2024 IEEE/ACM 46th International Conference on Software Engineering: New Ideas and Emerging Results (ICSE-NIER)

Designing Trustful Cooperation Ecosystems is Key to the New Space Exploration Era

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ABSTRACT

In the emerging space economy, autonomous robotic missions with specialized goals such as mapping and mining are gaining traction, with agencies and enterprises increasingly investing resources. Multirobot systems (MRS) research has provided many approaches to establish control and communication layers to facilitate collaboration from a *technical* perspective, such as granting more autonomy to heterogeneous robotic groups through auction-based interactions in mesh networks. However, stakeholders' competing *economic* interests often prevent them from cooperating within a proprietary ecosystem. Related work suggests that distributed ledger technology (DLT) might serve as a mechanism for enterprises to coordinate workflows and trade services to explore space resources through a transparent, reliable, non-proprietary digital platform. We challenge this perspective by pointing to the core technical weaknesses of blockchains, in particular, increased energy consumption, low throughput, and full transparency through redundancy. Our objective is to advance the discussion in a direction where the benefits of DLT from an economic perspective are weighted against the drawbacks from a technical perspective. We finally present a possible DLT-driven heterogeneous MRS for map exploration to study the opportunities for economic collaboration and competitiveness.

CCS CONCEPTS

• **Computing methodologies** → *Distributed computing methodologies*; • **Applied computing** → **Aerospace**; Astronomy; *Information integration and interoperability*; Cross-organizational business processes; • **Computer systems organization** → **Peer-to-peer architectures**; *Self-organizing autonomic computing*; **Robotic autonomy**; **External interfaces for robotics**.

ICSE-NIER'24, April 14–20, 2024, Lisbon, Portugal

ACM ISBN 979-8-4007-0500-7/24/04.
https://doi.org/10.1145/3639476.3639760

KEYWORDS

Autonomous Agent, Blockchain, Coordination, Coopetition, Multi-Agent Systems, Multi-Robot Systems, Space Economy

ACM Reference Format:
Renan Lima Baima, Chovet Loïck, Johannes Sedlmeir, Miguel Angel Olivares Mendez, and Gilbert Fridgen. 2024. Designing Trustful Cooperation Ecosystems is Key to the New Space Exploration Era. In *New Ideas and Emerging Results (ICSE-NIER'24), April 14–20, 2024, Lisbon, Portugal.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3639476.3639760

1 INTRODUCTION

The development of the new space economy was bootstrapped thanks to policies and agreements by governments and international organizations [3]. The industry's transition from a centralized model to a decentralized free market system [38] has increased the number of companies and startups in the new space economy, with 80% of the revenue generated in the last 16 years coming from private investments [9]. Major space agencies, including NASA [37], have outlined goals for in situ resource utilization (ISRU), such as destination reconnaissance, mapping, and resource acquisition. These plans aim to establish a long-term human presence on celestial bodies (e.g., Moon and Mars) through robotic lunar missions that utilize ISRU technology [12] to perform tasks from mining to manufacturing solar panels.

MRS are groups of robots that collaborate to complete specific tasks or support each other based on individual capabilities. They can comprise both homogeneous and heterogeneous groups of robots and find applications in diverse fields such as precision farming, search and rescue, and space exploration [41]. The main advantage of using MRS is that a team of geographically distributed robots can outperform single robots [14]. However, its effectiveness hinges on robust, data-integrated coordination mechanisms that facilitate the exchange of norms, maintain team identity, and promote group confidence [46]. To avoid the issue of information asymmetry in coordination mechanisms and the resulting "market for lemons" dilemma [2], it is crucial to minimize the knowledge gap between sellers and buyers. While financial incentives and sanctions can encourage cooperation and aid in meeting legal and regulatory requirements, managing resources and coordinating interactions among multiple organizations and countries can be challenging.

In *coopetitive* MRS [21], various operators' economic incentives often compete, making it difficult to achieve common objectives and ensure participation. With over 60 countries involved in space activities [7], many actors may be reluctant to join a centralized platform due to concerns about monopolistic or oligopolistic ownership, conflicts of interest, and treaty violations [29].

As organizations increasingly collaborate to achieve shared objectives [24], deploying cross-border and cross-organization MRS arguably becomes increasingly critical for future missions. However, the efficiency of ISRU in such heterogeneous MRS missions depends on effective communication and coordination among robots [33], such as the location and availability of critical resources, e.g., water and iron. The challenge of aligning the economic interests of competing stakeholders in a shared, non-proprietary digital space is expected to shape the new era of space exploration [38]. DLT has been proposed to facilitate collaboration among these entities, enabling autonomous, decentralized, peer-to-peer decision-making in MRS for space missions [13, 26]. In this regard, DLT has shown promise in previous research [13, 28]. In the context of space missions, it could allow robots to autonomously negotiate resource usage, such as shelters, without a central authority. However, it is essential to note that DLT is not without technical limitations. Although it offers similar automation capabilities to centralized platforms through smart contracts, it is generally less efficient due to the inherent replication of transaction processing and storage [8, 44]. Consequently, deploying DLT in MRS and space exploration missions is particularly challenging [47], given the limited resources in such a remote environment. Additionally, the inherent transparency of blockchains complicates data access management, as information is either visible to all participants or none [45].

