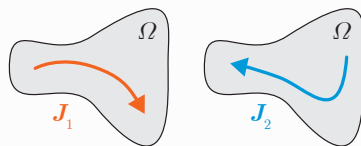
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The optimal antenna design leads at least to a partial antenna synthesis!

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Modal Decomposition

- ▶ any operator can be subject of decomposition

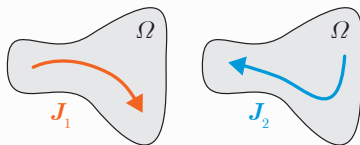


Modes J_1 and J_2 are depicted.

$$\mathbf{J} = \sum_m \alpha_m \mathbf{J}_m$$

Modal Decomposition

- ▶ any operator can be subject of decomposition
- ▶ radiation modes³



Modes \mathbf{J}_1 and \mathbf{J}_2 are depicted.

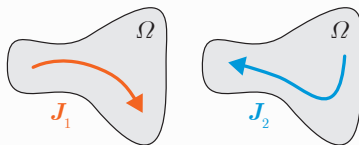
$$\mathbf{J} = \sum_m \alpha_m \mathbf{J}_m$$

$$\mathbf{R}\mathbf{I}_m = \zeta_m \mathbf{I}_m \quad (2)$$

³K. R. Schab and J. T. Bernhard, "Radiation and energy storage current modes on conducting structures", *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5601–5611, 2015. DOI: 10.1109/TAP.2015.2490664

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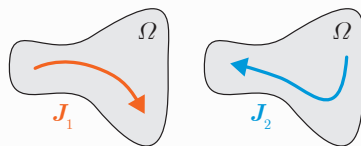
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- ▶ characteristic modes (CMs) decomposition

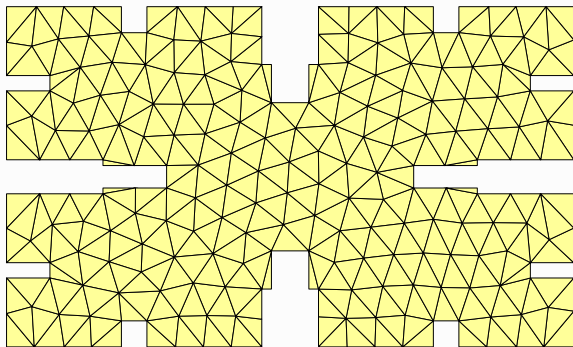
$$\mathbf{X}\mathbf{I}_m = \lambda_m \mathbf{R}\mathbf{I}_m \quad (4)$$

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Characteristic Modes

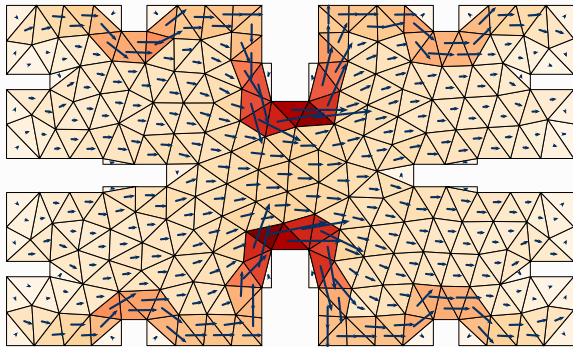
Example: CMs of PEC plate



IFS fractal, 2nd iteration, PEC, $ka = 0.5$.

Characteristic Modes

Example: CMs of PEC plate



Current density for 1st characteristic mode.

Radiation pattern for 1st characteristic mode.

