Integration of smart contracts and artificial intelligence using cryptographic oracles

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Abstract

Artificial Intelligence (AI) and Distributed Ledger Technology (DLT) together address complex tasks by optimizing and automating business processes and creating innovative new products. Despite their shared digital nature, integrating these two technologies is a challenging process that requires sophisticated solutions. AI relies on large amounts of data and computational power, which are difficult to provide within distributed ledgers. However, the integration of DLT with AI, particularly its interaction with smart contracts, is made possible through the use of an intermediary data exchange and transfer mechanism known as an oracle. This paper analyzes various methods of smart contract interaction with distributed ledgers and hypothesizes the existence of decentralized AI technology. By exploring the methods and techniques for using oracles to facilitate AI and blockchain interaction, we can assess new opportunities for the decentralized economy arising from their combination with AI services and models, and predict the emergence of new decentralized products enhanced by AI technologies.

Keywords

blockchain, cryptography, smart contracts, artificial intelligence, AI, web3, crypto-economy, decentralization, oracle, decentralized artificial intelligence

1. Introduction

1.1. Smart contracts and cryptography: ensuring security in decentralized systems

Smart contracts are traditionally defined as programs that operate on blockchain technology [1], requiring a decentralized virtual machine capable of programming and data processing [2]. The defining characteristic of smart contracts is that, once deployed on the virtual machine, they execute autonomously according to the program's instructions, without control by any user. The execution of smart contracts can result in the creation of new types of digital assets, allowing for full or partial management by the user of the smart contract. These characteristics of smart contracts enable the development of economic and financial digital systems [3] that utilize various other digital technologies for data collection [4], analysis [5], and asset management [6]. Trust between participants in smart contracts is established through cryptographic algorithms and protocols that ensure secure communication and data protection. This security is achieved through the application of various cryptographic methods in smart contracts, such as Homomorphic Encryption, Zero-Knowledge Proofs, Multi-Party Computation, and Quantum-Resistant Cryptography.

For users of smart contracts, cryptography represents a commitment scheme that allows for the selection of execution conditions in secret, with the ability to reveal these conditions later [7]. This is made possible by using Zero-Knowledge Proof (ZKP) technology, which enables transaction verification without identifying participants or data. Cryptographic methods used for smart contracts, including Homomorphic Encryption, Zero-Knowledge Proofs, Multi-Party Computation, and Quantum-Resistant Cryptography, can be employed in projects focused on decentralized identity, decentralized finance, and medical research where privacy is paramount. In this way, cryptography ensures secure communication between parties and guarantees the security of data involved in the operation of smart contracts.

The Promising and Complex Integration of AI Technologies in Smart Contracts

Among the most promising and complex technologies to be applied within smart contracts are AI technologies, which are associated with large volumes of data and advanced tools for their analysis. The concept of AI

CQPC-2024: Classic, Quantum, and Post-Quantum Cryptography, August 6, 2024, Kyiv, Ukraine
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encompasses a variety of data analysis and management technologies, ranging from simple machine imitations of human intelligence, as envisioned by Alan Turing, to deep learning technologies for training neural networks. Modern AI technologies can utilize models for Natural Language Processing (NLP), Computer Vision, Expert Systems, Genetic Algorithms, and Multi-agent Systems, which enhance and improve AI models.

Attempts to integrate smart contracts with AI lead to several challenges due to their inherent complexity, which require resolution [8]. The primary issue with smart contracts is the technical difficulty of storing and directly utilizing large amounts of data in distributed ledgers. It is well known that AI can significantly contribute to the development of decentralized products and asset management by preprocessing and analyzing data through normalization and cleansing before submitting it to the blockchain structure, thereby reducing the excessive load on the ledger. Additionally, machine learning techniques have been developed that can be used to build and refine smart contract code, including through the use of NLP [9]. AI enhances the adaptability of smart contracts by incorporating logic, neural graphs, and neural networks through its integration into the smart contract code or external usage to verify and ensure contract integrity. Tools such as deep learning frameworks like TensorFlow are considered promising for their integration into smart contracts [10].

1.2. The role of distributed ledger technology in static and dynamic models

Distributed ledger technology (DLT) has demonstrated its effectiveness in static models for accounting financial transactions, managing reputation systems, handling agreements, and confirming ownership rights. In contrast, AI algorithms require dynamic data updates to create and maintain training models. Training models based on smart contracts cannot guarantee accurate predictions, partly due to the lack of support for fixed-point arithmetic and differences in computational architectures. One potential solution is to apply the Naive Bayes algorithm in smart contracts, which requires probability calculations using floating-point numbers based on Gaussian probability [11].

