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AI-Driven Digital Twins for Smart Cities †

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Abstract: This paper explores the issues of building digital twins for smart cities, which can be controlled manually or with the assistance of intelligent systems. For these purposes, a specialized logic platform, Delta, is being built, which has such properties as transparency, reliability, and predictability. The Delta platform allows us to represent the digital twins of cities as a network of smart contracts that interact with each other within a unified multi-blockchain system. The inclusion of Delta-learning and Delta-connection modules facilitates knowledge acquisition and utilization for AI-driven process management and sensor integration within smart cities.

Keywords: smart cities; digital twins; Delta platform; artificial intelligence; multi-blockchain

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1. Introduction

Smart cities [1] are the backbone of any digital economy [2]. This concept entails the end-to-end integration of IT technologies within a smart city, including tracking passenger traffic; monitoring transport and crime rates; managing household expenses, such as heating, water, and electricity; facilitating interaction between citizens and the government; providing automatic payroll and taxes; paying for health insurance; interacting with assistants and chatbots; and much more. All these achievements are aimed at improving reliability and the quality of life of ordinary citizens.

The successful implementation of these processes requires a robust IT infrastructure that includes computers, sensors, and controllers. This infrastructure generates huge amounts of data that require processing, storage, and analysis. Artificial intelligence algorithms play a pivotal role in addressing these challenges, encompassing pattern recognition, voice recognition, chatbots, and intelligent assistants. These sophisticated mechanisms enable the analysis and processing of the acquired information.

In this context, we are introducing a novel blockchain-based [3] platform, Delta. This platform enables the creation of digital twins of smart cities [4], accurately simulating all processes and relationships within them. The Delta platform implements a hierarchical approach to data storage and processing in which there are multi-blockchains using blockchains in combination with other big data stores as the underlying information stores. The work of intelligent systems in a smart city is described using smart contracts (SCs) that are executed within multi-blockchain structures, thereby ensuring efficient and secure functionality. To obtain new knowledge and predictions, we use a specially developed learning theory for intelligent systems based on the requirements of maximum specificity presented in the works of Carl Hempel [5].

2. Smart Cities

When we say smart city, what do we mean by it? This is not only the digitalization of all processes, but also the intellectual component. A smart city must independently solve some of the problems within the boundaries set by its developers. We cannot do this without introducing artificial intelligence. IT solutions should make life as easy as possible for ordinary citizens in cities. Moreover, a compromise must be found between total surveillance and the personal lives of citizens. This compromise could be for each person to manually set the parameters they allow to be used to track their activities.

A living unsuccessful example of total digitalization is the South Korean city of Songdo [6], in which, according to the plans of the South Korean authorities and developer companies, several hundred thousand people were supposed to live, but in fact it is inhabited by only 10–20% of this. There can be many reasons for this, ranging from the lack of cultural and leisure facilities to tracking most of the actions of each person. And there are dozens and hundreds of such ghost towns all over the world.

Therefore, the creation and planning of smart cities must be approached with all care and seriousness. A very important criterion, in our opinion, is that an ordinary user can control the level of outside interference in their personal life. Moreover, it is necessary for the residents themselves to be able to influence what smart technologies are introduced in their city [7].

Many experts consider the following to be the main areas of development in smart cities: public and personal transport, smart homes, energy optimization, medicine, security, clean water, and waste recycling. In all these areas of development, we must not only create software, but we must teach these programs to think for themselves within their competences.

3. Digital Twins for Smart Cities

The first ideas of digital twins appeared in David Gelernter's book *Mirror Worlds* [8]. The concept of a digital twin was first described in 2002 by a professor at the University of Michigan, at a Society of Manufacturing Engineers conference in Troy, Michigan [9]. Over the past 20 years, the term has evolved significantly and today has several different definitions. Therefore, we understand the term digital twin as a digital copy of a physical object or process, and a change in the work of a digital copy entails a change in the work of the physical object or process itself and vice versa. A good example of a digital twin is ADNOC's technological solution to create a single control center for all processes for 20 oil refineries and oil production enterprises [10].

The digital twin of a smart city should not only be a decision-making system for the operator, but should also have AI solutions that would help manage all the city's processes, such as managing electricity, water resources, food delivery, waste recycling, automatic research on the health of citizens, the prevention of crimes in real time, traffic management of the city, and the control of unmanned vehicles, sensors, controllers, and other devices in the city.