Spatial Decomposition



Division of Ω into two parts.

$$\mathbf{J} = \bigcup_{k=1}^K \mathbf{J}_k$$

- ▶ similar to structural decomposition in mechanical engineering

$$\mathbf{I}^H \mathbf{L} \mathbf{I} = \begin{bmatrix} \mathbf{I}_A & \mathbf{I}_B \end{bmatrix}^H \begin{bmatrix} \mathbf{L}_{AA} & \mathbf{L}_{AB} \\ \mathbf{L}_{BA} & \mathbf{L}_{BB} \end{bmatrix} \begin{bmatrix} \mathbf{I}_A \\ \mathbf{I}_B \end{bmatrix} \quad (5)$$

- ▶ to decide what part of a radiator stores significant portion of energy / radiates well⁵
- ▶ excellent for synthesis of reflect arrays⁶
- ▶ combination with CMs: sub-structure modes⁷

⁵M. Capek, L. Jelinek, P. Hazdra, *et al.*, “The measurable Q factor and observable energies of radiating structures”, *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 311–318, 2014. DOI: 10.1109/TAP.2013.2287519

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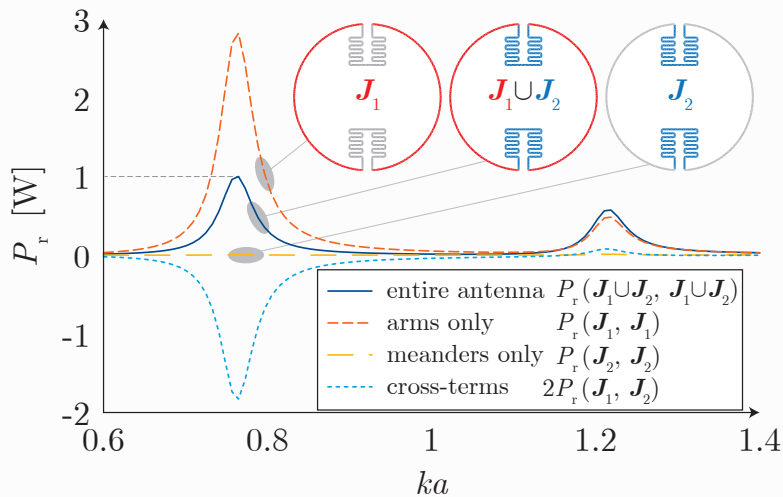
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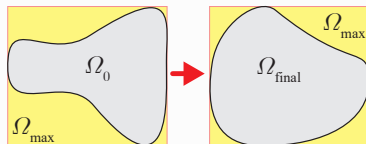
Spatial Decomposition

Example: Loop separation into arms and notches.



Structural decomposition of double U-notched antenna.

Optimization



Optimization of antenna's shape.

single-objective optim.:

$$\{y_j\} = \min_{\{x_i\}} \mathcal{F}(\mathbf{J})$$

multi-objective optim.:

$$\{y_j\} = \min_{\{x_i\}} \{\mathcal{F}_j(\mathbf{J})\}$$

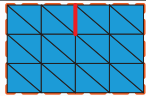
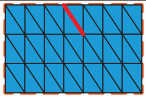
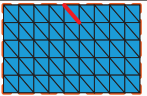

- ▶ both single- and multi-objective optimization can be utilized in order to obtain best antenna performance
- ▶ many objectives can be subjects of convex optimization⁸
 - \mathcal{F} has to be positive semi-definite⁹
 - convex optimization does not result in specific design, only minimizes given convex function

⁸M. Gustafsson and S. Nordebo, "Optimal antenna currents for Q, superdirectivity, and radiation patterns using convex optimization", *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, pp. 1109–1118, 2013. DOI: 10.1109/TAP.2012.2227656

⁹S. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge University Press, 2004

Excitation: NP-hard problem?

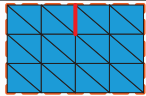
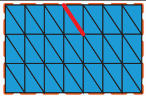
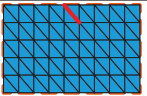

Certain synthesis problems resembles NP-hard problems...

How much DOF we have?				
N (unknowns)	28	52	120	∞
possibilities				
unique solutions				

Complexity of geometrical optimization for given voltage gap (red line) and N unknowns.