AI, which relies on a vast array of tools for model training and extensive databases, cannot operate within a blockchain environment in its current form due to the resource demands needed to perform the necessary computations and model creation. To integrate the decentralized protocol environment with AI, several solutions have been proposed, which will be discussed below.

One approach to organizing the interaction between AI and smart contracts is through the use of specific mechanisms known as oracles. Oracles enable the integration of AI systems with smart contracts, offering a range of possibilities [12]. The traditional form of an oracle that facilitates this interaction is depicted in Fig. 1

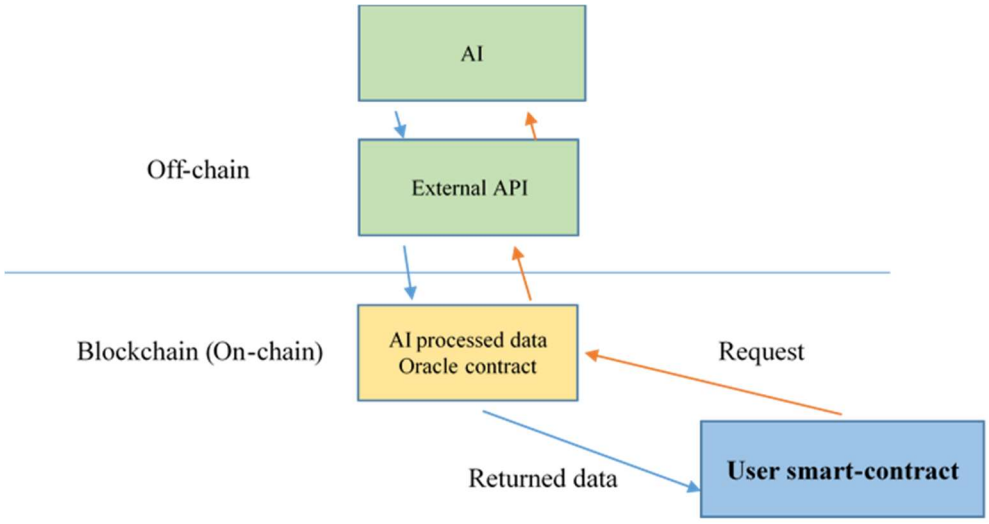

Figure 1: Traditional interaction of AI with smart contracts via an oracle

1.3. Oracles as mediators between blockchain and AI

Oracles are third-party services with smart contracts that act as intermediaries between blockchain and external systems, allowing smart contracts to access off-chain data, including data from AI models. By design, blockchains and smart contracts cannot access data outside the blockchain environment. The primary function of a blockchain oracle is to send requests, verify, and authenticate external data sources, and deliver this data to the user's smart contract [8]. The table below outlines the functions of oracles that facilitate the collection and provision of data for use in smart contracts and AI models.

1.4. Oracle functions and their characteristics

Table 1
Oracle functions in data provision for intelligent smart contracts

Oracle Functions	Function Characteristics
Data Collection for AI	– Collects and processes external data for centralized and decentralized AI models. – Transfers external data to AI algorithms.
Data Verification	– Ensures the reliability and authenticity of data, preventing manipulation and fraud. – Verifies data sources, reducing risks associated with inaccurate or falsified data.
Integration with AI	– Transfers and integrates analytical predictive data from AI into smart contracts.

To implement a smart contract, it may be necessary to obtain information from AI based on the analysis of external data, such as prices and exchange rates, sensor data, sports event results, flight information, insurance claims, and so forth. This can be achieved through an intelligent oracle, which acts as an on-chain agent providing information in response to queries to the AI model [13]. The intelligent oracle enables smart contracts to utilize AI analytics and forecasts for automated decision-making and contract execution, while also ensuring the verification of the accuracy of the information provided to the AI models [14].

An example of such an intelligent oracle is the Chainlink project, which represents a system of decentralized oracles. Each oracle in this system gathers data from independent sources and compares it to ensure its accuracy [8]. These intelligent smart contracts, capable of responding to monitored conditions, acquire the characteristics of dynamic smart contracts. They can autonomously make decisions after analyzing the information and then send commands and queries to other systems [15]. In these interactions, AI can be effectively used to execute logic for monitoring states and events and making appropriate decisions.

