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A Framework for Collective Robot Control: Integrating Crowd-Choice Mechanisms with DAO Governance

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Abstract. In the contemporary robotics landscape, decentralized governance mechanisms offer promising avenues for democratizing control over robotic activities. This paper introduces a new framework integrating crowd-choice mechanisms inspired by Decentralized Autonomous Organizations (DAOs) with robotic control systems. Our framework enables any stakeholder (individuals, companies, public institutions, NGOs and so on) to collectively determine robot activities through transparent and auditable decision-making processes. By leveraging blockchain technology, users can participate in prioritizing and executing robot actions, similar to DAO voting. We outline the architecture, implementation guidelines, and potential applications of the framework across diverse domains such as industrial automation, healthcare, and disaster response. Furthermore, we discuss the governance model, security considerations, and future research directions in advancing decentralized robotics governance. Through this framework, we envision a paradigm shift towards inclusive, transparent, and efficient multi-user robot control.

Keywords. decentralized control, collective framework, crowd-choice mechanisms, blockchain robotics

1. Introduction

Collective control represents a fundamental shift in the evolution of technological systems, particularly in robotics. Collective control fosters transparency, inclusivity, and adaptability in the management of activities, as it is based on a wide spectrum of stakeholders, each offering unique perspectives and expertise. Another key advantage brought by collective control is resilience. With decision-making authority distributed among multiple parties, systems can respond promptly to evolving circumstances. In

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contrast to traditional hierarchical structures, collective control fosters inclusivity, ensuring that all relevant parties have a voice in shaping decisions. This democratization of decision-making not only enhances the legitimacy of outcomes but also cultivates a culture of collaboration and shared responsibility. This paradigm could revolutionize industries ranging from manufacturing and logistics to healthcare and transportation.

The emergence of blockchain technology has been pivotal in facilitating collective control mechanisms. Originally conceived as the underlying architecture for cryptocurrencies, blockchain technologies evolved into systems that enable secure and transparent transactions without intermediaries. Smart contracts (SCs) were introduced with the advent of Ethereum and other Ethereum Virtual Machine based (EVM) chains [1]. These programmable agreements execute automatically when predefined conditions are met and store a verifiable record of transactions on-chain. This innovation laid the groundwork for many decentralized applications (dapps) and tokenized economies, where digital assets (tokens) represent ownership or access rights within a closed network [2].

Decentralized Autonomous Organizations (DAOs) are also based on SCs. DAOs are self-governing entities that operate autonomously through SCs [3]. Participants in a DAO collectively manage the organization's resources, make decisions, and allocate funds based on predefined rules encoded in SCs. DAOs embody the principles of crowd choice modelling, where decisions are made collectively by a distributed network of participants rather than centralized authorities. There are already many instances where DAOs are being used with successful results, most of them in decentralized finance (DeFi [4]), play to earn games [5], decentralized physical infrastructure networks (DePIN) [6], real-world assets (RWA) [7] and so on. In this context, converging collective control, blockchain technology, and DAOs offers a transformative approach to managing robotic activities. In certain instances, stakeholders need a system that can help them collectively determine robotic systems' behavior, priorities, and objectives in a transparent, auditable, and decentralized manner. This paper presents a pioneering framework that integrates crowd-choice mechanisms inspired by DAOs within robotic control systems, enabling users to participate in the collective control of robots across diverse domains.

2. Literature review

2.1. Collective robot control

Collaborative control for robots has evolved as a pivotal research area, facilitating advancements in hardware and software to enhance cooperation between robots and human operators. While much of the existing literature revolves around collaborative robots (cobots [8]) working alongside humans, there is a notable gap in exploring collaborative control - when the collaboration involves multiple human operators working collectively to control a robot. This section aims to cover the state of the art and elucidate the nuances of collaborative control, emphasizing the distinction between collaborative robots and collaborative operators in robot control scenarios.

When discussing collaborative robots, the emphasis is on developing robotic systems that can seamlessly interact with human operators in shared workspaces. Studies in this domain often focus on physical robot-robot and human-robot collaboration, where robots are designed to assist, augment, or work alongside human workers [9]. This collaboration involves ensuring safety, adaptability, and task-sharing capabilities, and has found applications in manufacturing, healthcare, and logistics. Existing research explores algorithms for collision avoidance, force sensing, and shared autonomy.

