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Re-Exploring Intelligent Systems: Reasoning, Learning, and Control Through the Lens of RLC Circuits

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Abstract: This paper explores the realm of intelligent systems through an analogy inspired by RLC circuits, delving into the interconnected dynamics of reasoning, learning, and control. Leveraging the simplicity and clarity of the analogy, we navigate the conceptual landscape, drawing parallels between electrical components and the cognitive functions of modern AI. The presented analogical framework is the conclusion of the author's personal experiences in developing intelligent systems, sparked by conversations with fellow researchers and students and presentations of research outcomes. It is worth recognizing the limitations of this analogy, as its reductionist nature may oversimplify the complexities inherent in intelligent systems. However, this exploration provides a fresh perspective on the foundational components of intelligent systems through the lens of the well-established RLC circuit theory.
Keywords: Artificial intelligence, intelligent systems, RLC, analogy

Akıllı Sistemlere Yeni Bir Bakış: RLC Devrelerinin Merceğinden Muhakeme, Öğrenme ve Kontrol

Özet: Bu makalede, RLC devrelerinden esinlenen bir analoji aracılığıyla akıllı sistemler alanı araştırılmakta olup, muhakeme, öğrenme ve kontrolün birbirine bağlı dinamikleri incelenmektedir. Analojinin basitliği ve açıklığından yararlanarak, elektrik bileşenleri ile modern yapay zekanın bilişsel işlevleri arasında paralellikler kurarak kavramsal zeminde akıllı sistemlerin modeli çıkarılmaktadır. Önerilen benzetmeler, yazarın akıllı sistemler geliştirirken edindiği kişisel deneyimlerinin, diğer araştırmacılar ve öğrencilerle yaptığı görüşmelerin ve araştırma sonuçlarının sunumlarından ortaya çıkmıştır. Sunulan benzetimin basitleştirici doğasının sınırlamalarının altı çizilmiştir. Bununla birlikte, bu inceleme, köklü RLC devre teorisinin merceğinden akıllı sistemlerin temel bileşenlerine yeni bir bakış açısı sağlamaktadır.
Anahtar Kelimeler: Yapay zeka, akıllı sistemler, RLC, analoji

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1 Introduction

In recent years, the huge success of deep learning has reshaped the landscape of Artificial Intelligence (AI), revolutionizing diverse applications ranging from image and speech recognition to natural language processing [1], [2]. The capabilities demonstrated by deep learning models, particularly in complex and unstructured data domains, have propelled us into an era where AI plays an increasingly integral role in our daily lives. As we navigate this world of ever-evolving AI, characterized by the advent of powerful language models [3], [4], it becomes essential to reflect on the conceptual foundations that underpin intelligent systems [5]–[8].

This paper explores the intriguing parallels between the architectures of RLC circuits and of intelligent systems. Drawing inspiration from the electrical components—Resistor (R), Inductor (L), and Capacitor (C)—we present an analogy connecting the Reasoning (R), Learning (L), and Control (C) components of intelligent systems. Thus, we present the equivalent RLC circuit models of the intelligent systems to easily describe the intelligent system.

The primary objective of this paper is to draw an analogy between RLC circuits and intelligent systems, with a focus on the components of Reasoning, Learning, and Control. Keep in mind that, just like any analogy, the RLC circuit analogy is a simplification, and the correspondence may not capture all the nuances of how intelligent systems truly operate. Yet, it offers a fresh perspective on the complicated interaction of algorithms and concepts that shape intelligent systems. By establishing connections between these realms, we aim to shed some light on the shared principles and insights that can mutually benefit the fields of electrical engineering and AI. Through presenting the autonomous vehicle, this exploration seeks to enhance the understanding of how these analogies can contribute to the advancement of intelligent systems design.

The presented analogical framework is the conclusion of the personal experiences of the author in developing intelligent systems, sparked by conversations with fellow researchers and students and presentations of research outcomes. During the preparation of this study, this paper emerges from a collaborative exploration of thoughts and ideas through a unique process by engaging in discussions with mainly ChatGPT 3.5, alongside Microsoft Copilot (formerly Bing Chat).

