Received: 2 November 2019 | Revised: 18 November 2019 | Accepted: 18 November 2019 | Published on: 19 December 2019

DOI: 10.1002/itl2.140

LETTER

WILEY

An efficient blockchain-based approach for cooperative decision making in swarm robotics

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Swarm robotics is an emerging robotic domain that aims to accomplish complex tasks with the cooperative effort of a group of simple robots. These robots communicate and share information to coordinate their actions for achieving a common goal. However, existing mechanisms of control and communications are not very secure, efficient, and also rely on centralized controlling authority. It is not flexible, and also has low transparency and tracking capabilities. Blockchain, a decentralized technology based on peer to peer communication along with smart contracts, can be a potential contender for addressing these challenges. However, blockchains are resource-intensive and not found suitable for resource-constrained devices. We propose a blockchain-based framework, which is based on Proof-of-Authority (PoA) consensus mechanism to ensure efficiency. We experiment with test-bed implementation using RaspberryPi. The results obtained demonstrate that the PoA mechanism is not a resource-hungry one (unlike other state-of-the-art consensus mechanisms). The blockchain with PoA in swarm robotics can provide the necessary security, transparency, decentralization, reliability, autonomy, etc.

KEYWORDS

Blockchain, Ethereum, PoA, smart contract, swarm robotics

1 | INTRODUCTION

Swarm robotics is a robotics approach which is concerned with managing a large number of autonomously operated simple robots that performs tasks in a cooperative manner.[1] Swarm robotics is inspired by nature and the observations made on the behavioral and communication patterns of creatures that live in dense groups such as ants, honeybees, and fish.[2] These creatures exhibit certain characteristics like collective effort, demonstrated by a colony of tiny ants carrying a much heavier payload compared to their combined weight. Self-healing and self-organizing property of a swarm of honeybees flying together, sometimes colliding with each other but still preserving the group. Similarly, predator avoidance and counter-invasion techniques exhibited by a school of fish. A robotic swarm is robust and flexible as each robot in the swarm is capable of autonomous operation that can be performed to respond to a variety of tasks without any physical modification to each robot.[3] Also, unlike the failure of a robot in an isolated form, the swarm is not likely to cause mission failure. As each robot in the swarm has a limited sensing and processing capabilities, it cannot have a global view of the entire system. The success of a robotic swarm depends on the information exchanged among the nodes in the swarm.

Some of the imminent challenges associated with swarm robotics are ensuring the security and privacy, minimizing energy consumption, differentiating normal and abnormal behavior, distributed decision making, reducing computation and communication overhead, adaptability and scalability, etc. Furthermore, there are several challenges in the implementation of an efficient robotic swarm, such as assuring the authenticity and truthfulness of the information exchanged, availability, and time required to propagate the information in the swarm.[4] The versatile and dynamic nature of swarm robotics makes it a challenging task to trace a robot's actions in the swarm. These challenges open doors for research and some of the open research problems are as follows: development of intelligent control and communication system, efficient approach for cooperative decision making, approach to deal with faults and byzantine behaviors, lightweight but strong security and privacy solutions. Blockchain has demonstrated its strength in various applications such as supply chain management, logistics, cryptocurrency and is also being studied in swarm robotics.[5] The blockchain technology, with its inherent features of decentralization, transparency, and high availability, can improve the decision making task in a robotic swarm.

Maintaining blockchain is a resource-intensive task and may not be suitable for resource-constrained devices. With existing blockchain-based approaches, its offerings can not be utilized in areas like swarm robotics that are driven by devices with limited resources. Some of the emerging applications of such swarm robotics are smart logistics, rescue robots (searching for survivors trapped under debris), precision farming, etc. Motivated by these facts, we propose a lightweight PoA-based approach, a lightweight consensus mechanism for permissioned blockchains.

