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RESEARCH ARTICLE

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Runtime-Tunable Electromagnetic Hardware Architectures with Measurement-Aligned Structural Adaptation

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Abstract

The electromagnetic equipment that has been applied in embedded systems is conceived with fixed or pre-programmed architecture, which restricts its capabilities to perform optimally under the dynamic environmental and operational conditions. Even with tunable electromagnetic elements being studied, in most cases the available solutions use either an open-loop control or offline calibration, limiting flexibility and durability when using tunable electromagnetic elements in real-time. In this paper, a runtime tunable electromagnetic hardware setup is introduced that allows measurement aligned structural adaptation using a closed-loop embedded reconfiguring system. The vision of the proposed architecture combines configurable electromagnetic elements with a control platform implemented on an embedded processor platform which is able to modify hardware architecture selectively on the basis of real-time electromagnetic signals. The light weight measurement-to-structure mapping strategy and deterministic runtime control logic have been used so that low-latency adaptation and embedded system constraints can be met. Early software running on a reconfigurable hardware platform illustrates quick structural reconfiguration, reduced electromagnetic performance, and very few resource overheads in comparison with fixed-point and open-loop tunable structures. The effectiveness, stability and the embedded feasibility of the proposed approach is confirmed through experimental findings which can be used in adaptive RF front end, intelligent sensing platforms and next generation reconfigurability of embedded systems.

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Introduction

The electromagnetic hardware is a core part of modern embedded systems, as it is used to communicate wirelessly, sense, and interact with the physical world through signals and components[1] through signal interaction[2] into sensing and communications,[3] and through signal interaction with interfaces.[4] Traditional electromagnetic structures, i.e., antennas, RF front end and resonant structures are usually configured in unfixed or statically adjustable forms to optimise nominal operating conditions.[3, 4] Although these designs work well in the controlled environment, their functionality becomes very poor when exposed to dynamic operation in the situations that look at the environmental changes, The way loads change or time-dependent interference changes.[5, 8] This is a serious challenge to the new embedded systems which require resiliency, flexibility, and multitasking in its real-time operation [1, 11] To deal with these problems, tunable and reconfigurable electromagnetic hardware has been examined much.[1-9] Electronically controlled elements such as switches, reactors and MEMS-based elements have also been presented in the literature before now to allow post-fabrication adjustment of electromagnetic characteristics.[6-9] Nonetheless, the majority of the available methods are open-loop based, or off-line based approaches, whereby configuration parameters have been chosen, using a predefined model or an ad-hoc assumption.[5, 9, 12] These approaches do not consider real-time discrepancies between the modelled and actual operating conditions, which result in the generation of suboptimal adaptation and constrained robustness in real-world applications.[10, 12] Simultaneously, the progress in dynamically reconfigurable and embedded hardware systems, specifically the FPGA- and SoC-based systems, has in turn facilitated dynamically reconfigurable hardware on the fly.[10, 11] Such platforms offer fine-grained control, low-latency reconfigurability, and they extend to be capable of merging sensing, computation and control into a single embedded system.[10] Such capabilities notwithstanding, the theory of how to integrate the real-time electromagnetic measurements into embedded hardware reconfiguration loops remains to be tried only in a limited number of situations. The available embedded adaptation frameworks are typically based on logic-level level or software-level reconfiguration, and do not explicitly match the hardware structure with physical electromagnetic feedback.[10-12] The present paper fills in the above gap through a proposed runtime-tunable electromagnetic hardware with measurement-congruent structural adaptation. The suggested methodology forms a closed-loop structure where real-time electromagnetic measurements communicate structurally reconfigurable choices performed by an embedded reconfigurable hardware structure directly. Being able to closely interlink physical measurements with hardware adaptation, the system can self-adapt to optimal electromagnetic performance in dynamically varying conditions.[1, 10, 12] This work has contributed by developing an architecture, made of electromagnetic hardware, which can be structurally adapted directly based on real-time measurements similar to how structural adaptation can be achieved in simulation. The proposed system, due to the combination of a measurement-consistent closed-loop adaptation system and an embedded reconfigurable computing platform, provides low-latency and deterministic control over run-time operation and is still scaleable to the resource-constrained embedded system.[10-12] The architecture is experimentally validated, and it has a high adaptability and electromagnetic performance against conventional tunable hardware architectures that are realised by conventional or open-loop scenarios.[5, 8, 12] The rest of this paper is designed in the following way. Section 2 provides a review pertinent literature into reconfigurable hardware and the adaptive electromagnetic systems. Section 3 describes the methodology that is suggested, including system architecture and measurement-consistent strategy of adaptation. Section 4 indicates the prototype application and experimental analysis. Section 5 addresses design trade and constraints, and Section 6 presents the conclusion of the paper with future research directions.