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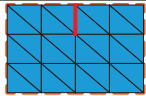
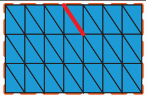
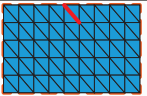

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unique solutions	$2.68 \cdot 10^8$	$4.50 \cdot 10^{15}$	$1.33 \cdot 10^{36}$	∞

Complexity of geometrical optimization for given voltage gap (red line) and N unknowns.

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Antenna synthesis – how far can we go?

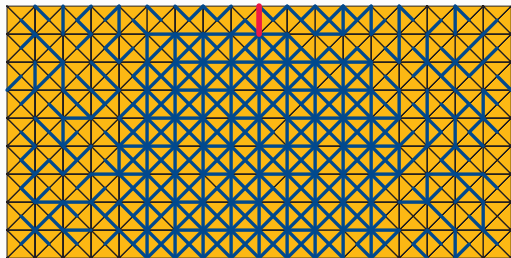
► On the present, only the heuristic optimization...



Pixelling with Heuristic Optimization

Example: Shape optimization (pixelling) with *ad hoc* specified feeding placement, PEC plate $L \times L/2$, $ka = 0.3$.

Computational time: 12116s

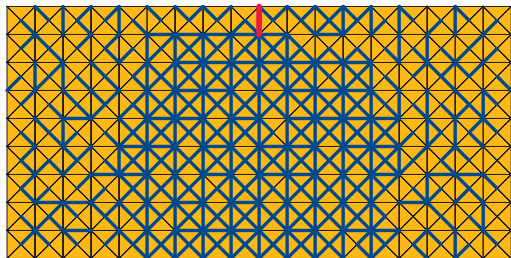


Result of heuristic structural optimization using MOGA
NSGAI from AToM-FOPS.

Pixelling with Heuristic Optimization

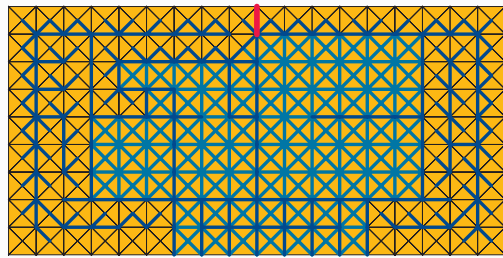
Example: Shape optimization (pixelling) with *ad hoc* specified feeding placement, PEC plate $L \times L/2$, $ka = 0.3$.

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Result of heuristic structural optimization using MOGA NSGAI1 from AToM-FOPS.

Computational time: 1155s

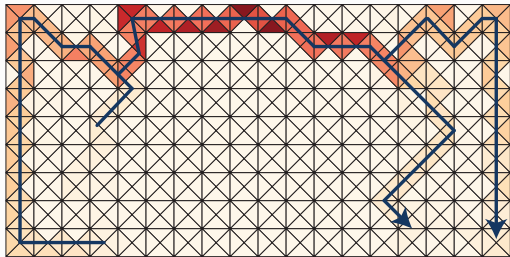


Result of deterministic in-house algorithm removing in each iteration the "worse" edge.

Pixelling with Heuristic Optimization

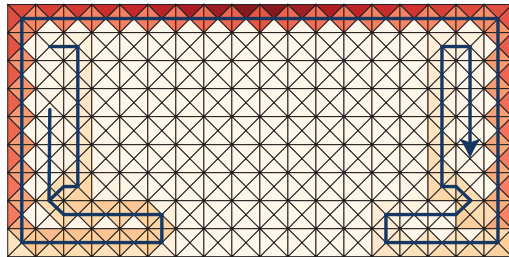
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$$Q(\mathbf{I}) / Q_{\text{Chu}}^{\text{TM}} = 7.23$$



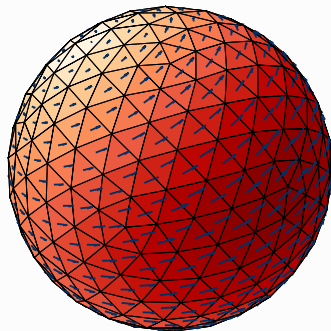
Resulting sub-optimal current approaching minimal value of quality factor Q .

$$Q(\mathbf{I}) / Q_{\text{Chu}}^{\text{TM}} = 7.24$$



Resulting current given by in-house deterministic algorithm.