3.1. Delta Platform for Digital Twins

To build digital twins of large and complex systems such as smart cities, it is necessary to have stable and reliable software in which modular solutions based on neural networks [11] and other AI systems can be easily implemented. Such a solution is a combination of smart contracts and blockchains. Blockchains with a POW consensus algorithm [3] have already established themselves as one of the most reliable computer networks. Therefore, the technological platform must be implemented on the basis of blockchain technology, in which algorithms are implemented using smart contracts executed within these blockchains. This will ensure the security, decentralization, and transparency of all actions. But due to the well-known blockchain trilemma, high values of parameters of security, decentralization, and scalability cannot be achieved within a single blockchain. Therefore, multi-blockchains are entering the arena. Multi-blockchains gained great popularity after the release of the TON White Paper by the Durov brothers Nikolai and Pavel [12]. Their previous work made a splash in 2017 and forced us to turn our attention to this technology.

The Delta platform incorporates all of the above solutions that are necessary for the implementation of digital twins of smart cities. Due to multi-blockchains and other data structures, we manage to achieve both high security and decentralization, as well as scalability. All processes occurring in a smart city are described by smart contracts using the p-complete language L* [13]. The p-completeness of a high-level programming language provides a solution to the halting problem that occurs in Turing-complete languages. A program in a p-complete language is always executed in a time not exceeding a polynomial of the length of the input data. In this language, the program is some suitable term of the logical p-complete language L [13], in the construction of which both special termal constructions and Δ_0-formulas can participate. The AI modules for learning and interaction between the platform and the smart city were also taken into account.

3.1.1. Multi-Blockchain Structures

As already shown in [3], the theory of blockchain structures can be axiomatized in first-order logic. This allows us to build computable models and simulate their work using special libraries.

Let us inductively define the class of multi-blockchains, MB:

(1) MB_1 = <B_1> is a multi-blockchain if B1 is a blockchain.
(2) MB_k = <MB_{k-1},B1, . . ., B_n> is a multi-blockchain if Mb_{k-1} is a multi-blockchain and all B_i are blockchains.

As shown in Figure 1, for each object (home, store, office, company), all data from sensors, controllers, and user requests are stored in local-level blockchains and, periodically, the hash of this blockchain is sent to higher-level blockchains. Moreover, any blockchain can store smart contracts that emulate the operation of certain internet devices in a smart city.

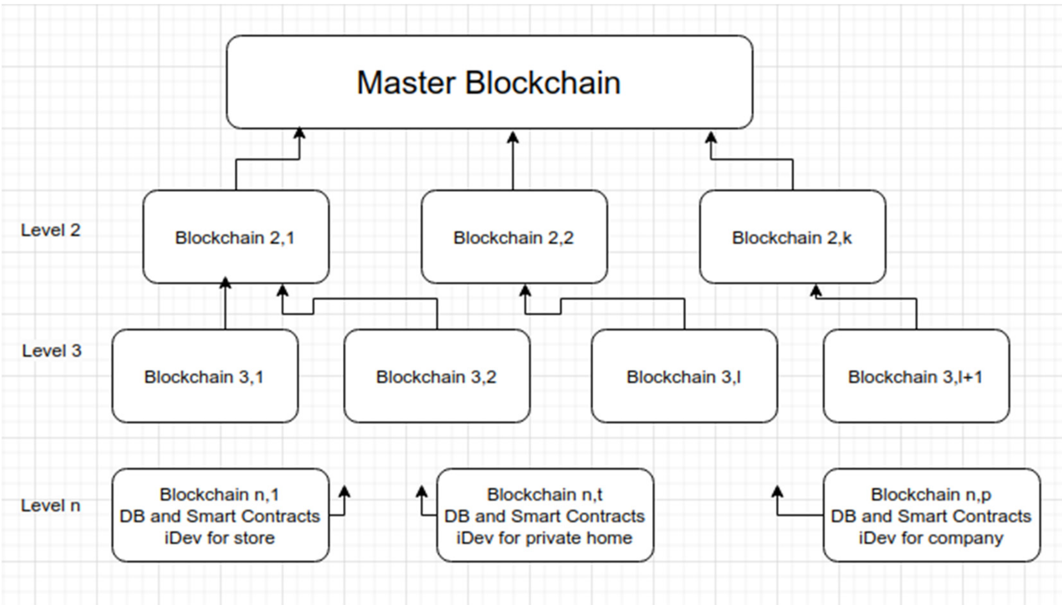

Figure 1. Multi-blockchain structure where iDev is an abbreviation for internet devices.