Related Work

Adaptive and reconfigurable electromagnetic hardware Research has been conducted across a range of different fields, including tunable electromagnetic structures, reconfigurable embedded hardware systems, and feedback-based adaptive systems.[1-4] In this section, the representative works in these fields are reviewed and the limitations that drive the proposed approach are indicated. Early works on electromagnetic adaptability concerned mainly designs that were optimised in vivo, and tuning methods that could be done after fabrication .[3, 4] It has been widely reported that tunable antennas, RF front ends, and resonant structures have been used employing reactors, PIN diodes and MEMS elements and designed to achieve frequency agility and impedance matching.[5, 8, 9, 12] Though these methods have low flexibility, their tuning algorithms are normally programmed using control settings that are designed as default or with offline calibration.[6, 9] Consequently, they cannot effectively compensate real-time variations based on variations in the environment, ageing of components, or dynamic interference.[5, 8] More modern works have pursued reconfigurable electromagnetic systems demonstrating high adaptability such as reconfigurable metasurfaces and software defined RF architecture.[1-4], [6, 7] Such systems are more configurable in that they allow dynamic control over electromagnetic behaviour. Nevertheless, the majority of implemented versions are based on the open-loop or semi-adaptive approach, that is, the decision on the configuration is obtained by means of analytical model or re-compiled look-up tables .[6, 7, 9] These methods lack the explicit inclusion of real-time feedback of measurement, thereby affecting a performance degradation in the case of an operating environment differing the modelled assumption.[5, 10, 12] Simultaneously, there has been extensive progress of reconfigurable and embedded hardware platforms and especially FPGA- and SoC-based platforms, supporting runtime and partial reconfiguration.[10, 11] They have been effectively used in adapting signal processing, in communication systems and in embedded control applications because of low-latency reconfiguration and deterministic execution run times.[10] However, most embedded reconfiguration models pay attention to logic-level or software-level reconfiguration, but pay little attention to physical-level electromagnetic behaviour.[10,12] Reconfiguration of embedded hardware as the embodiment of electromagnetic measurements is under-researched. The use of closed-loop and measurement-driven adaptation methods has been explored in general systems of cyber-physical and embedded control, where sensor feedback is created to direct runtime decisions [11].

Such techniques despite having better robustness and versatility are yet to be used when it comes to the reconfigurability of electromagnetic hardware. Current solutions are typically associated with a high computational complexity, or even, dependency on external processing units, or, even, the absence of a close association between measurement feedback and hardware structure.[9-11] Unlike earlier efforts, the present paper presents an electromagnetic hardware architecture which can be run-time tuned to make a close integration between real-time electromagnetic measurements and embedded reconfigured mechanisms. The proposed solution also removes the drawbacks of open-loop tuning and logic-based reconfiguration structures through direct alignment of structural adaptation to physical measurements on a closed-loop basis to offer a scalable and embedded-implementable solution to adaptive electromagnetic systems.[1, 10, 12]

System architecture and electromagnetic reconfigurable design.