2 Intelligent Systems: Definitions and Goals

Intelligent System is a broad term that encompasses various aspects of AI alongside natural language processing, computer vision, and robotics [8]–[10]. Intelligent systems can perform tasks that normally require human intelligence, such as reasoning, learning, decision-making, and perception. Let us first examine the definitions of intelligent systems in literature:

Definition 1. An intelligent system is "a system that acts rationally, that is, in a way that is appropriate for its circumstances and its goals, given its perceptual and computational limitations" [8].

Definition 2. An intelligent system is "a system that incorporates intelligence into applications being handled by machines. It can also be considered as a system that is able to learn from data and/or the environment and exhibit adaptive, complex, and intelligent behavior" [10].

In literature, there is no universally agreed-upon definition of intelligent systems, as different disciplines and domains may have different perspectives and criteria for what constitutes intelligence. For instance, from a control engineering application point of view, the intelligent system, i.e intelligent control description is as follows:

Definition 3. An intelligent control system is the intersection of artificial intelligence and automatic control to develop intelligent control systems that simulate human-like intelligence for efficient and adaptive control processes [11].

Whereas in [12] a more formal definition is presented:

Definition 4. Intelligent Control can be defined as a function of knowledge level and expectations determined by the historical era [12].

There are many more definitions coined with respect to the application domain [13]–[17]. Yet, regardless of the disagreement, or maybe more correctly the diversity in defining an intelligent system, three primary goals guide their design as abstracted in Fig. 1. The goals are:

- **Autonomy** refers to the system's capacity to make decisions independently, allowing it to navigate and respond to various scenarios without constant human intervention.
- **Flexibility** involves the system's ability to adapt to new conditions, learning from experience and adjusting its behavior accordingly.
- **High Accuracy** is paramount, ensuring the system reliably produces correct and precise results.

Nowadays, through the massive deployment of AI, a 4^{th} goal explainability/interpretability has appeared [5]–[7], [18].

Achieving the goals of intelligent systems involves integrating three fundamental components, namely, Reasoning, Learning, and Control.

- **Reasoning (R)**: The ability to handle uncertainty and imprecise information for decision-making. For instance, Fuzzy logic [15], [19] and Reinforcement Learning [20] contribute to autonomous decision-making.