In this paper, we propose a blockchain-based approach for cooperative decision making in a robotic swarm. In particular, we strive to implement an authoritative blockchain. With P2P as the underlying communication mechanism, we provide faster and reliable dissemination of information. We also maintain the transaction logs for the actions of a robot in the swarm on the blockchain providing traceability of events in the swarm for later investigations. We use smart contracts for specifying the rules governing the automated decision-making process. Thus, our proposed approach provides a common and robust platform for the robots in a swarm with diverse opinions to reach a consensus-based conclusion and can provide similar flavors of blockchain security, reliability, availability, and transparency with lower resource consumption.

The rest of this paper is organized as follows. In Section 2, we discuss related works in the domain. Section 3 gives a brief description of Blockchain, Smart Contract, and Proof of Authority. We present the system model in Section 4 and propose our blockchain-based mechanism in Section 5. Section 6 consists of the experimental details, and we discuss results in Section 7. Finally, we conclude our work in Section 8.

2 | RELATED WORK

In this section, we discuss studies that proposed blockchain-based mechanisms in swarm robotics.

Ferrer[6] described how blockchain technology could help solve four key issues of the swarm robotics: security, decision making, behavior differentiation, and business models. Lopes et al.[7] proposed a blockchain-based architecture and demonstrated how smart-contract could help to control robots. Strobel et al.[5] the authors analyzed the performance of a blockchain-based approach in a collective decision-making scenario. The authors also demonstrated how blockchain could be used for collective estimation, shared knowledge platform, and reputation management in robot swarms.[8] Huang et al.[9] have discussed how existing industrial IoT systems are vulnerable to malicious attacks and single points of failure. Swarm robotics has a significant role to play in Industrial IoT applications as well. Attacks and failures, however, can have a severe impact on service stability. To address these challenges, the authors proposed a blockchain-based system, which uses a lightweight credit-based proof-of-work (PoW) consensus mechanism. Thus, now, trends are toward optimizing the blockchain consensus approach for reducing computational complexity, maintaining security, and guarantee transaction efficiency. Similar goals motivate our study for swarm robotics.

3 | BLOCKCHAIN, SMART CONTRACTS, AND PROOF OF AUTHORITY (POA)

In this section, we provide background details of the technologies and methods that we have used in our work.

Blockchain Technology gained attention with the introduction of Bitcoin.[10] Blockchain can be seen as a decentralized, distributed ledger that provides verifiable and immutable records of transactions. It provides the features of availability, and immutability as the same copy of data is stored in multiple locations. The notion of Public Key Infrastructure (PKI)

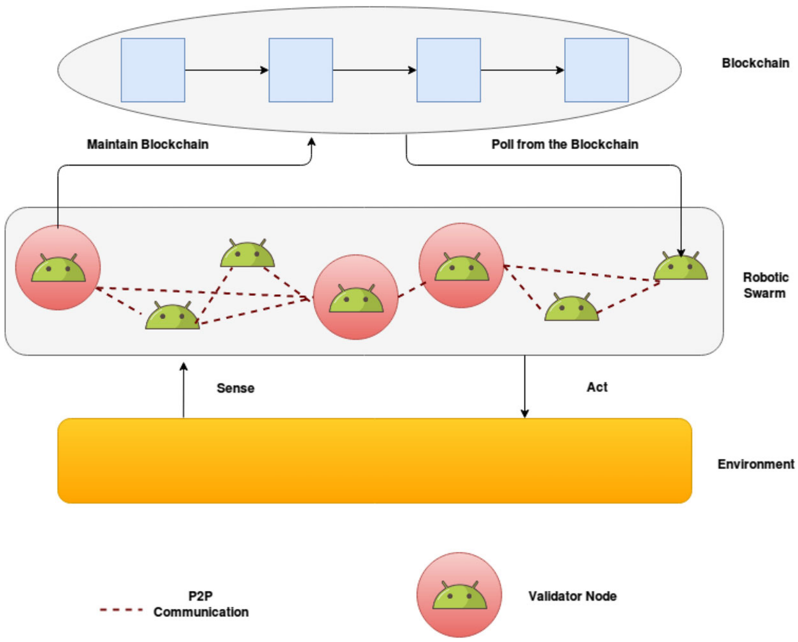

FIGURE 1 System model

provides authentication. A blockchain essentially is a series of blocks containing a certain number of transactions. These blocks are linked with each other with the help of cryptographic hashes. A blockchain network is maintained by a set of special nodes in the network known as the miners, they collect the incoming transactions generated by the users of the network and try to form blocks that are later on appended onto the blockchain via a consensus mechanism.

