Blockchain Technology for Robot Swarms: A Shared Knowledge and Reputation Management System for Collective Estimation

Volker Strobel(✉) and Marco Dorigo

IRIDIA, Université Libre de Bruxelles, Brussels, Belgium
{vstrobel,mdorigo}@ulb.ac.be

In swarm robotics research, it is often assumed that robots do not have access to shared knowledge. By sharing knowledge, however, it may become easier to determine whether the robots agree on an outcome or to aggregate the information of the individual robots. We argue that having a medium of shared knowledge can possibly facilitate the implementation of several swarm robotics algorithms and can pave the way for novel swarm robotics applications (e.g., computationally lightweight machine learning algorithms). Sharing knowledge, however, introduces several challenges, such as detecting whether someone has tampered with the shared data or how to reach consensus in case of conflicting information.

We propose a blockchain as shared knowledge medium, computing platform, and reputation management system for robot swarms. A blockchain is a tamper-proof decentralized system used as database and computing platform. Using the *Ethereum* framework [1], arbitrary applications can be executed in a decentralized and secure way via blockchain technology. These applications—called blockchain-based smart contracts—are containers that encapsulate variables and functions executed via blockchain technology. The participants (robots in this work) of a blockchain network locally keep a copy of the blockchain. They create transactions and distribute them among their peers, whenever they are in communication range. The data of the transactions is then used as input to the functions of smart contracts.

The idea of using blockchain technology in combination with robot swarms was first proposed in [2]. In previous work [4], we provided the first proof-of-concept by adding a security layer on top of an existing collective-decision making approach via blockchain technology. In the scope of the present work, we developed a new algorithm exploiting the blockchain's possibilities: the robots use a blockchain-based smart contract to collectively estimate the relative frequency of black tiles (a value between 0.0 and 1.0) in an environment where the floor is covered with black and white tiles.

We conducted three experiments using the robot swarm simulator ARGoS [3], showing (i) the feasibility of the approach, (ii) the trade-off between blockchain size and accuracy, and (iii) the suitability of the blockchain as a reputation management system. In each time-step, a robot determines if it is above a black

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or a white tile and, every 30 sec, it creates a blockchain transaction with its quality estimate. The smart contract aggregates the estimates of the individual robots to obtain a collective estimate and tells the robots to stop exploring as soon as the uncertainty in the estimate is below a threshold. Therefore, consensus in the swarm is achieved in a fully decentralized way without the need of an external observer. To be able to identify robots with malfunctioning sensors, the reputation of the individual robots is stored and managed via a blockchain-based smart contract. Robots with properly functioning sensors are likely to increase their reputation, while a malfunctioning robot's reputation is likely to decrease.

In case of conflicting blockchain versions, Ethereum achieves consensus by agreeing on the longest blockchain, i.e., the one that required the highest Proof-of-Work (PoW). PoW requires the participants to solve a computational puzzle. This ensures that writing information into the blockchain is computationally expensive. The complexity of the puzzle depends on the computational power of the blockchain participants, i.e., it can adapt to the limited power of robots. Other consensus protocols, such as Proof-of-Stake or using permissioned blockchains might be suitable alternatives to PoW.

Blockchain technology introduces additional computational and memory requirements for the robot swarm. These requirements depend on the number of participants in the network (the blockchain size scales linearly with the number of robots) and the amount of information that is sent to the blockchain. Therefore, it is important to determine which information is security-relevant and should be stored on the blockchain, and which information can be locally processed by the robots.

In future work, we will transfer the blockchain system to physical e-puck robots to study the energy impact of blockchain technology and the possibilities of consensus protocols tailored to robot swarms.

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