In a multi-blockchain structure, the most secure and decentralized blockchain is the Master Blockchain. Blockchains at the second level and beyond are less decentralized, but are cheaper for users or devices to interact with. The fastest and cheapest are the lowest-level blockchains. Information from internet devices, such as motion detectors, sensors, vehicles, houses, offices, companies, etc., is written to these blockchains.

Let some p-computable hereditarily finite list superstructure HW($\mathfrak{m}$) of signature σ be fixed [14], in which some elements of the main set HW(M) are blockchains, and there is a one-place predicate blockchain that selects these elements. Using the polynomial analogue of Gandy's fixed point theorem [14], as well as the process of constructing a monotone operator [14], one can easily obtain the following lemmas:

Lemma 1. *There is a generating family of L-formulas F which define a monotone operator* Γ_F *with the fixed point property. The smallest fixed point of this operator defines the class of multi-blockchains MB.*

Lemma 2. *The class MB is polynomially computable.*

3.1.2. Smart Contracts

Within the framework of the concept of semantic programming [13], we define the concept of L* contract, which is an L* program with the following syntactic constructions:

1. The special word Contract comes first, then the contract name.
2. After this comes the contract constructor, in which all variables are initialized when they are placed on the blockchain, including the public address of the contract owner.
3. After this comes a list of properties.
4. After this comes a list of functions with access modifiers.

Within one contract, you can call the properties and methods of another contract, but only if it has already been defined earlier and stored on the blockchain (recursive calls and looping are excluded). Due to the fact that the L* contract is similar to an L* program, the following lemma is true.

Lemma 3. *The computational complexity of any L* contract is a polynomial.*

3.1.3. Delta-Connection Module (DCM)

In order for this platform to be flexible and smart, it is also necessary to introduce AI modules for managing the operation of all smart contracts within the multi-blockchain. For these purposes, we propose using a special Delta-connection module, which analyzes information inside the multi-blockchain and interacts with the necessary smart city systems. Delta-connection is a bridge between the multi-blockchain and smart city. Moreover, all information received from sensors can go either directly to the multi-blockchain or through the Delta-connection module, if this is allowed within the framework of security and access. It processes bidirectional interactions from the smart city to the multi-blockchain and from the multi-blockchain via the Delta-connection module to the smart city. Moreover, the Delta-connection module monitors the synchronization of the execution of smart contracts within the multi-blockchain with the processes, sensors, and states of a smart city (Figure 2).

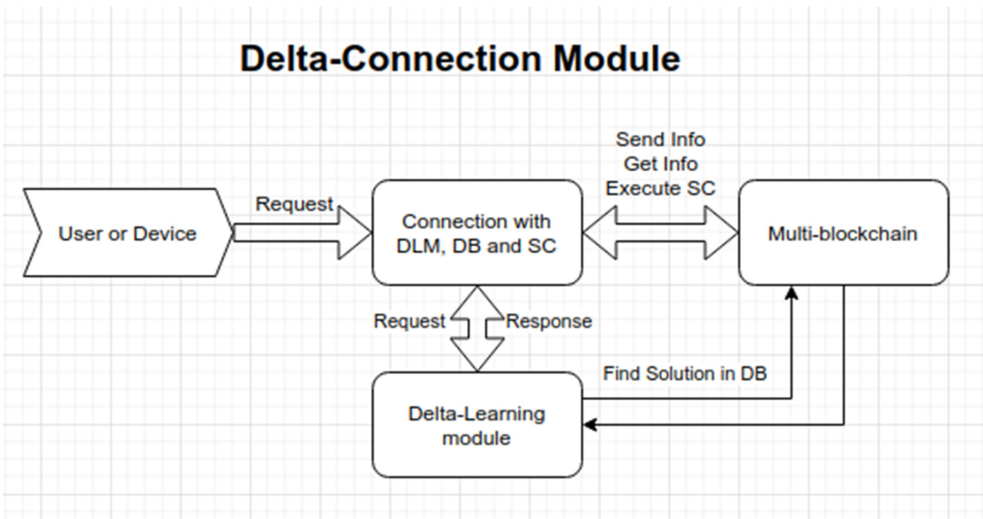

Figure 2. Delta-connection module.