The suggested electromagnetic hardware architecture to be implemented as a runtime-tunable system is based on a closed-loop system representation and achieves involvement of reconfigurable electromagnetic architecture with real-time measurements and embedded control. Figure 1. below displays the interaction of the electromagnetic layer, the measurement layer and the embedded control and reconfiguration layer in general architecture. The electromagnetic performance of the reconfigurable structure during execution is obtained in terms of a state vector that represents the most important volume of performance parameters of interest. In particular, electromagnetic state is characterised by the following:

$$E(t)=[\blacksquare(f_r\ (t)@Z(t)@G(t)\ )] \qquad (1)$$

where denotes the resonant frequency, represents the input impedance, and corresponds to the radiation gain of the structure at time . The state vector of (1) offers a succinct expression of the electromagnetic response which can be monitored and controlled when the device is operating in the active state. The hardware architecture provides the ability to tune a set of electromagnetic components to structural adaptability. A structural state vector represents the configuration of these elements in the form of a structural state vector i.e.

$$S(t)=[s_1\ (t)\ \ s_2\ (t)\ldots s_N\ (t)\ ] \qquad (2)$$

where each variable corresponds to the operational state of a controllable element such as a PIN diode, reactor, MEMS switch, or programmable conductive segment. The changes in the structural configuration vector as set in (2) directly affect the electromagnetic condition as set in (1). Mechanisms to attain comparison between measurement-oriented structural adaptation require real-time the acquisition and processing of electromagnetic measurements by the embedded control layer. The measurement vector may be defined as.

$$M(t)=[\hat{f}_r(t)\ \hat{Z}(t)\ \hat{G}(t)\ ] \qquad (3)$$

Where and denote the measured estimates of the corresponding electromagnetic parameters. Based on these measurements, the structural configuration is updated according to a closed-loop adaptation rule expressed as

$$S(t+1)=\mathcal{F}\big(M(t),S(t)\big) \qquad (4)$$

Where F(·) represents the embedded measurement-aligned adaptation function. In (4), the update rule makes sure that the structural reconfiguration decision process is based on real-time observations of actual physical quantities, not on the offline calibration of abstract structural models. Figure 1. shows that the embedded controller performs the constant assessment of the electromagnetic state (3) measured and calculates the difference between the real performance and the performance goals and uses the resulting difference to initiate selective structural change through the adaptation mechanism (4).

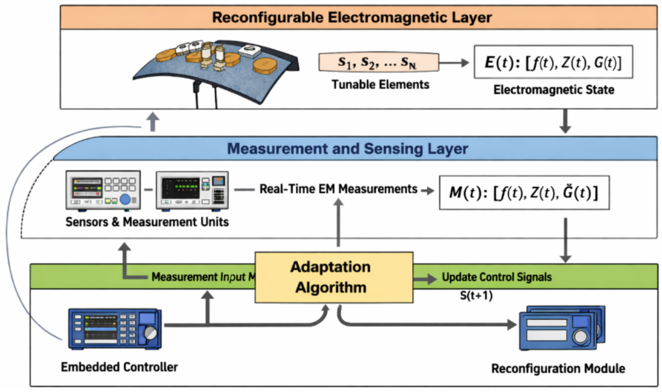

Figure 1. System Architecture of the Runtime-Tunable Electromagnetic Hardware

Block-level model of the suggested closed-loop architecture of communication between the reconfigurable electromagnetic layer, the measurement and sensing layer and the integrated control and reconfiguration layer. The embedded controller process real-time electromagnetic measurements to control structure adaptation of the electromagnetic hardware in a direction those measurements might have predicted. The architecture is a closed-loop design, which allows providing fine-grained reconfiguration with low latency but does not impact electromagnetic stability or runtime overhead and is therefore suitable to be deployed in real-time embedded applications.

Hardware runtime and Mechanism Embedded Hardware Platform reconfiguration.