In contrast, the concept of collaborative operators controlling a robot shifts the focus to human-centric collaboration in the control process [10]. Rather than emphasizing physical interaction, this scenario involves multiple human operators working together to control and manage robots' activities. The collaboration may occur in real-time or through distributed decision-making systems. Research in this space explores human-robot interfaces, multi-user control systems [11], and distributed decision architectures. Although understanding the dynamics of how human operators collaboratively influence a robot's behavior is required for designing systems that align with human intentions and preferences, there are just a few studies that tackled this issue, mainly due to the low practicality.

There are several reasons why multiple operators should control a single robotic entity. Collaborative control systems offer unique opportunities for enhanced human-robot interaction. By allowing operators to work together, these systems can leverage human operators' collective intelligence, skills, and expertise to achieve complex objectives. Furthermore, these systems facilitate distributed decision-making processes – decisions are made collectively by a group of human operators rather than relying on a single centralized authority. This approach promotes inclusivity, diversity of perspectives, and adaptability, leading to more robust and resilient control systems. Collaborative control systems are well-suited for applications in complex and dynamic environments where human operators play a crucial role in decision-making and task execution. Examples include search and rescue robot operations, drone piloting for military operations, robotic systems for disaster response scenarios, and space exploration missions.

Studying collaborative operators controlling a robot provides insights into group dynamics, collaboration patterns, and teamwork strategies [12]. Based on how human operators communicate, coordinate, and negotiate control tasks, we can develop models, algorithms, and guidelines for effective collaboration.

2.2. Blockchain robotics

Blockchain technology can be included in robotics in various ways. One of the first uses relates to supply management [13]. Stakeholders can track the provenance and movement of robotic components and parts throughout the supply chain. By recording transactions and data related to manufacturing, shipping, and assembly on a distributed ledger, blockchain ensures transparency and traceability, reducing the risk of counterfeiting, fraud, and errors in supply chain operations. Another use case is related to ownership. Blockchain enables secure and immutable recording of ownership and usage rights. SCs can automate the transfer of ownership, leasing agreements, and maintenance schedules, ensuring that all stakeholders have transparent and auditable access to asset-related information. Blockchain facilitates secure and decentralized data sharing among multiple robotic systems and operators. By creating a tamper-proof record of data transactions, blockchain ensures data integrity, confidentiality, and auditability [14].

Moreover, blockchain introduces new monetization mechanisms. Through tokenization and SCs, robotic systems can autonomously engage in economic transactions, such as payment for services rendered, sharing resources, and rewarding contributions from human operators and participants. Last but not least, DAOs can be used to govern and coordinate robotic fleets and networks, which brings us closer to the next section.

2.3. DAO governance

DAO is a governance model supported by blockchain that involves the collective decision-making and management of an organization through decentralized mechanisms. DAOs are typically implemented using SCs on blockchain platforms that support them, such as Ethereum or any other EVM-compatible or RUST-based chain. SCs are self-executing contracts with the terms of the agreement directly written into code. These automatically enforce conditions without the need for intermediaries. Participants holding tokens representing ownership or voting rights within the organization can vote with a voting power determined by the number of tokens held. DAO governance typically involves voting mechanisms where token holders can propose, discuss, and vote on decisions related to the organization's operations, investments, or other matters. These decisions can include approving new proposals, allocating funds, or changing the parameters of the DAO. Through decentralized decision-making mechanisms, DAOs enable stakeholders to transparently manage activities, resource allocation, and task prioritization. As there are already a multitude of DAO applications as open-source, when considering a DAO SC for robot control, we don't need to reinvent the wheel. One utility that can be attributed to DAOs is the coordination of robotic fleets and networks, which is closer to the purpose of this research. The particularities offered by any EVM dapp (transparency, security, decentralization and immutability) are inherited by our framework. Since we are talking about a blockchain SC, DAOs are characterized by audibility. All transactions, proposals, and voting outcomes are recorded on the blockchain and, therefore, visible to all participants. This ensures accountability and trust in the decision-making process. No single entity or individual has unilateral control over the organization. Instead, decisions are made collectively by the community of token holders based on majority consensus.