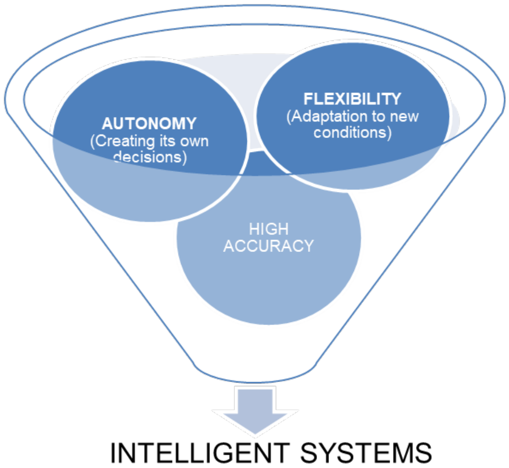

Fig. 1 A graphical abstract of intelligent systems

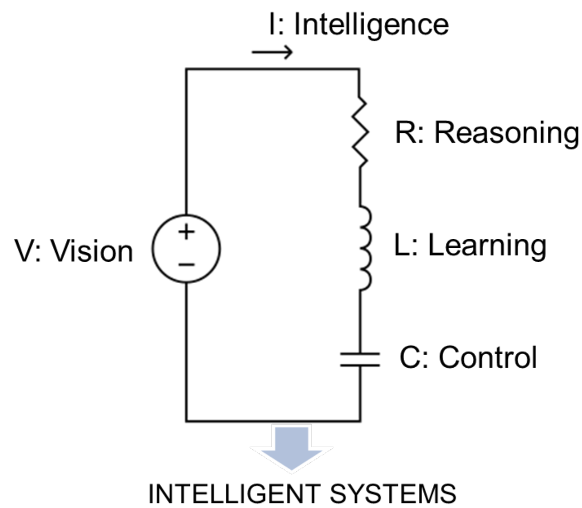

Fig. 2 A graphical abstract of the analogy

- **Learning (L)**: The ability of an intelligent system to adapt and improve its performance over time based on data. Machine/ deep learning models such as neural networks play a vital role in learning [1].
- **Control (C)**: The capability to facilitate the organization and regulation of the system's actions. Optimization techniques further enhance accuracy, fine-tuning the system's performance to achieve optimal outcomes. Nice exemplars are optimal control and model predictive control [14], [21].

To sum up, intelligent systems strive to embody autonomy, flexibility, and high accuracy through the synergy of components RLC.

3 Bridging RLC Circuits and Intelligent Systems

RLC circuits require no extensive introduction due to their widespread use in control, electronics and electrical engineering, and various applications, such as signal processing, filters, and communication systems [22]. In this section, as depicted in Fig. 2, we provide a unique perspective by drawing parallels between electrical components and configurations of RLC circuits and the components of intelligent systems. The analogy can serve as a conceptual framework to help explain the functionalities and relationships between reasoning, learning, control, vision, and intelligence in a system.

3.1 Component-wise analogy

Let us break the analogy component-wise:

(i) **Variable $i(t)$:** *Current & Intelligence*. Just as current is the flow of electric charge, intelligence can be seen as the flow or output of the intelligent system, representing its decision-making, problem-solving, or action-taking capabilities. The movement of current can be likened to the dynamic nature of intelligence in adapting and responding to inputs.

(ii) **External Source V_s:** *Voltage input & Vision input*. Voltage represents the potential energy in an electrical circuit, and vision is often considered a fundamental element in the potential and perception of intelligent systems. Thus, similar to how voltage represents the energy employed in a circuit, it represents external stimuli or information sources that provide input to the intelligent system. Vision or observation space can be considered the potential information that the intelligent system can utilize for decision-making and learning.

(iii) **External Source I_s:** *Current input & Prior Intelligence/ Expert knowledge.* A current source can be seen as a predefined intelligence or a knowledge-based system. It represents a set of rules, facts, or domain knowledge that serves as a foundational input influencing the behavior of the intelligent system.

(iv) **Element R:** *Resistance & Reasoning*

- Resistance introduces resistance to the flow of electric current ($i(t)$) and follows Ohm's Law, which states that the current across a resistor is: $i(t) = v(t)/R$.
- Just as resistance in a circuit impedes the flow of current, reasoning in an intelligent system can be seen as the cognitive process that may slow down or guide or act as a constraining factor in decision-making, ensuring that choices align with logical principles.

(v) **Element L:** *Inductor & Learning*:

- The inductor stores energy in a magnetic field when the current flows through it. It defines an integral operator (i.e. accumulation): $i(t) = 1/L \int v(\tau)d\tau$
- Similar to how inductance stores energy, learning in an intelligent system involves accumulating knowledge and adapting based on experience or data. It represents the ability of the system to store and utilize learned information.

(vi) **Element C:** *Capacitor & Control*.

- Capacitor has a role in storing and releasing electrical energy based on dynamic voltage fluctuations as $i(t) = Cdv(t)/dt$.
- Control in an intelligent system can be seen as the capacity to store and manage information, directing the behavior of the system based on its goals and objectives. The ability to store and release "control energy" metaphorically aligns with the role of a capacitor.

To sum up, the current captures the dynamic aspect of the intelligent system's behavior, representing the continuous flow of intelligence as it responds to external inputs and processes information.

3.2 Configuration-wise analogy

The circuit configuration of RLC alongside the deployed circuit components depends on the application. For instance, a series RLC circuit (left in Fig. 3) can be designed for a tuned radio frequency receiver while a parallel RLC (right in Fig. 3) one for a bandpass filter.