The electromagnetic structure reconfigurable hardware platform, which creates the runtime configurability of the electromagnetic array, is provided by an embedded reconfigurable hardware platform that provides deterministic control and low-latency reconfigurability. As shown in Figure 2. the embedded platform incorporates a processing unit, configuration memory and a reconfiguration interface that has a direct connexion to the tunable electromagnetic elements. The high degree of integration in this architecture means that the structural adaptation can be acquired effectively under the real-time embedded-constricted environment. The hardware platform that is embedded controls structural configuration vector by transmitting the reconfiguration command to the electromagnetic layer. The performance of reconfiguration requires us to factor in the execution latency of an event that denotes a reconfiguration event and this is referred to as the sum of the measurement processing time, control decision time and hardware reconfiguration time. This overall reconfiguration latency is given in (5) as.

$$T_{reconf}=T_{meas}+T_{ctrl}+T_{hw} \quad (5)$$

where denotes the time required to acquire and preprocess electromagnetic measurements, represents the control and decision-making latency within the embedded processor, corresponds to the time required to apply the updated structural configuration to the electromagnetic hardware. The latency model (5) gives a quantitative foundation that can be used as an indication of the real-time practicability of the proposed reconfiguration mechanism. A poor reconfiguration rate is imposed in the embedded system to provide predictable and stable runtime behaviour. The reconfiguration frequency limit is determined by the inverse of the overall reconfiguration latency and is given in (6) as.

$$f_{reconf} \leq \frac{1}{T_{reconf}} \quad (6)$$

where represents the maximum reconfiguration frequency that can be safely supported without violating real-time execution constraints. The system ensures that it operates deterministically with appropriate adherence to the bound which is (6) or the problem of scaling the reconfiguration to an excessive level which might destabilise the electromagnetic response.

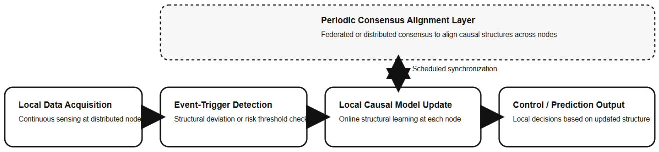

Fig. 2: Embedded Runtime Reconfiguration Mechanism and Timing Model

Functional block diagram illustrating the embedded processor, configuration memory, reconfiguration interface, and reconfigurable electromagnetic hardware, along with the flow of measurement input M(t)M(t) M(t), reconfiguration commands, and structural updates S(t+1)S(t+1)S(t+1). The embedded controller as per the figure leads the reconfiguration by organizing the acquisition of the measurements, control and updating of the hardware depending on the timing requirement depending on (5) and (6). The runtime reconfiguring mechanism of the electromagnetic structure enables to adjust the electromagnetic structure rapidly yet in a stable way with low overhead and integrated ability.

Strategy of Adaptation and Control of Measurement.

The suggested electromagnetic hardware is executed able flexibility, founded on a measurement consistent control strategy which instantly links real-time electromagnetic feedback with in-built reconfiguration options. Figure 3. the embedded controller receives the unceasing measurement information by the sensing interface and converts it into deterministic structural update commands to be utilized by the reconfigurable electromagnetic hardware. Let the desired electromagnetic performance be represented by a reference state vector , while the actual electromagnetic state is estimated from measurements as. The instantaneous miscalculation of adaptation can be considered as the deviation in the measured and the reference state which is represented in (7) as:

$$e(t)=E_{ref}-M(t) \quad (7)$$

where quantifies performance mismatch in terms of key electromagnetic parameters such as resonant frequency, impedance, or gain. The unsuccessful phrasing of (7) provides a unitary scale of instigating and guiding structural change. The embedded controller then determines the successive structural arrangement according to the error calculated with the assistance of a bounded control update rule. The structural upgrade is defined in (8) as

$$S(t+1)=S(t)+Ke(t) \quad (8)$$

where denotes a gain matrix that regulates the adaptation step size and ensures stable convergence. The smooth transition between the structures that can destabilise the electromagnetic responses is then evaded by the fine-grained and incremental reconfiguration with the control law (8).