This New Ideas and Emerging Results paper intentionally steers from presenting an exhaustive list of applications and challenges to showcase practical application development. It emphasizes exploring new ideas and the suitable needs of using DLT for non-proprietary market-based coordination of MRSs in space. Our approach is not about pioneering a specific, feasible application in space exploration and multirobotic coordination. We revisited the market-based MRS space mapping case presented by Dias et al. [16], which we have already begun implementing to evaluate the next steps. Our primary contribution is investigating the economic benefits and assessing potential solutions' technical challenges in space exploration requirements [19, 32, 50]. By leveraging DLT for distributed open coordination, we aim to address the global cost-efficiency problem in market-based MRS coordination [42], advocating for creating a trustworthy cross-organizational platform. Section 2 introduces the foundations of DLT, including smart contracts and tokens, and reviews existing works on DLT in MRS and space. Section 3 details the technical challenges of using DLT in space MRS. Finally, Section 4 presents a use case for distributed auction-based mapping exploration, focusing on the ESA-ESRIC Space Resource Challenge [30]. We conclude in Section 5.

2 RELATED WORK

We draw upon systematic literature reviews on market-based approaches in MRS [16, 42], research on space MRS [18], and the application of DLT in robotics and the space industry [1, 26].

DLT gained prominence with its first application, the cryptocurrency Bitcoin [36]. As a subset of DLT, blockchain technology is characterized by the replicated synchronized transaction processing and a decentralized consensus algorithm with different levels of participation, permissionless vs. permissioned, and access, public vs. private [8]. DLT offers novel opportunities for digital interaction in a non-proprietary digital infrastructure, such as creating trust within consortiums and enabling new trading streams via Fungible and Non-Fungible Tokens (NFTs). NFTs can represent, among many other possibilities, ownership of an non-interchangeable asset, such as collectibles or art pieces [25]. Besides the simple transfer of ownership, DLT also allows implementing programming logic through uploading code known as smart contracts and invoking this code's exposed methods through transactions. In essence, smart contracts allow DLT to provide the same functionality as a centralized platform, with two exceptions: first, non-deterministic methods are not supported, and second, the smart contract code, as well as all its inputs, intermediary results, and outputs, when triggered through a transaction are available to all DLT nodes owing to the replicated execution and storage of transactions [27].

Market-based approaches have been suggested for various applications in MRS [42] and, specifically, space mapping [16]. These approaches often leverage auction systems as suitable tools to efficiently decide which resources to use in a competitive space environment [50]. Previous research suggests that robots can offer dependable services to each other by incorporating DLT [31], thereby opening up possibilities for space exploration, such as selling maps, facilitating decentralized decision-making, and enabling autonomous behavior. Integrating DLT is also said to leverage agent cooperation and communication aimed at detection, learning, and autonomous penalization [40], improving heterogeneous robots' capabilities allowing them to perform complex tasks collaboratively.

Applications of DLT in space have also been suggested for recording orbital positions, mining licenses, and managing space traffic [10]. Another suggested application of DLT in space is to support the efficient and effective coordination of MRS missions, such as in-orbit operations [11], satellite formations, surface, and planetary exploration. By enabling robots to communicate and make transactions and decisions autonomously, DLT is said to support the independent operation of individual robots and enable them to adapt to dynamic environments. Examples of single-entity deployments of DLT that consider economic transactions include the AIRA [31] project, which introduces the concept of "Robonomics," where heterogeneous robots and humans can contract and offer services and receive payment through smart contracts.

Despite advancements, earlier suggestions have focused on centralized single-entity settings. As such, they are not considering the main reason for using DLT in a multi-participatory and competitive space environment and the novel challenges that may arise from it. In other words, all the platform functionalities that related work relies on could also be provided as a service through a dedicated provider that creates the needed digital infrastructure for one or multiple platforms in space [38] or uses a decentralized peer-to-peer communication network to create such a platform. Moreover, existing works still need to adequately address the need for flexible information representation and autonomous robot task learning in dynamic environments [5]. A better understanding of the economic opportunities and technical challenges is indispensable to assess and implement DLT in this context.