A smart contract[11] is a self-executable block of code that is deployed on the blockchain. The code specifies the rules that govern the interaction between the participating parties of the blockchain. Smart contracts ensure bias-free implementation of the rules.

Ethereum[12] the blockchain platform used in our experiment implements a proof-of-authority consensus mechanism named Clique in its Geth (Golang based Ethereum client) implementation. The Clique PoA mechanism provides availability and partition tolerance with an eventual consistency guarantee.

PoA is a consensus algorithm mainly suitable for private and permissioned blockchains. The algorithm relies on a set of trusted entities called validators or the authorities. A validator collects transactions coming from the clients, bundles them in a block, and adds it onto the chain. Consensus with PoA is reached in rounds where, in each round, a set of validators are allowed to propose a block. A set of validators are used for block proposal to dismiss any chances of a single validator not proposing any block in his round. Also, one of the validators is the leader; a leader is a validator who has got the highest priority of block proposal then other validators are used as relievers whose blocks are considered in case the leader does not proposes any block. The leader is changed in every round, and the cycle continues. Each validator checks for the validity of the received block and adds the block in the blockchain only if the block is found to be valid.

4 | SYSTEM MODEL

Figure 1 describes our system model consisting of a swarm of robots and has three key components.

4.1 | Blockchain

A blockchain is maintained among the robots where each robot act as a node in the blockchain network. The owner of the swarm deploys the blockchain and generates the genesis block. The owner is also responsible for inserting the task instructions for the robots and deploying the corresponding smart contract containing appropriate logic onto the blockchain maintained in the swarm. There are certain nodes in the swarm, which act as validator nodes. These nodes collect and verify transactions generated from the other peer nodes and form a block. At each round, a single validator node broadcasts the formed block to the other validator nodes who check for the validity of the block. Then, they commit the block onto their local blockchain if found valid, thus, reaching a global consensus on the transactions. This initialized blockchain acts as a base for the swarm intelligence and cooperative decision making.

4.2 | Communication

Nodes exchange information with each other to reach a common consensus on the state of the blockchain. This exchange of information takes place in a P2P manner, where each peer node exchanges information with its peer. Peers of a node changes overtime.

4.3 | Sensing and execution

Robots continuously monitor their surroundings and execute transactions based upon received precepts from the environment. The robots poll the blockchain for deciding appropriate actions to be performed. They also write task-specific data (as encountered) onto the blockchain as they progress on the mission. The written transactions are committed onto the blockchain and are governed by the smart contract. Since the blockchain data is immutable and consistent, each robot will have the same view of the data as the others. This assures that non-faulty, and uncompromised robots in the environment will perform the same action independently resulting in a cooperative effort.

5 | COOPERATIVE DECISION MAKING

In this section, we present the logic of our blockchain-based approach for achieving co-operative decision making in the robotic swarm with a use case scenario of efficient search and exploration by rescue robots.

The robots in the swarm communicate with each other via the smart contract. Each robot sense its surroundings. Whenever a robot detects an occurrence of an event, it executes a transaction. To implement our blockchain-based approach for the considered scenario, we simulate a game called *Color Consensus*. The game is defined as follows:

The game takes place in a square grid. The square grid is colored with three colors. A majority of the grid is colored with *Gray*. However, two of the ends of the grid is colored with *White* and *Black*, respectively. Initially, the swarm rests in the center of the grid. Each robot R_i in the swarm S sense the color of the floor where it is standing on. For each detected color *White* and *Black* the robot glows its beacon light *Red* and *Green* respectively. The beacon light of the robot is turned off when it detects a *Gray* color. The swarm starts exploring the grid; each robot moves in the grid in random directions with a specified velocity. The catch of the game is that once the robots have started moving in the swarm, they should come to a consensus on glowing the light of a particular color, either *Green* or *Red*. To achieve the objective of the game, we use our blockchain-based approach.