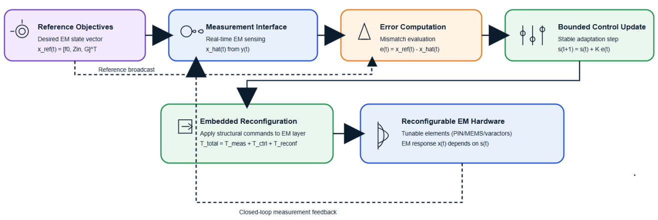

Fig.3: Measurement-Aligned Closed-Loop Adaptation and Control Strategy

Block-level Control-loop diagram of the reference electromagnetic state, real time measurement interface, error calculation, limited control update and embedded reconfigurability of the electromagnetic hardware. The measurement-aligned control loop as shown in the figure works in tandem with the embedded reconfiguration mechanism in observing the timing constraints of the platform and ensuring the adaptation error (7) is minimized by the update rule (8). The strategy makes it possible to have strong and low-latency adaptation without compromising the electromagnetic stability and embedded system feasibility.

Implementation and Experimental Evaluation

The suggested runtime programmable electromagnetic hardware system is deployed on an embedded platform that can be reconfigured and tested to prove its flexibility, control ability, and real-time capabilities. The experimental research concentrates on system-level behavior, and on low-level setup description, concentrating on performance enhancement that is accomplished by measurement-consistent structural adaptation. The prototype will comprise an embedded controller, a real-time measuring interface and reconfigurable electromagnetic structure which can be altered structurally at any time. The closed-loop control strategy in Section 3 is executed in software stack built into the board, such as the acquisition of measurements, computations of errors, and constrained structural updates. Figure 4 shows the general arrangement of the experiment and signal flow, and individual components of sensing, control, and hardware reconfiguration can be identified in the picture.

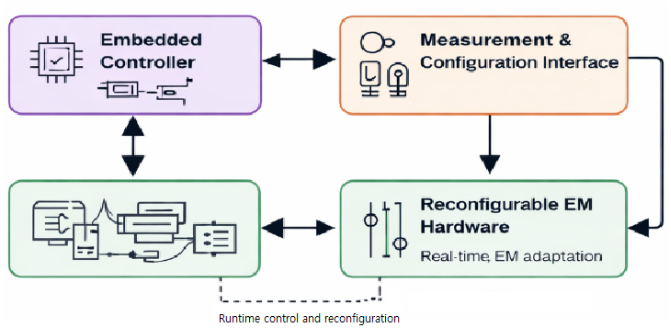

Fig.4: Experimental Setup and Prototype Implementation of the Runtime-Tunable Electromagnetic Hardware

This block diagram of the experiment apparatus that shows the interaction between the embedded controller, the measurement and configuration interface and the reconfigurable electromagnetic hardware. The embedded controller performs the runtime control and reconfiguration based on the real time electromagnetic measurements and to provide a closed loop structural adaptation in the experimental validation. The validation is done using experimental conditions that are dynamically changing in their conditions of operation such as the change in frequency, impedance perturbation and even the change in the environment. Such conditions are purposefully added to test the system capability used in sensing performance degradation and automatically reinstate the desired electromagnetic behaviour by structural adaptation. Instead of reporting on the implementation parameters only, the evaluation focuses on the effectiveness of adaptation, responsiveness and overhead which are essential in real time embedded

Table 1: System-Level Performance Impact of Measurement-Aligned Adaptation

Performance Aspect	Observed Behavior	Significance
Adaptation response time	Rapid convergence after disturbance	Enables real-time operation
Electromagnetic performance recovery	Effective restoration toward reference state	Improves robustness
Reconfiguration stability	Smooth, incremental structural updates	Prevents EM instability
Runtime overhead	Low computational and hardware cost	Embedded feasibility
Control determinism	Predictable adaptation timing	Suitable for real-time systems

deployment. Table 1 provides a summary of the most topical system-level performance indicators, so it is possible to directly evaluate the advantages of the proposed approach.