3 RESEARCH GAP AND OPEN CHALLENGES

Our discussion is grounded in existing research that tackles the challenges of DLT from various angles, such as resource consumption, performance, and transparency [44, 45]. While Aditya et al. [1] have explored the general challenges that DLT faces in robotics, we focus on five specific open problems particularly relevant to DLT in space [26] and market-based MRS [16, 42].

The first challenge is achieving high levels of autonomy in resource-limited environments, a recurring issue in space exploration [32, 47]. While ontologies and semantic web have been proposed as a solution [34], they often face difficulties dealing with data heterogeneity and system stability in resource-limited settings. Furthermore, establishing a fault-proof infrastructure and a trustless environment is crucial for autonomous coordination [38, 42]. Given the constraints on storage and computational capacity in space robots due to the need for temperature and radiation hardening [18], thorough modeling and testing of DLT in MRS are essential. This includes evaluating public vs. private networks, permissionless vs. permissioned topologies, and possible ISRU-specific consensus mechanisms, such as consensus-based auction and bundle algorithms [42]. The most advanced existing solutions for heterogenous MRS, such as [43] and [15], assume a fully cooperative system. Evaluating a coopetitive system remains an open problem.

The second challenge involves the universal cost/reward function for MRS in market-based coordination [42]. Despite various proposals to improve bid valuation, such as distance-based metrics or performance indexes, the computational complexity of combinatorial auctions still needs to improve [16]. Consequently, researchers have explored alternatives, such as clustering from single-item auctions to consensus-based bundle algorithms. However, current solutions often rely on proprietary frameworks, needing more transparency and trustless requirements for a digital platform in the emerging space economy [38]. To optimize ISRU global efficiency, companies must consider outsourcing mapping data to other MRS companies willing to sell instead of individually mapping it.

Thirdly, public narratives about blockchain technology are vital for its acceptance in governing outer space [13], and misconceptions about high energy consumption have been a barrier [44]. The replicated processing of transactions storage using blockchain still increases the total resource consumption in terms of bandwidth, computing power, and electricity by a factor of N in a blockchain network of N nodes compared to a centralized platform, without taking necessary backups into account [44]. Nevertheless, design decisions such as not using proof of work as a consensus mechanism and approaches like sharding, roll-ups, and off-chain payment channels can somewhat mitigate these inefficiencies [25, 31, 44, 46]. Moreover, further investigation is needed to understand how to maintain trust and collaboration in a *coopetitive* economy [21].

Fourth, for a comprehensive evaluation of opportunities and challenges, DLT research should also investigate alternatives, such as solutions that propose a cloud-based system that could be used in spacecraft networks to address data complexity and heterogeneity [6]. These alternatives require further investigation, especially

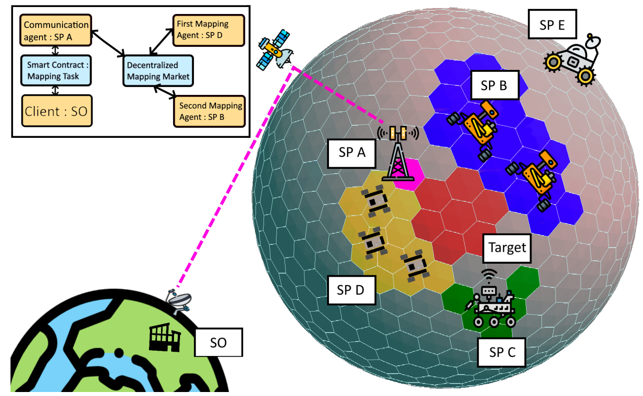

Figure 1: Scelestial mapping scenario, where each zone color represents a company's collaboration

concerning latency sensitivity in DLT solutions for satellite communication [26]. Primarily, latency characteristics should be investigated, as DLT is known to be highly latency sensitive despite the safety guarantees even in non-synchronous environments [20, 23].

Lastly, recent works have demonstrated the potential of using artificial intelligence (AI) agents to autonomously learn incremental affordances [5] and achieve Pareto efficiency and improve equality and productivity in competitive and dynamic market simulations [49]. While these results promise to promote universal shared efficient knowledge, there needs to be more comprehensive coverage and insights on autonomous economic interactions in the existing literature on machine economies in general [25] and DLT in heterogeneous space MRS in specific. DLT has been suggested to manage heterogeneous space systems and efficiently support decentralized behavior [17]. The increasing interest from the scientific community and industry participants [48] also supports the need for further research on cost-effective MRS. Traditional optimization techniques have also been used to achieve decentralized, shared economies without DLT [39]; further performance comparisons are needed to understand the approximation heuristics of decentralized combinatorial optimization systems.