Despite its potential benefits, DAO governance presents challenges, including scalability, security vulnerabilities, governance conflicts, and legal and regulatory compliance issues. DAOs can enable stakeholders to manage robotic activities collectively. To the best of our knowledge, this endeavor has not been pursued. In this paper, we address the issues arising from this endeavor by proposing a framework connecting any robot to a generic DAO SC.

3. Framework design

This section proposes a DAO-inspired framework that uses EVM-based SCs to interact with one or multiple robots in the same ecosystem.

3.1. System architecture

Let the following be the complete set of n actions than can be taken by the robotic system which we can control at a certain time instance t:

$$A(t) = \{A_1, A_2, \ldots, A_n\} \quad (1)$$

The entire set *A* from (1) can be mapped by a SC, linking a particular action to its cost, using a simple cost function, as presented in (2):

$$C(A_x) = c_x \quad (2)$$

where c_x represents the amount of tokens associated for the action A_x.

Considering *m* users, each with a different voting power *v*, and the choice made by each user represented as a binary function *D* which can take only values 0 or 1, after making their choices, each available action will have the following associated rank value:

$$V(A(t)) = \{\sum_{i=1}^{m} C(A_1) * v_i * D, \sum_{i=1}^{m} C(A_2) * v_i * D, \ldots, \sum_{i=1}^{m} C(A_n) * v_i * D\} \quad (3)$$

Sorting the set *V* in descending order will automatically show which is the action with the highest rank, and which should be taken by the system, considering the DAO voting process.

The model could become more complex if we are considering multiple actions to be voted together as subsets (if they need to be done chronologically one after the other, noted with *ChrA(t)*), if we consider actions to be non-exclusive, meaning that they can be done at the same time (multiple choice – noted with *MultiA(t)*), or if, at a certain time instance, some of the actions are not available (noted with *NaA(t)*). Nevertheless, we can reduce each of these cases by assessing them as singular actions that can be part of the same *A(t)* set:

$$A(t) = A(t) \cup ChrA(t) \cup MultiA(t) \cup NaA(t) \quad (4)$$

The core of the proposed architecture is based on three concurrent modules:

- a smart contract (SC) that provides a secure, decentralized, and operational base
- the web3 event-based decentralized application (dApp) that furnishes the user interface (UI) for the robot operators
- the communication API between the dapp and the physical robotic system

The resulting solution can be implemented on any blockchain supporting SCs and robotic systems with a mapped activities space.

The first module is represented by the blockchain. It handles the backend operations, including transaction validation, data storage, and execution of predefined rules encoded in the smart contract. The output of this module is a tamper-proof ledger of transactions, ensuring transparency and integrity in decision-making processes.

The second module, represented by the user interface, facilitates interaction between the robot and its operators. It offers three outputs: real-time monitoring of robotic activities and sensors, communication with the SC for voting and decision-making functionality, and interaction with the third module through the mapped options.

The third module represents the API connecting the web3 app to the physical robotic system, which executes actions based on instructions received from the events produced by the SC. This module ensures seamless integration between the digital and physical components of the system. Fig. 1 presents the architecture of this system.

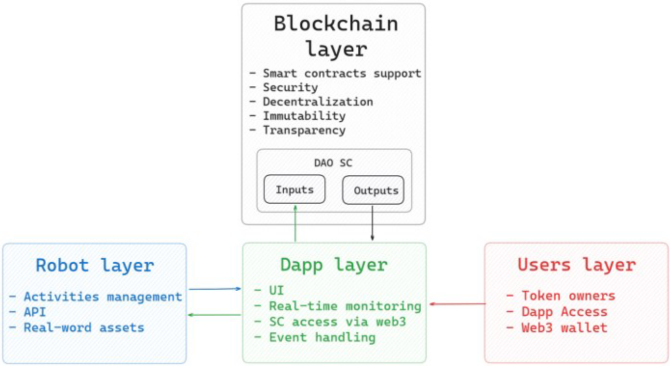

Figure 1. System architecture

Notice that users have a distinct module/layer. Given a DAO ERC-20 token, we can conclude that their voting power can be influenced by the amount of tokens held in their web3 wallets. Users owning a larger amount of tokens will have a higher voting weight, as opposed to users who have invested or acquired a smaller token balance.