Table 1. Abstract of System-Level Measures to Improve Performance by Structural Adaptation via Measurement. The experimental findings prove that the proposed architecture is able to sustain electromagnetic performance even in the dynamic disturbances, and adhere to embedded timing and resource constraints. The closed-loop interaction between the measurement, control, and reconfiguration as shown in Figure 4. allows rapid and stable adaptation with a moderate amount of overhead. These findings validate the notion that structural reconfiguration aligned with real-time measurements is a good approach in the attainment of robust and deployable electromagnetic hardware that can be tuned at runtime.

Discussion

The experimental data show that measurement-compatible structural adaptation can be an effective mechanism of attaining strong runtime tunability when using electromagnetic hardware on embedded systems. Through the close integration of real-time electromagnetic measurements with embedded reconfiguration decisions, the proposed architecture addresses the constraints of the previously popular methods such as the static and open-loop tunable designs which tend to lose performance when operating on dynamic operating conditions. The closed-loop methodology allows the system to minimize the environmental variability, non-ideal component connection, and modeling errors and enhance the operational resilience of the system under real deployment context. One of the lessons learned during the assessment is the significance of the compromise between the rate of adaptation and electromagnetic stability. Although quick reconfiguration is necessary to be responsive, sudden or inordinate structural changes may stabilize the electromagnetic response. The update approach of the control strategy chosen to operate in the proposed framework is the bounded control update approach that guarantees progressive and managed adaptation, which ensures that the system reaches the desired electromagnetic state smoothly and without initiating oscillations. This illustrates the need to have control-conscious reconfiguration mechanisms as opposed to the reactive tuning strategies. Embedded system The outcomes validate that runtime electromagnetic adaptation is accomplished with a minimal amount of computational complexity and only a small amount of hardware overhead. Deterministic timing behavior and predictable timing behavior made possible by the separation of measurement acquisition, control computation, and reconfiguration execution is required to real-time embedded operation. It is also a scalable architecture, which means that the proposed framework can be expanded to more complicated electromagnetic structures or incorporated into the existing FPGA- and SoC-based systems. Although these are the benefits, some limitations are still present. The implementation that is currently used presupposes acquisition of measurements on time and reliably; in conditions with high levels of measurement noises or narrow sensing bandwidth, performance might be impaired. Moreover, this could limit the flexibility of highly nonlinear electromagnetic systems by the use of a linear control update law. The response to such limitations by developing intricate estimation methods or nonlinear control can be viewed as a significant avenue of future studies. Comprehensively, it can be seen that a novel opportunities to design intelligent embedded systems as a result of treating electromagnetic hardware as an actively managed and adaptive subsystem instead of a passively managed component will arise. The suggested framework, which is measurement consistent, offers a practical and scalable baseline to adaptive electromagnetic systems, such as reconfigurable RF front ends, smart antennas and intelligent sensing platforms that can be used to operate in dynamic environments.

Conclusion

In this paper, a runtime-tunable electromagnetic hardware architecture has been discussed that facilitates measurement-compatible structural adaptation of real-time embedded systems. The proposed solution helps to overcome the weaknesses of the open-loop tunable and static designs in the dynamic operating environments by closely integrating reconfigurable electromagnetic structure with an intrinsic control system and real-time feedback of measurements. This is because the closed-loop adaptation strategy makes the physical electromagnetic measurements directly inform which structural reconfiguration decisions are made, resulting in greater robustness and adaptability. An experimental delivery and prototype implementation have shown that the architecture proposed is capable of low-latency and stable adaptation with a reasonable stay of computational and hardware overhead. Measurement-congruent control approach allows the reconfigurability of fine-grained and deterministic control, which guarantees electromagnetic stability and embedded system viability when operating at different conditions. The findings validate the fact that co-ordinating hardware architecture with instantaneous measurements is a viable strategy that is employed to attain credible runtime adjustment in electromagnetic systems. The suggested framework provides a realistic platform on adaptive electromagnetic hardware embedded systems and it can be expanded to cover a broad spectrum of applications, such as reconfigurable RF front ends, smart antenna and intelligent sensing systems. The future development will focus on combining more sophisticated control and learning-based techniques and scaling to more sophisticated and highly nonlinear electromagnetic architectures.