AI models may involve using services to collect meteorological, agricultural, seismic, and other real-world data, which is then structured for subsequent monitoring and analysis [16]. Distributed ledgers alone cannot perform these tasks without special tools. On the other hand, smart contracts can manage interactions with AI models. For example, the SingularityNET project represents a decentralized platform that allows the creation and sharing of AI models and their monetization in a marketplace based on the ERC20 standard within the Ethereum network. Similar solutions are offered by projects such as Namahe, Neuromation, TraDove, AdHive, ATN, Cortex, and NAM [17]. The table below lists some services that offer solutions for integrating AI into smart contracts.

The literature identifies three main methods for AI interaction with traditional smart contracts: Edge AI, AI-centric smart contracts, and Swarm Intelligence. The table below presents these methods along with their characteristics, as well as other theoretically possible ways AI could interact with smart contracts. The concept of Swarm Intelligence Smart Contracts, based on swarm intelligence principles for decision-making and task execution, appears particularly interesting as it integrates well with the logic of smart contracts.

Table 2
Classification of smart contracts by methods of interaction with AI (compiled based on the source [10])

Method of AI Interaction with Smart Contracts	Characteristics
Edge AI Smart Contracts	Smart contracts that combine AI technologies with edge computing capabilities, enabling data processing and contract execution closer to the data source. This approach reduces latency and enhances efficiency. Key features include: – Local data processing. – Reduced communication delays. – Improved overall performance.
AI-Centric Smart Contracts	Smart contracts that integrate AI capabilities with automated contract execution on the blockchain. This allows for the creation of intelligent contracts that can analyze data, make complex decisions, and automatically execute actions based on the results. Key features include: – Data analysis capabilities. – Decision-making based on AI insights. – Automated contract execution.
Swarm Intelligence Smart Contracts	Smart contracts that utilize swarm intelligence principles for decision-making and task execution. Swarm intelligence refers to the collective behavior of decentralized, self-organizing systems, typically observed in natural systems such as ant colonies, bee swarms, or bird flocks. In the context of smart contracts, this means using multiple agents interacting with each other and their environment to achieve a common goal or perform tasks. Key features include: – Collective decision-making. – Decentralized coordination. – Task execution based on swarm dynamics.

1.5. Direct integration of AI into smart contracts

Another technology is the direct integration of AI into smart contracts without using an intermediary like oracles, which eliminates the trust issue. This approach involves utilizing ASIC-resistant frameworks through specialized consensus algorithms and standards for ensuring operational compatibility between infrastructure and deep learning tools. An example of such technology is the Cortex project, which employs the Material Representation Tool (MRT) technology compatibility standard and the Cuckoo Cycle consensus mechanism.

Embedding artificial intelligence directly into smart contracts in an on-chain mode requires careful consideration, as training AI models on the blockchain is currently a rather cumbersome process [8]. However, some projects have achieved notable success by adapting networks to leverage AI capabilities, including creating specialized networks with their consensus algorithms, such as Proof of Intelligent Mining (PoIM) in Matrix and Delegated Proof of Stake (DPoS) in Cortex. The PoIM consensus algorithm, developed for intelligent mining and operating a decentralized network based on machine learning technology, increases the number of transactions per second and facilitates the use of intelligent models within the network.