3.2. Security considerations

Blockchain technology offers several inherent security features that address common concerns in decentralized systems:

- Immutability: Transactions recorded on the blockchain are cryptographically linked and stored across multiple nodes, making it virtually impossible to alter historical data without consensus from the network participants.
- Decentralization: Blockchain operates on a decentralized network of nodes, eliminating single points of failure and reducing the risk of malicious attacks or data manipulation.
- Cryptography: Transactions on the blockchain are secured using cryptographic algorithms, ensuring confidentiality, integrity, and authentication of data exchanged between parties.
- Security: SCs enforce predefined rules and conditions autonomously, reducing the need for trust in third-party intermediaries and minimizing the risk of manipulation.

One of the first developments proposed by the Ethereum Foundation was ERC-20. Today, this is a widely adopted standard for creating fungible tokens on the Ethereum blockchain. Fungible tokens are interchangeable and indistinguishable from each other, making them ideal for representing assets such as currencies, securities, or rewards within dapps.

One of the most important components of the ERC-20 standard is the transfer function, as it enables the transfer of tokens between addresses. This function typically includes parameters such as the sender's address, the recipient's address, and the amount of tokens to be transferred. Before executing the transfer, the function verifies that the sender has a sufficient balance of tokens and that the sender or recipient's addresses are not 0 (as it will then be transformed into the mint and, respectively, burn functions). Then, it deducts the transferred amount from the sender's balance while adding it to the recipient's balance, updating the private array _balances, as presented in Fig. 2. Basically, the array _balances stores the entire distribution of token across all the wallets of the users. Finally, the function emits an event that external third-party entities can listen to. This process is executed atomically within a single transaction, ensuring consistency and integrity of token transfers:

```
function _transfer(address sender, address recipient, uint256 amount) internal virtual {
    require(sender ≠ address(0), "ERC20: transfer from the zero address");
    require(recipient ≠ address(0), "ERC20: transfer to the zero address");
    _beforeTokenTransfer(sender, recipient, amount);
    uint256 senderBalance = _balances[sender];
    require(senderBalance ≥ amount, "ERC20: transfer amount exceeds balance");
    _balances[sender] = senderBalance - amount;
    _balances[recipient] += amount;
    emit Transfer(sender, recipient, amount);
}
```

Figure 2. ERC-20 internal transfer function

Typically, simple ERC-20 SCs are expanded with Governance capabilities to obtain an ecosystem ready to be used in a DAO. OpenZeppelin is a popular open-source library for building secure and audited SC on the Ethereum blockchain. It provides reusable and modular components, including standard contracts for ERC-20 tokens, access control, ownership management, and our primary focus, governance. At the moment of writing, IGovernor.sol is the main governance library. It's interface offers 5 events and the functionality that support these: ProposalCreated, ProposalCanceled, ProposalExecuted, VoteCast and VoteCastWithParams [15].

When discussing blockchain technology, Transactions Per Second (TPS) and time to finality are critical metrics that directly impact the usability of the proposed system.

TPS refers to the number of transactions a blockchain network can process per second. It is a crucial metric for measuring the scalability and throughput of a blockchain system. Higher TPS enables the network to handle many transactions. Achieving high TPS is essential for applications requiring real-time transaction processing, such as payment systems, supply chain management, decentralized exchanges, or the one proposed in this paper. However, increasing TPS often comes with trade-offs, such as increased network complexity, larger storage requirements, and higher computational costs.