Fundamental Bounds and Optimal Currents



- ▶ optimal¹⁰ (minimum / maximum)
 - quality factor Q
 - D/Q ratio
 - radiation efficiency η_{rad}
 - antenna gain G
 - other parameters...
- ▶ additional constraint of current resonance can be enforced

Optimal Q on a spherical shell.

¹⁰M. Capek and L. Jelinek, "Optimal composition of modal currents for minimal quality factor Q ", , *IEEE Trans. Antennas Propag. (Early Access)*, vol. PP, 2016. DOI: 10.1109/TAP.2016.2617779. [Online]. Available: arXiv:1602.04808, L. Jelinek and M. Capek, "Optimal currents on arbitrarily shaped surfaces", , 2016, eprint arXiv:1602.05520, M. Gustafsson and S. Nordebo, "Optimal antenna currents for Q , superdirectivity, and radiation patterns using convex optimization", *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, pp. 1109–1118, 2013. DOI: 10.1109/TAP.2012.2227656, M. Gustafsson, D. Tayli, C. Ehrenborg, *et al.*, "Antenna current optimization using MATLAB and CVX", , *FERMAT*, vol. 15, no. 5, pp. 1–29, 2016

Advanced Post-processing

Getting physical insight...



Feeding network synthesis.

$$\beta_{m,n} = \text{Re} \{ \alpha_m \alpha_n^* \}$$

where:

$$\alpha_m = \frac{\langle \mathbf{J}_m, \mathbf{E} \rangle}{1 + j\lambda_m}$$

- ▶ any antenna parameter can be defined by functional containing current(s)
- ▶ recently derived:
 - radiation efficiency without IBC¹¹
 - measurable Q_Z factor¹²
 - energies for sub-wavelength radiators¹³ ($ka < 1$)
 - no matter if modal / structural / total current is substituted

¹¹M. Capek, J. Eichler, and P. Hazdra, “Evaluation of radiation efficiency from characteristic currents”, *IET Microw. Antenna P.*, vol. 9, no. 1, pp. 10–15, 2015. DOI: 10.1049/iet-map.2013.0473

¹²M. Capek, L. Jelinek, P. Hazdra, *et al.*, “The measurable Q factor and observable energies of radiating structures”, *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 311–318, 2014. DOI: 10.1109/TAP.2013.2287519

¹³G. A. E. Vandenbosch, “Reactive energies, impedance, and Q factor of radiating structures”, *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1112–1127, 2010. DOI: 10.1109/TAP.2010.2041166

AToM: Antenna Toolbox For Matlab

"Antenna source concept" – New approach to antenna design.



AToM (Antenna Toolbox for Matlab)
third-party product developed by CTU in Prague and BUT.

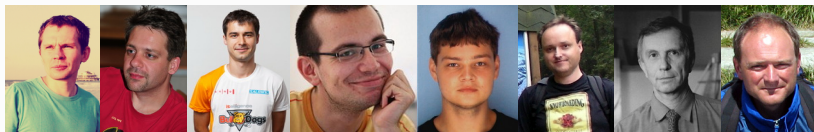


Logo of the AToM project.

The main idea behind the AToM toolbox is to develop new package that will be able to:

- ▶ utilize the source concept features
- ▶ handle with data from third party software
- ▶ accept other codes from the community
- ▶ make it possible the fast-prototyping of advanced antenna designs