We make each robot in the swarm execute a transaction as it senses a looked for color, that is, *White* or *Black*. A robot is allowed to execute a transaction only once. We set a *threshold* value for each looked-for color in the smart contract. The looked-for color, which reaches the threshold value, first is considered to be the *consensusColor* and is accepted by the swarm. The robots in the swarm periodically poll the smart contract to check whether a consensus is reached. If a consensus is reached the members in the swarm starts glowing the *consensusColor* continuously.

6 | EXPERIMENTAL SETUP

We test our blockchain-based approach for cooperative decision making in a robotic swarm with a test-bed implementation, as shown in Figure 2A.

We simulate the *ColorConsensus* game with a swarm of eight footbot robots on ARGoS[13] robot swarm simulator. The simulation is executed on a PC with the following configuration: 8GB RAM, 1 TB HDD, Intel Core i7-700 CPU @ 3.60 GHz X 8 processor. A private blockchain network is maintained with three Raspberry Pi's (RPi's). The Raspberry Pi's are of model 3 B+, and each RPi ran Geth (an Ethereum blockchain client) version 1.8.27. The blockchain network runs

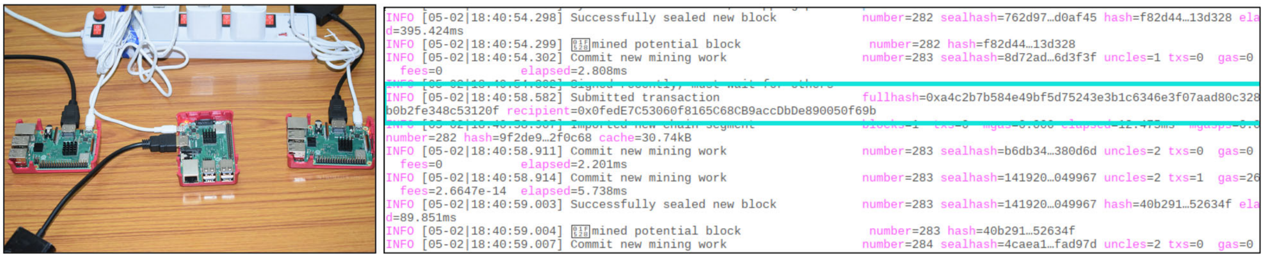

FIGURE 2 A, Testbed setup. B, A transaction executed by a robot

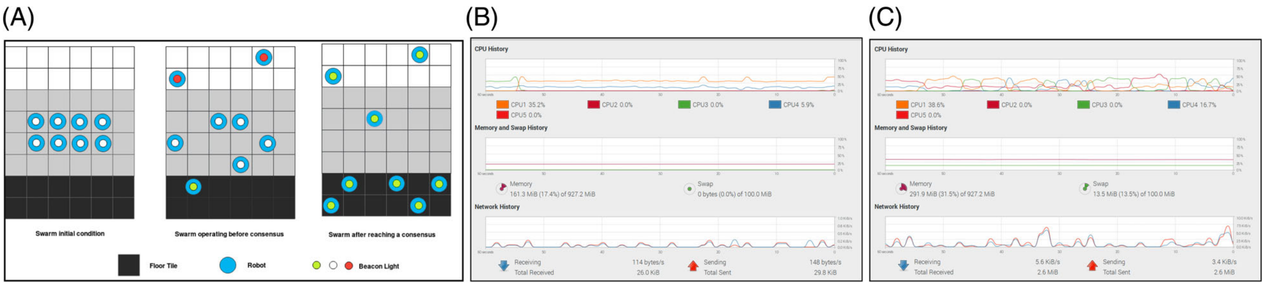

FIGURE 3 A, Swarm status as simulation progresses. B, Results during idle condition. C, Results during PoA consensus