Time to finality measures the duration for a transaction to be confirmed and considered irreversible on the blockchain. In traditional proof-of-work (PoW) blockchain networks like Bitcoin, transactions are considered final after a certain number of confirmations, which can take several minutes to hours depending on network congestion and block confirmation times. This happens much faster in proof-of-stake (PoS) and delegated proof-of-stake (DPoS) blockchains, as they either reduce the number of block confirmations required or use a deterministic finality mechanism. Time to finality is key for applications requiring quick settlement and confirmation of transactions, such as financial transactions, online payments, or, as expected, the multi-user control system proposed here.

In conclusion, when implementing our solution, we need to use blockchains with the highest TPS and the shortest time to finality. In Table 1, we have listed some of the most common blockchains and their TPS and time-to-finality data.

Table 1. TPS and time to finality [16]

Blockchain	Ticker	Time to finality	TPS
Bitcoin	BTC	60m	3 – 7
Ethereum	ETH	78s – 15m	12 – 14
Solana	SOL	2.3s – 40s	2000 – 3000
Binance Smart Chain	BNB	7.5s – 45s	50 – 70
Internet Computer	ICP	1.4s – 2s	3000 – 11500
Aptos	APT	0.9s – 1s	2 – 7
Avalanche	AVAX	0.1s – 1.3s	50 – 700
Fantom	FTM	0.9s – 1s	10 – 4000

Utilizing Aptos (APT), Avalanche (AVAX), or Fantom (FTM) can be advantageous for our proposal, considering their respective transaction speeds and throughput capacities. Aptos offers a relatively fast time to finality (1s), although with a moderate TPS, making it suitable for applications where quick transaction confirmation is essential but with lower transaction volumes. Avalanche boasts extremely fast transaction speeds and high TPS, which is ideal for applications demanding near-instantaneous transaction confirmation and scalability. Fantom combines fast transaction speeds similar to Aptos, with a very high TPS as well, striking a balance between efficiency and capacity.

3.3. Use cases

This section explores the application of decentralized autonomous organization (DAO) paradigms in real-world scenarios where operators collaboratively control robots. Through the following for use cases – manufacturing, logistics, healthcare, and emergency response - we demonstrate how this approach empowers operators to optimize robotic operations through transparent decision-making.

Operators could use a DAO governance framework in manufacturing facilities to control robotic arms and machinery on assembly lines collectively. Operators could prioritize tasks, adjust production schedules, and allocate resources based on real-time demand and operational requirements through a decentralized decision-making process. This approach would enhance flexibility, efficiency, and adaptability in manufacturing processes, enabling rapid reconfiguration of production lines and optimizing resource utilization (Fig. 3).

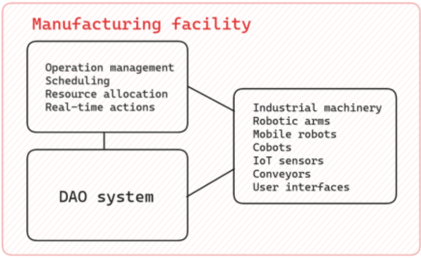

Figure 3. DAO-inspired multi-control in manufacturing and assembly lines

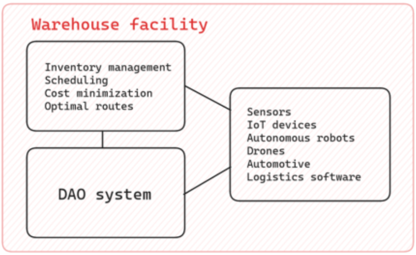

Figure 4. DAO-inspired multi-control in logistics

In logistics and warehouse environments, operators could utilize a DAO-based system to coordinate the movement and handling of goods by autonomous robots and drones. Operators could collectively determine optimal routes, scheduling, and inventory management strategies through decentralized governance. Using real-time data and feedback from sensors and IoT devices, operators could optimize warehouse operations, minimize transportation costs, and improve order fulfilment efficiency, ultimately enhancing customer satisfaction and reducing operational overhead. Industry 4.0 already brought a fresh light over the field of logistics, and with the help of blockchain-based SCs, there are several improvement venues that could be tackled by researchers in the near future (Fig. 4).