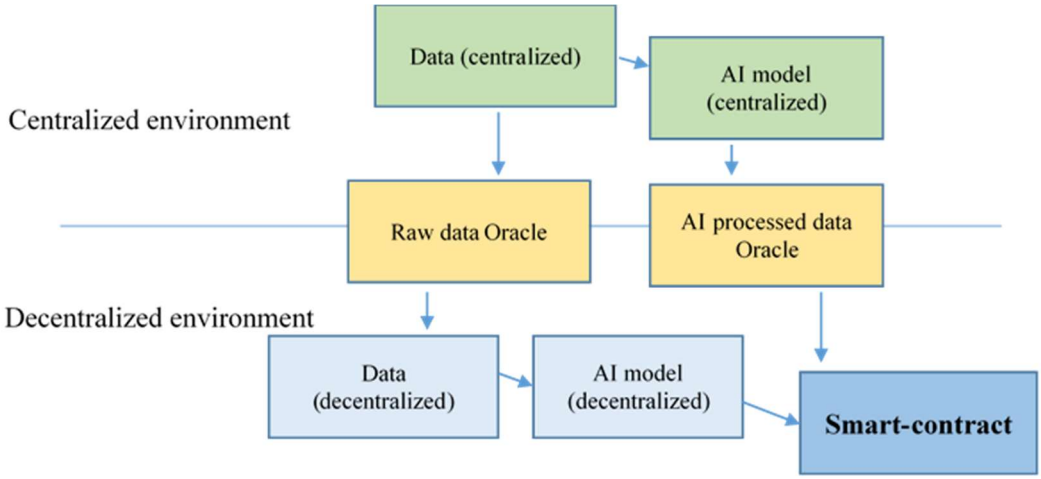

Figure 2: Generalized Structure of Data Transmission in Smart Contracts Using an AI Oracle

The oracle structure for interacting with smart contracts involves the smart contract itself, a tool for retrieving data from an AI model, a database, and a dynamic data source for the model. Upon meeting certain conditions, the smart contract sends a request to the oracle, which in turn returns data from the AI model to the smart contract. Popular Oracle services that can work with AI models include Oraclize (Provable), Town Crier, Reality K, Witnet, and Chainlink, among others. An example of using Oraclize is the Etherisc project, which uses an oracle to access flight delay data to automate insurance payouts in case of flight delays. Another project, Ethersquares, implements logic for sports betting, where users can verify the accuracy of received data through the oracle [17].

The Cortex and Matrix platforms offer solutions for integrating AI models into the blockchain and subsequently using them in smart contracts. Users can incorporate the proposed Cortex AI system into existing smart contracts. In the Cortex project, this is achieved through the Cuckoo Cycle consensus algorithm, known for its high efficiency in handling large volumes of data. The Matrix platform, on the other hand, employs the Proof of Intelligent Mining (PoIM) algorithm, which leverages AI for optimizing mining processes and consensus tasks. Matrix provides components for semantic and syntactic analysis, security verification of smart contracts, and identification of issues in transaction models [8]. These platforms' solutions enable the creation of decentralized AI models for implementation in DAO smart contracts to optimize decision-making and manage participant relationships.

An example of an AI oracle is the GainForest project, where a smart contract is used to distribute bets based on data about deforestation status using artificial intelligence [18]. The oracle automatically analyzes and evaluates satellite images and detects deforestation issues using remote sensing algorithms. Based on the collected and analyzed information, bets are redistributed among participants. Fig. 3 illustrates the operation of such an oracle.

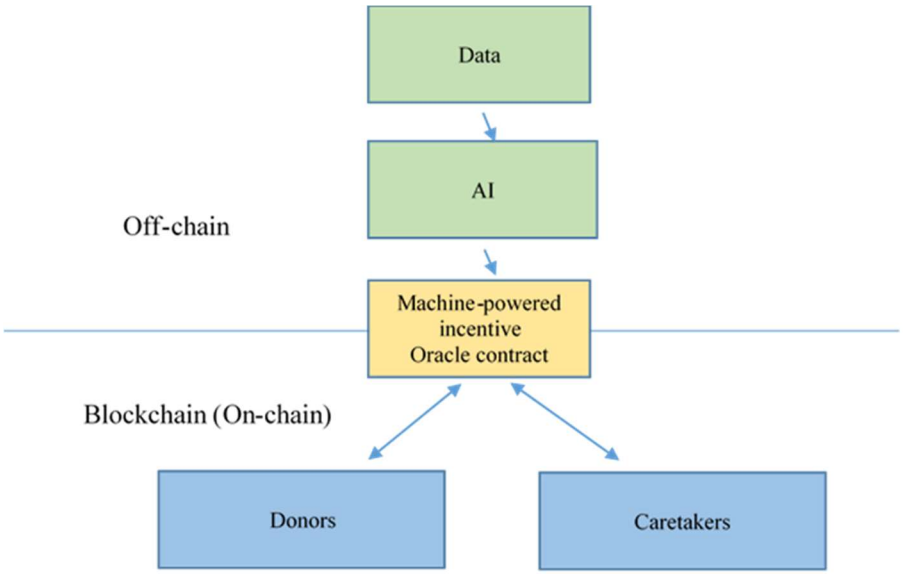

Figure 3: Machine-powered incentive system in GainForest (compiled based on the source [19])