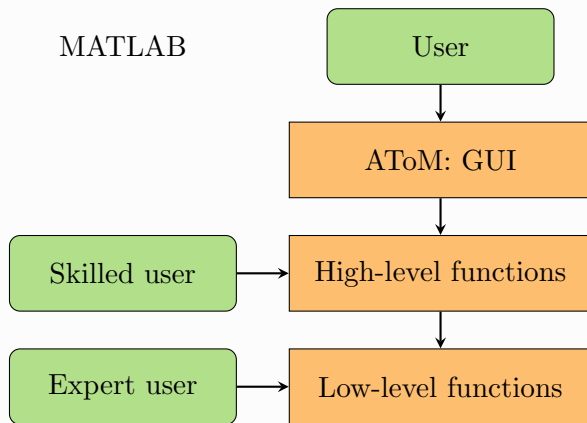
- ▶ 3 participants:
 - CTU in Prague, BUT, MECAS ESI (subsidiary of ESI Group)
- ▶ current project's staff (from left to right, no Czech diacritic marks)
 - Miloslav Capek, Pavel Hazdra, Petr Kadlec, Vladimir Sedenka, Viktor Adler, Jaroslav Rymus, Milos Mazanek, Zbynek Raida



- ▶ students (from left to right, no Czech diacritic marks)
 - Martin Marek, Martin Strambach, Vit Losenicky, Michal Masek, Miroslav Cupal



Matlab-like Conception



Scheme of AToM – completely written in OOP.

Why Matlab?

Pros

- ▶ high-definition language
 - excellent for fast-prototyping
 - many built-in functions are embedded
- ▶ new functionality can easily be published¹⁴
- ▶ maybe other...

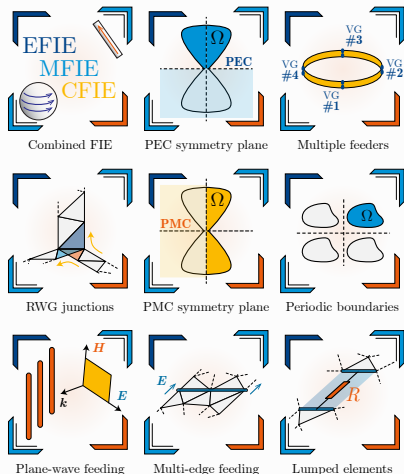
Cons

- ▶ still not as fast as e.g. C
 - and to be efficient, Matlab needs very good programming skill
- ▶ not open-source
- ▶ to make standalone application is a nightmare
- ▶ maybe other...

- ▶ What is your opinion??

¹⁴www.mathworks.com/matlabcentral/fileexchange

MoM Features We Are About To Have

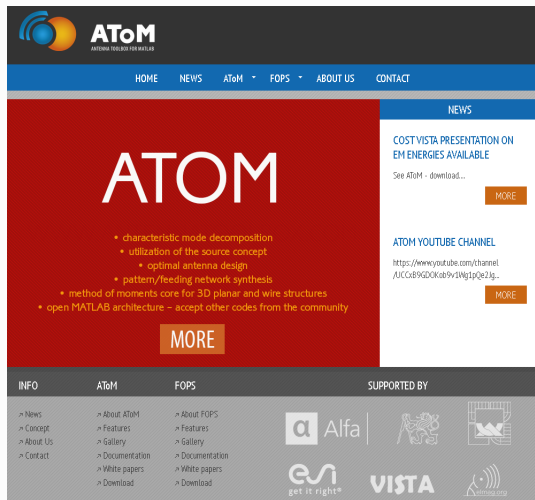


Scheduled features.

- ▶ CFIE (EFIE + MFIE),
 - ▶ lumped elements,
 - ▶ periodic structures,
 - ▶ analytic expressions of $\partial \mathbf{Z} / \partial \omega$,
 - ▶ static \times dynamic part¹⁵ of \mathbf{Z} .
-
- ▶ BEM,
 - ▶ EP / GEP solvers,
 - ▶ rect. MoM (?),
 - ▶ MLFMA (?).

¹⁵T. L. Simpson, J. C. Logan, and J. W. Rockway, “Decomposition of the moment method impedance matrix into quasi-static and residual components”, in *Proceedings of IEEE Energy and Information Technologies in the Southeast*, 1989, pp. 291–295. DOI: 10.1109/SECON.1989.132382

Lear More About AToM...