In the healthcare industry, DAO-enabled robots offer numerous opportunities to enhance patient care. In this use case, healthcare facilities such as hospitals and nursing homes benefit from integrating DAO-enabled robotics by automating routine tasks. The proposed framework can handle medication reminders, patient monitoring, data collection, and even collective surgery using robotic surgical systems such as Da Vinci. Starting with patient reminders, recording vital signs and other health metrics, and possibly notifying healthcare providers of any abnormalities or emergencies, collective-controlled robots reduce the burden on staff and ensure that patients receive consistent care. Another interesting aspect is that this system allows other stakeholders, including healthcare providers, insurance companies, family members, and even patients, to participate in decision-making processes. DAOs ensure that care plans are tailored to individual needs and preferences. Stakeholders can propose and vote on treatment protocols and discharge plans and make allocation decisions. This inclusive approach leads to more effective and patient-centric care delivery (Fig. 5).

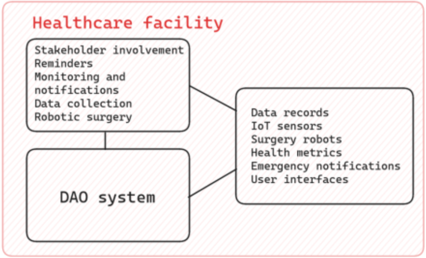

Figure 5. DAO-inspired multi-control in healthcare

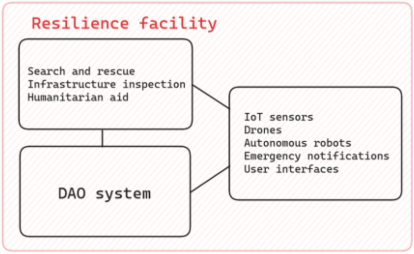

Figure 6. DAO-inspired multi-control in emergency situations

During emergency response and disaster relief efforts, operators could employ a DAO governance framework to coordinate the deployment of robotic systems for search and rescue missions, infrastructure inspection, and humanitarian aid delivery. Operators could prioritize tasks, allocate resources, and coordinate collaborative efforts between autonomous robots, drones, and human responders in real-time based on a DAO. This approach would enhance emergency response operations' speed, coordination, and effectiveness, potentially saving lives and mitigating the impact of natural disasters and humanitarian crises.

4. Conclusions

Integrating decentralized governance mechanisms with robotic control systems presents a promising paradigm for democratizing decision-making processes and optimizing robotic activities across diverse domains. Through the framework introduced in this paper, stakeholders from various sectors, including individuals, companies, public institutions, and NGOs, can collectively determine robot activities through transparent and auditable processes inspired by DAOs. By leveraging blockchain technology and crowd-choice mechanisms, users prioritize and execute robot actions akin to DAO voting, fostering inclusivity, transparency, and efficiency in multi-user robot control. Exploring collective control in robotics, blockchain technology, and DAO governance has unveiled transformative opportunities for enhancing collaboration, adaptability, and resilience in robotic systems. The convergence of these technologies offers a novel approach to managing robotic activities, revolutionizing industries such as manufacturing, logistics, healthcare, and emergency response. Through real-world use cases, we have demonstrated how collective control mechanisms empower operators to optimize robotic operations, streamline workflows, and respond effectively to dynamic challenges. Security considerations play a crucial role in implementing decentralized robotics governance. Blockchain technology provides inherent security features, including immutability, decentralization, and cryptography, ensuring transparency, integrity, and authenticity in decision-making processes. Adopting standard protocols such as ERC-20 for tokenization and SCs for governance further enhances security and auditability. Open-source libraries like OpenZeppelin offer robust and audited SCs for building secure and scalable decentralized applications, facilitating the implementation of DAO governance frameworks in robotic control systems. When considering blockchain platforms for implementing decentralized robotics governance, factors such as Transactions Per Second (TPS) and time to finality are crucial metrics. Platforms like Aptos, Avalanche, and Fantom offer fast transaction speeds and scalable throughput capacities, making them suitable for real-time transaction processing and quick settlement applications.

In conclusion, integrating decentralized governance mechanisms with robotic control systems represents a paradigm shift towards inclusive, transparent, and efficient multi-user robot control. The framework outlined in this paper lays the foundation for future research and development in decentralized robotics governance.

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