The blockchain-based platform for artificial intelligence systems, SingularityNET, provides the capability to integrate autonomous agents into smart contracts, connecting them to data exchange channels and AI systems that interact with modules [8]. This technology enables smart contracts to interact with real-world sensors and devices, obtaining information simultaneously with AI-driven decisions on subsequent actions. The structure of smart contracts allows to make and execute decisions automatically based on AI [8]. Other mentioned services offer methods for integrating smart contracts with AI models for use in operations or provide mechanisms for collaboration, where AI models are applied to manage incentive systems, reward distribution, and evaluate participation in joint projects.

Table 3
Classification of smart contracts by AI application areas

Smart Contracts AI Interaction Technology	Characteristics
Federated Learning Smart Contracts	Smart contracts utilizing federated learning for training AI models on decentralized data without centralizing it in one location. Data remains on local devices, and models are trained locally, exchanging only model updates.
Reinforcement Learning Smart Contracts	Smart contracts incorporating reinforcement learning algorithms for decision-making. RL models are trained based on rewards and penalties for actions, optimizing decision-making strategies.
Predictive Analytics Smart Contracts	Smart contracts incorporating reinforcement learning algorithms for decision-making. RL models are trained based on rewards and penalties for actions, optimizing decision-making strategies.
Natural Language Processing (NLP) Smart Contracts	Implementation of natural language processing technologies for understanding and analyzing text data. Smart contracts can interact with users through text interfaces, analyze documents, and automatically execute contract terms based on textual information.
Computer Vision Smart Contracts	Use of computer vision technologies for analyzing images and video. Smart contracts can make decisions based on visual data, such as automatically detecting defects on a production line.
Multi-agent Systems Smart Contracts	Employment of multi-agent systems where agents interact to achieve a common goal. Each agent can operate autonomously while exchanging information with other agents, facilitating the creation of complex and adaptive systems.
Autonomous Negotiation Smart Contracts	Application of AI for automatic negotiation and agreement formation between parties. Smart contracts can autonomously negotiate terms based on predefined criteria and the interests of the parties.

Table 4
AI services integrated with blockchain and their possible uses in smart contracts (compiled based on the source [8, 19–21])

Service	General Description and Functions	Usage in Smart Contracts
Cortex	Decentralized Artificial Intelligence Platform that supports AI smart contracts and AI inference.	Analysis of decentralized data for decision-making and process automation
Matrix AI Network	Intelligent contracts service that combines smart contract capabilities with AI elements, allowing for handling large volumes of transactions and integrating AI services into dApps.	Using AI in smart contracts for management and interactions
SingularityNET	Decentralized AI marketplace and AI Publisher, running on blockchain with Distributed Atomspace (DAS) to represent and store primary knowledge for AI agents, and it encapsulates any computational results achieved during their execution	Data collection and analysis, process automation
Namahe	Responsible Supply Chain based on Blockchain & Artificial Intelligence for managing the supply chain using smart contracts and AI on the Hyperledger Sawtooth platform.	Organizing production and supply of goods and services
Fetch.AI	Decentralized platform for creating commercial models combining AI and smart contracts based on Neo blockchain technology.	Using autonomous economic agents for process automation and asset management.
Numerai	Hedge fund platform based on artificial intelligence for predicting financial markets and creating AI models.	AI model competitions in the Numerai Tournament, fund management, and strategic investment decisions.
Eligma	AI-powered chatbot for asset value prediction.	Process automation for asset management, decentralized loyalty programs for communities, and data analysis for decision-making.
Peculium	Analytical platform using AI and machine learning for analyzing market trends and decision-making.	Developing automated investment strategies for asset management.
DeepBrain Chain (DBC)	AI computational platform with access to a distributed network with unlimited scalability. Analyzing large volumes of data, modeling and forecasting, integrating AI models into business processes, and sharing computational resources.	Analyzing large volumes of data, modeling and forecasting, integrating AI models into business processes, and sharing computational resources.
Neural	Neural network algorithms for AI for forecasting, analysis, and asset management.	Forecasting future events, decision-making, risk management, and business process optimization
BurstIQ	The platform for simplifying the collection, evaluation, and analysis of data with a consensus mechanism at the storage level.	Managing medical data, storing confidential participant information, providing decentralized medical services, and managing medical records.
LifeGraph	Machine learning platform for generating relational maps of verified data elements collected from “consent contracts”.	Collecting, monitoring, and analyzing mental health and behavioral data, solutions for personnel, and resource management.
Vytalyx	Decentralized database of clinical and non-clinical data managed by AI.	Real-time biometric monitoring of participants, and personalized medical solutions.
Neuromation	Ecosystem for creating AI models using distributed computing and incentive models.	Providing computational resources for training AI models.
Synapse AI	Machine learning model training platform and creation of autonomous agents with data sharing service.	Decentralized data exchange and management, creating autonomous agents for process optimization.
StyleGAN2	The platform for generating and managing digital art using AI and Generative Adversarial Networks (GAN).	Automated solutions for profit distribution, trend prediction NFT management, and art generation.
NFTGAN	NFT Art Generation platform using GAN neural network architecture, combining two generators and discriminators to generate texts, images, and sounds.	Creating and managing NFTs, content monetization, and participant engagement, and managing intellectual property rights.