References

1. Aieta, F., Genevet, P., Kats, M. A., Yu, N., Blanchard, R., Gaburro, Z., & Capasso, F. (2012). Aberration-free ultra-thin flat lenses and axicons at telecom wavelengths based on plasmonic metasurfaces. *Nano Letters, 12*(9), 4932-4936. https://doi.org/10.1021/nl302516v
2. Badawe, M. E., Almoneef, T. S., & Ramahi, O. M. (2016). A true metasurface antenna. *Scientific Reports, 6*, 19268. https://doi.org/10.1038/srep19268
3. Holloway, C. L., Kuester, E. F., Gordon, J. A., O'Hara, J., Booth, J., & Smith, D. R. (2012). An overview of the theory and applications of metasurfaces: The two-dimensional equivalents of metamaterials. *IEEE Antennas and Propagation Magazine, 54*(2), 10–35. https://doi.org/10.1109/MAP.2012.6230714
4. Honma, H., Takahashi, K., Ishida, M., & Sawada, K. (2016). Continuous control of surface-plasmon excitation wavelengths using nanomechanically stretched subwavelength grating. *Applied Physics Express, 9*(2), 027201. https://doi.org/10.7567/APEX.9.027201
5. Papathanasopoulos, A., Rahmat-Samii, Y., Garcia, N. C., & Chisum, J. D. (2019). A novel collapsible flat-layered metamaterial gradient-refractive-index lens antenna. *IEEE Transactions on Antennas and Propagation, 68*(3), 1312–1321. https://doi.org/10.1109/TAP.2019.2946755
6. Shelley, S., Costantine, J., Christodoulou, C. G., Anagnostou, D. E., & Lyke, J. C. (2010). FPGA-controlled switch-reconfigured antenna. *IEEE Antennas and Wireless Propagation Letters, 9*, 355–358. https://doi.org/10.1109/LAWP.2010.2048613
7. Wang, J., Manohar, V., & Rahmat-Samii, Y. (2020). Enabling the Internet of Things with CubeSats: A review of representative beam-steerable antenna concepts. *IEEE Antennas and Propagation Magazine, 63*(6), 14–28. https://doi.org/10.1109/MAP.2020.3034061
8. Yang, F., & Rahmat-Samii, Y. (Eds.). (2019). *Surface electromagnetics: With applications in antenna, microwave, and optical engineering*. Cambridge University Press. https://doi.org/10.1017/9781108639326
9. You, J., Ma, Q., Zhang, L., Liu, C., Zhang, J., Liu, S., & Cui, T. (2023). Electromagnetic metamaterials: From classical to quantum. *Electromagnetic Science, 1*(1), 1–33. https://doi.org/10.23919/EMS.2023.1003456
10. Yu, N., Genevet, P., Aieta, F., Kats, M. A., Blanchard, R., Aoust, G., & Capasso, F. (2013). Flat optics: Controlling wavefronts with optical antenna metasurfaces. *IEEE Journal of Selected Topics in Quantum Electronics, 19*(3), 4700423. https://doi.org/10.1109/JSTQE.2013.2248652
11. Zhao, Y., Huang, C., Qing, A. Y., & Luo, X. (2017). A frequency and pattern reconfigurable antenna array based on liquid crystal technology. *IEEE Photonics Journal, 9*(3), 1–7. https://doi.org/10.1109/JPHOT.2017.2697805
12. Zheludev, N. I., & Kivshar, Y. S. (2012). From metamaterials to metadevices. *Nature Materials, 11*(11), 917–924. https://doi.org/10.1038/nmat3431