4 RESEARCH PLAN

By outlining the methodology, objectives, and critical components of our research plan, grounded in a hypothetical scenario developed as part of the ESA-ESRIC space resource challenge [30], we aim to explore the integration of blockchain technology extending to the proposed market-based MRS for space exploration [16].

In the given scenario, depicted in Figure 1, six main actors are involved: the Service Orderer (SO), an Earth-based organization responsible for mission directives, and five Service Providers (SP) – entities that execute the tasks in-situ – as roles elaborated in Table 1. While the decentralized MRS coordination concept dates back to the 1980s [4, 35], recent surveys lacking related approaches [1, 42] indicate that the full potential of DLT in this domain still needs to be explored. To fill the research gaps, we prioritize in our plan the following essential requirements:

Table 1: List of service providers.

SP	Color	Robotic Fleet	Main Focus
A	Pink	Communications satellites, Multiple antennas	Moon-earth communications
B	Blue	Medium size offline fleet of robots	Mapping
C	Green	Few robots w/ embedded sensors	Resource analysis
D	Yellow	Large fleet of small robots	Fast mapping with less precision
E	None	A single robot	Mapping

i. **Network**: Enable a mesh network that lets clients create job postings and robots to communicate and coordinate trustfully via market-based tasks [16, 42].
ii. **Data Sharing Transparency**: Ensure transparency in data sharing to foster a *coopetitive* environment with reduced information asymmetry [21, 32].
iii. **Robot Agnostic System**: Develop a system compatible with any robotic platform and scalable to growing demands [16].
iv. **Data Loss Resistance**: Implement safeguards to ensure data integrity and accessibility, even in the face of local system failures or network disruptions [32, 37, 38].

In the scenario depicted in Figure 1, each polygon, structured using the Goldberg polyhedron, represents a sub-map owned and traded by network members [22]. This approach reduces the coordination complexity and allows for a fixed data size for each map segment, optimizing the data storage on the blockchain. However, because different sections of the map may represent distinct territories to be explored, ownership of the gathered information is transferred to the client rather than the explorer. When a robot creates data, it is desirable to represent it as an NFT to prove the authenticity of the knowledge produced and shared on the network. Such would, for instance, prevent unauthorized marketing as the original explorer, yet excessive information about the map would render its value because other DLT nodes could retrieve it for free.

Our initial implementation involves a decentralized system of three rovers designed for resource identification, context analysis, and environmental mapping. These rovers have components comparable to space-graded hardware and can run blockchain nodes. The system uses a mesh network for communication and centralized data processing. However, as the MRS for exploration design decision, the ultimate aim is to transition to a fully decentralized system supported by our successful simulations under similar Lunar network conditions. While our research plan offers a comprehensive approach to integrating DLT with MRS, as we argued in Section 2, a critical aspect of future research will be to focus on optimizing the throughput and resource consumption of blockchain nodes. The initial data organization strategy significantly enhanced data transmission efficiency, particularly regarding critical bandwidth usage. Yet, it is essential to investigate the specific conditions under which DLT is most effective compared to authenticated and accountable bilateral communication based on digital signatures.

5 CONCLUSION

This paper has presented a comprehensive research plan for integrating DLT with market-based heterogeneous MRS in space exploration. We have critically examined the existing literature to identify significant research gaps and articulated the necessity for interdisciplinary endeavors encompassing legal, regulatory, engineering, organizational, and economic aspects. Our proposed research agenda, while ambitious, aims to develop an MRS architecture incorporating DLT and enabling autonomous economic decision-making among robotic agents. We have also highlighted the unique technical challenges that arise when deploying DLT-based systems in the harsh conditions of outer space. While the primary focus is on space applications, the principles, and architectures discussed have broader implications, potentially revolutionizing economic routes that could be adapted for terrestrial applications.

It is important to note that while this paper emphasizes practical application and feasibility, the challenges and use cases presented are not exhaustive. Our objective is to stimulate further research and discussion in this area, and we invite other scholars to extend, critique, or build upon our proposed framework. By laying the groundwork for future research, we hope to contribute to developing more efficient, transparent, and autonomous systems for space exploration. Designing such a system integrating DLT with MRS can significantly advance the field of software engineering, especially for robotics and automation software, offering new avenues for innovation and collaboration.

ACKNOWLEDGMENTS

This research was funded in part by the Luxembourg National Research Fund (FNR) in the FiReSpARX (ref. 14783405) and PABLO (ref. 16326754) projects, and by PayPal, PEARL grant reference 13342933. For the purpose of open access, and in fulfillment of the obligations arising from the grant agreement, the author has applied a Creative Commons Attribution 4.0 International (CC BY 4.0) license to any Author Accepted Manuscript version arising from this submission.

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Received 4 September 2023; revised 22 November 2023; accepted 21 December 2023