Kojii.ai	AI platform to enhance public perception of artworks, train artists, and gather information for AI models.	Intelligent chatbots for participants, organizing communications with communities, investment decisions, and creating recommendations for project participation.
PrimeIntellect	Service for training large AI models using distributed resources, reducing costs, and democratizing AI development.	Tools for forecasting and analyzing market data, asset and risk management strategies, and business process automation.
Nous Research	Incentive system using tokens for participation in AI model creation.	Tools for asset management and large data volumes, cybersecurity protection.
DanKu	Service for creating and accessing machine learning models with an incentive system and evaluation using smart contracts.	Collaborative development of AI models for token-based rewards.

The interaction between AI and smart contracts raises several issues, including questions about AI's responsibility regarding the consequences of executing a contract by an autonomous agent or providing false or incorrect information for the execution of a smart contract [22]. Due to these risks, the use of AI in DAOs brings up the need for standardization of smart contracts and crypto-assets for their compatibility with AI models. Known token standards such as ERC-20, ERC-721, and ERC-1155 are used in economic models or reward systems created by AI. AI can also create unique content and release it as NFTs. The idea of more global use of AI in smart contracts has led to the development of specific smart contract standards designed to facilitate their integration with AI. Below are some of these standards along with their characteristics.

Table 5
Smart contract standards in the Ethereum environment, adapted for interaction with AI

Standard	Characteristics
ERC-2362	Standard for decentralized oracles, which can be used to obtain external data for smart contracts, including data from AI or forecasting models.
ERC-3001	Standardizes the integration of decentralized oracles, allowing the incorporation of external data from AI to provide more accurate and informed decisions.
ERC-8000+	Standards are used for proof of work (PoW) and other consensus mechanisms, which can be utilized for managing resources and computations with AI.
ERC-7007	A specifically designed standard for verified AI-generated content. Allows for the tokenization of AI-generated content with verification of source and generation parameters [23].
ERC-7231	Standard for tokens of verified AI-generated content, aimed at improving data sovereignty and user control over digital identities. Integrates Web2 and Web3 identities into a single non-fungible token (NFT), enabling users to own, manage, and monetize their online presence across various platforms.

Standardization of smart contracts is crucial for uniform task typing for AI models to handle various data classes, analyze their performance, and create necessary integration modules for AI. Through these modules, smart contracts can interact with each other and organize intelligent decentralized systems with self-learning and environmental adaptation capabilities. Additionally, the standardization of intelligent smart contracts will ensure the automated and autonomous development of intelligent systems. Inter-network integration and data exchange with the physical world should be managed by oracles adapted to intelligent networks, which presents new challenges. The use of different types of AI, with varying structures and complexities, requires finding new integration solutions.

2. Conclusion

The integration of smart contracts and AI undoubtedly offers significant advantages, as blockchain provides the potential for cryptographic storage of large volumes of data and its use for training AI models, securely transmitting data between digital systems, and implementing economic model logic. Despite the complexities involved in integrating smart contracts and AI, methods and solutions for such integration already exist. In this context, the need for standardizing the methods of linking smart contracts and AI arises to enable the mutual integration of various solutions (services). The assertion that "If Smart Contracts Are the Body of the Digital Deal Era, Artificial Intelligence is the Mind" aptly describes the importance of intelligent oracles and cryptography in ensuring the interaction between systems.

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