The screenshot shows the AToM website homepage. The main header features the AToM logo and navigation links: HOME, NEWS, AToM, FOPS, ABOUT US, CONTACT. The main content area has a large red section with the text 'ATOM' and a list of features:

- characteristic mode decomposition
- utilization of the source concept
 - optimal antenna design
- pattern/feeding network synthesis
- method of moments core for 3D planar and wire structures
- open MATLAB architecture – accept other codes from the community

 A 'MORE' button is located below this list. To the right, there are sections for 'NEWS' (with a link to 'COST VISTA PRESENTATION ON EM ENERGIES AVAILABLE') and 'ATOM YOUTUBE CHANNEL' (with a link to the channel). The footer contains navigation links for 'INFO', 'AToM', 'FOPS', and 'SUPPORTED BY', along with logos for Alfa, VISTA, and elmag.org.

▶ antennatoolbox.com

- source concept (CMs, optimization, post-processing)
- white papers, news,...

▶ questions at [info\[at\]antennatoolbox.com](mailto:info[at]antennatoolbox.com)

▶ [YouTube](#) channel

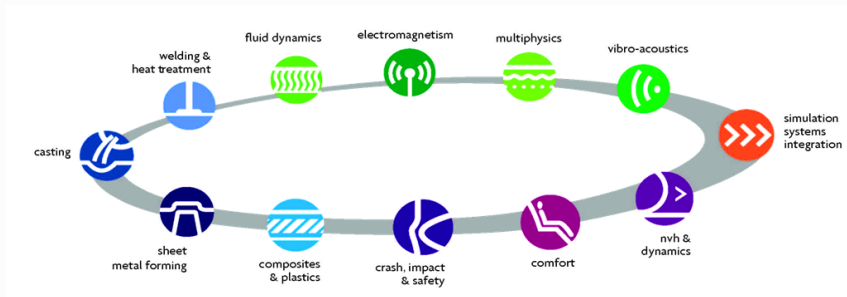
- AToM's core is complete
- numerical methods are now implemented

▶ now being [MathWorks](#) pre-product partners

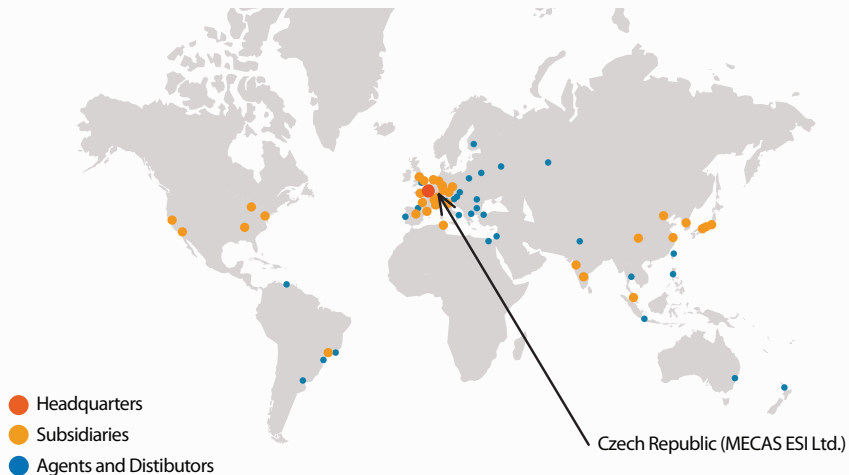
AToM → CEM One

The key functionality of the AToM will be implemented into Visual Antenna package, developed by MECAS ESI company (subsidiary of ESI Group).

- ▶ Visual Antenna is a module for CEM One, which integrates simulation tools for CEM developed and distributed worldwide by ESI Group
- ▶ ESI offers complete solutions for End-to-End Virtual Prototyping



ESI Group and MECAS ESI



ESI Group has more than 1000 employees, 15 subsidiaries, covers more than 40 countries and operates worldwide.



For complete PDF presentation see [▶ capek.elmag.org](http://capek.elmag.org)

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17. 11. 2016, v0.99