a Proof-of-Authority (PoA) consensus mechanism. We configure all the three RPi's as signers. The robots in the swarm sense the color and execute transactions accordingly to increase the count of the respective color, which is either *White* or *Black* in the smart contract. We incorporated appropriate logic in the smart contract assuring that no robot can submit a transaction more than once when any looked for color is sensed. The robots also periodically poll the smart contract to find whether a consensus on the color is reached. If a consensus is reached, they start glowing the *consensusColor*, or else they continue to sense and execute the transaction. The robots execute the transaction via the Remote Procedure Call (RPC). The executed transactions get broadcasted and committed to the maintained blockchain network. Figure 2B shows a transaction released by a robot.

7 | RESULTS AND DISCUSSION

Each robot in the swarm holds an account on the deployed blockchain network. Figure 3A shows the initial condition, condition before reaching a consensus and condition after reaching a consensus in a swarm. At the start of the simulation, the robots stand on the gray color floor, and the beacon light of the robots is off. The robots start moving on the floor, as the simulation progresses, sensing the color of the floor grid. After a period of time, the robots reach a consensus on a single color that has crossed the specified threshold first. The robots, then, glow their beacon light in the consensus color. We implement the logic for maintaining the count of each color sensed by the robots in a smart contract on the blockchain.

We analyze the performance of the blockchain network by measuring the CPU performance, memory usage, and network characteristics of a Raspberry Pi node maintaining the blockchain. Figure 3B shows the statistics in idle condition, and Figure 3C shows during our PoA execution. From these figures, we can easily analyze that the PoA approach is not a resource-intensive and can be considered as one of the efficient mechanism. We also measure the storage consumption by executing a set of 1000 transactions explicitly from one of the robots onto the blockchain network. The transactions are a call to a setter method that updates a value in the smart contract. We found a set of 1000 transactions consumed about 0.7 MB (approx.) of storage space.

The choice of PoA as the consensus mechanism is made as the participants in the swarm are known prior, and the swarm operates with a preconfigured set of identified participants, which does not require the addition of extra members while on an operation. Another reason for choosing PoA is its characteristics of being lightweight, less power consuming, and providing higher throughput. Implementing traditional consensus mechanisms such as Proof-of-Work (PoW) in the swarm may provide true decentralization in the system. However, it may become the bottleneck in blockchain-based systems for swarm robotics as the nodes in the swarm in most cases are power-constrained and exhibit limited computing capability, whereas PoW based consensus mechanisms are power-intensive and require extensive computations.

Our blockchain-based architecture provides authentication and non-repudiation of the information exchanged in the swarm. Since each robot in the swarm sign transactions executed by it with its private key, it can be easily verified by other robots. Moreover, the architecture also makes any attempt of DDoS attack difficult as the robots can be instructed to accept and forward messages received from a set of known participants only.

Our proposed system does not consider the Byzantine behavior of the robots. Trust, reputation management, and misbehavior detection are out of the scope of this work.

8 | CONCLUSION

In this work, we proposed a blockchain-based framework for cooperative decision making in a robotic swarm. With the help of Proof-of-Authority as the blockchain consensus mechanism, we significantly minimized the usage of system resources. The results are evidence of the efficiency of the approach. We demonstrated how blockchain could enhance the decision making process with its feature of availability, replication, and immutability. Our work will be of importance to minimize resource consumption in a practical blockchain-based solution of swarm robotics. The proposed solution is suitable for various applications of smart logistics, factory, rescue robots, and different other scenarios of industrial IoT. However, our work has some limitations and does not cover the scenario when some misbehaving and faulty nodes exist in the swarm. We aim to address these issues in our future works.

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How to cite this article: Singh PK, Singh R, Nandi SK, Ghafoor KZ, Rawat DB, Nandi S. An efficient blockchain-based approach for cooperative decision making in swarm robotics. *Internet Technology Letters*. 2020;3:e140. https://doi.org/10.1002/itl2.140