3.1.4. Delta-Learning Module (DLM)

The Delta-learning module is a module that allows us to extract new knowledge and predict events based on the data contained in the multi-blockchain (Figure 3). For these purposes, both neural networks and logical-probabilistic inferences are used based on the theory of maximum specificity requirements announced by Carl Hempel in 1968 in [5]. This module can receive and store knowledge in special blockchains (databases).

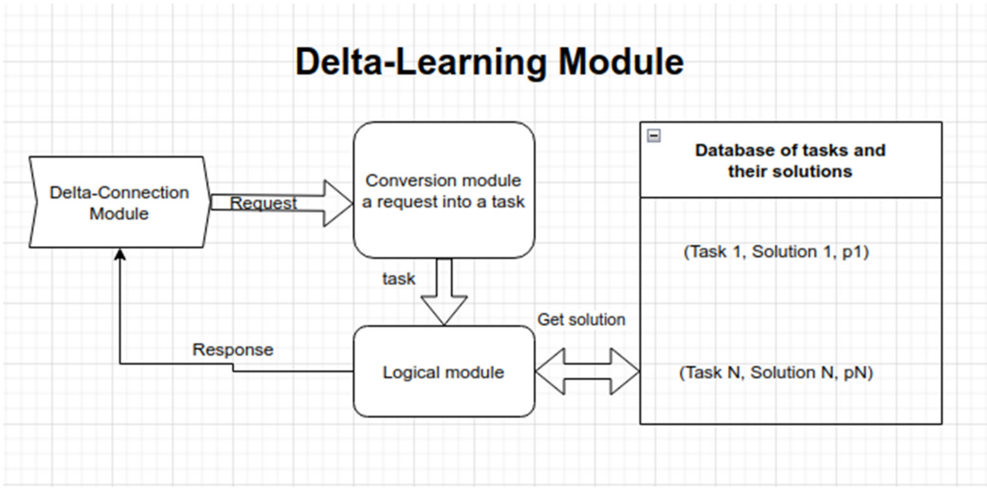

Figure 3. Delta-learning module.

The main idea of this module is to translate a natural request from a user or device via the Delta-Connection Module into a task (logical formula) and for this task to find the most effective solution, which is highly likely to be suitable (probability pk) for a given case. To perform this, all the facts and their generalizing problems with solutions are stored in the knowledge base.

All tasks are given by logical formulas of the following form:

$$\forall x\ \exists y\ \Phi(x,y) \rightarrow \Psi(x,y) \tag{1}$$

where the variable x can be considered a list of input parameters, and the variable y can be considered a list output parameters.

The conversion module can be either some neural network or some logical-probabilistic implementation. This module translates a user or device request from their language into the language of logical formulas. After that, a logical module is connected, whose task is to find the most effective solution to this logical formula (task) from the database.

Formulas of type (1) with the solution y = t(x) are generalizations with some probability pk of facts from the database in the form

$$\Phi(c_i,t(c_i)) \rightarrow \Psi(c_i,t(c_i)),\ I \in I \tag{2}$$

From the database, we select the most effective solution y = t(x) for this task with the maximum probability pk.

4. Results

This paper presented the blockchain-based Delta platform for building digital twins of smart cities. At the same time, the platform has a built-in Delta-learning module, which allows it to learn from multi-blockchain data as well as use the knowledge gained in managing smart cities. The Delta-connection module monitors the states of the multi-blockchain elements and issues commands and signals to the smart city elements. Through this module, it is also possible to transfer information to the multi-blockchain.

It was also shown that the computational complexity of smart contracts is also polynomial, and the smallest fixed point of the operator that inductively generates multi-blockchains is also polynomially computable.

5. Discussion

The development of smart cities has been actively happening for the last 10 years, but there is still a lot to be done. In this work, we have not touched on the financial issues that people face in their daily lives. It is also important to discuss the levels of citizens' access to various locations in the city, which is important for the safety of the city. We would also like to discuss issues related to a single control center for the digital twins of tens and hundreds of cities, and possibly for the management of entire countries.

6. Conclusions

This paper introduces the universal multi-blockchain-based Delta platform, which is designed for constructing digital twins of smart cities. This platform comprises multiple modules that enable the segregation of tasks such as data storage, interaction with smart city infrastructure, and real-time learning for extracting new insights. This instills optimism for its prompt deployment in practical scenarios. Furthermore, the platform facilitates the management of digital twins for multiple cities and the establishment of centralized and decentralized control hubs.

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