- The series RLC circuit, where components share a common current but have individual voltages, might be analogous to a sequential or hierarchical processing structure in intelligent systems. In this context, each component represents a distinct stage in the processing pipeline, akin to the sequential flow of information through reasoning, learning, and control modules within the intelligent system.

- In a parallel RLC circuit, where components share a common voltage but have individual currents, one might draw parallels to distributed or parallel processing in intelligent systems, where different subsystems operate concurrently. This analogy can illuminate how various aspects of reasoning, learning, and control occur simultaneously, each contributing to the overall intelligence of the system.

We can conclude that, just as in RLC circuits where components engage in mutual dependencies and affect each other's behavior, intelligent systems exhibit a dynamic and interdependent interaction among reasoning, learning, and control components. This intricate interplay contributes to shaping the overall intelligence of the system.

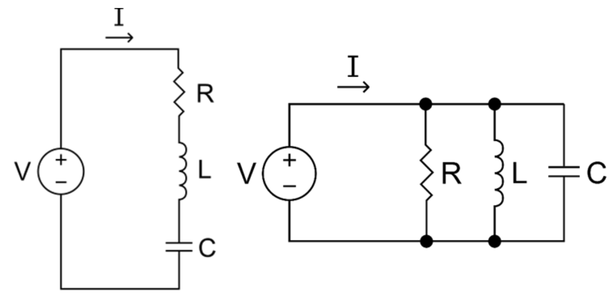

Fig. 3 Illustration of serial (left) and parallel (right) RLC circuits

4 Case study: An Autonomous Vehicle

Here, we present an example to illustrate how the components of the analogy align with the key functions of an intelligent system in a real-world application. In this context, let's consider an autonomous vehicle scenario where the analogy of RLC circuits is applied.

- **Resistor - Reasoning**: In the context of an autonomous vehicle, reasoning involves processing sensory data, making decisions, and planning actions. The resistance corresponds to the cognitive load or complexity of the decision-making process. For instance, if the vehicle encounters a complex traffic situation, the reasoning component (analogous to the resistor) assesses and guides the decision-making process.

- **Inductor - Learning**: In the case of autonomous vehicles, learning refers to the system's ability to adapt based on experiences gathered from feedback data. For example, the vehicle's inductor might store knowledge gained from past situations, enabling it to recognize and respond more effectively to similar scenarios in the future.

- **Capacitor - Control**: In the autonomous vehicle system, control involves regulating and managing the vehicle's movements. The capacitor represents the system's ability to store and utilize control strategies or policies. For instance, in situations requiring sudden braking or acceleration, the capacitor-like control component ensures a smooth and controlled response of the vehicle.

- **Voltage Source – Vision**: In the autonomous vehicle context, the voltage source could include data from cameras, sensors, traffic signals, and communication with other vehicles. These external inputs influence the vehicle's decision-making and response.

- **Current Source – Domain Knowledge**: In the scenario of autonomous vehicles, this could be a set of rules, traffic regulations, and domain-specific knowledge based on expert knowledge. The predefined intelligence guides the system's behavior in adherence to established principles.

5 Conclusion, Discussions and Limitations

In this exploration of intelligent systems through the lens of RLC circuits, we have unveiled intriguing parallels that shed light on the intricate dynamics of reasoning, learning, and control. Drawing inspiration from the analogy, we navigated the conceptual landscape where these fundamental functions interact, much like the components of an electrical circuit influencing each other. While the equivalent circuit analogy offers a conceptual framework for understanding intelligent systems, it is important to acknowledge its limitations. One notable constraint lies in the simplicity of the analogy, which may not fully capture the complexity and nonlinearity inherent in real-world intelligent systems. The analogy also neglects certain nuances, such as the adaptability and dynamic evolution of intelligence, which are integral aspects of modern AI applications. Additionally, the analogy may oversimplify the feedback loops and intricate decision-making processes present in intelligent systems. Yet, further analysis can be performed as there is a well-established literature on adaptive RLCs with feedback.

In conclusion, the RLC circuit analogy provides a valuable perspective on the core functions of intelligent systems through the lens of the well-developed circuit theory.

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