Advancements and Future Visions in Earthmoving Swarm Technology

Mikko Hiltunen[1] **and Rauno Heikkilä**[2]

[1]University of Oulu, Finland

Mikko.Hiltunen@oulu.fi, Rauno.Heikkila@oulu.fi

Abstract -

This study examines autonomous earthmoving systems with collaboration among diverse machine types. It focuses on their application in a practical use case involving excavator loading, dumper transport, bulldozer spreading, and roller compacting for road construction. The study focuses on directly observed systems that primarily or partially align with the prescribed use cases. Drawing insights from evaluated systems, the research addresses implementation considerations such as the degree of human intervention, compatibility with diverse machine types, support for multiple simultaneous operations, adaptability to dynamic changes, integration of InfraBIM, reported productivity gains, and qualitative advantages. The study highlights the pioneering role of the earthmoving sector in adopting sensing and information technologies to reduce operation costs, enhance productivity, and improve automation and safety standards. The findings and use case formulation provide a foundation for the development of remote-controlled and autonomous earthmoving swarms, marking progress toward a future where complex construction tasks can be efficiently executed with minimal manual intervention.

Keywords -

Autonomous; Earthmoving; Robot Swarm;

1 Introduction

In recent years, the development of autonomous earthmoving has advanced to commercial solutions, with remote control as the current state-of-the-art technology [1]. This could potentially transform the labor-intensive and on-site nature of earthmoving into a desk job, changing the way we approach construction and excavation projects. The integration of remote-controlled and autonomous systems not only enhances the safety of earthmoving operations but also introduces the concept of supervising multiple machines simultaneously.

One interesting aspect of currently commissioned autonomous earthmoving solutions is their capability to record detailed operational routes and methods employed during a task. This feature allows repeating tasks with precision, minimizing human intervention and maximizing the overall efficiency of the operation. The ability to store and reproduce complex maneuvers opens new possibilities for synchronizing and optimizing earthmoving processes and achieving a higher level of consistency.[2]

The current development of radio technology has also played a major role in advancing autonomous and remote control capabilities of earthmoving. Reliable and broad radio communication has enabled remote control across great distances, transcending geographical boundaries [3]. The introduction of Gbps-level cellular networks enables live streaming of various sensor and telemetry data or ultra-high-resolution video feeds and remote controlling with tolerable latency, ensuring almost real-time responsiveness between input and feedback when operating machinery located even continents apart. This global reach not only enhances the flexibility of earthmoving operations but also transforms the traditional constraints of on-site management.

Swarm intelligence is described as a collective behavior of self-organized systems, which can operate without relying on any external or centralized control [4]. Examples of swarm intelligence can be found in many natural systems such as insect colonies or bird flocks.

A swarm of machines could be determined as multiple simultaneously moving and collaborating machines. It is often composed of homogeneous robots working towards a common goal hard to accomplish by a single robot but can also be formed from different types of machines that have tasks requiring interaction. [4]

Swarm is sometimes misleadingly used as a synonym for machine fleet [4]. The main difference between the two is that autonomous swarm machines can collect and share information to function more intelligently and coordinate joint tasks. The interaction may be accomplished with direct communications or indirectly through the environment.

This paper aims to determine the status of recent developments of cooperating machines in remote-controlled and autonomous earthmoving to underpin the beginning of the national Autonomous Swarm project led by the Digital Construction and Mining Research Group from the University of Oulu. Solutions in the construction and mining sector from around the world are briefed and their challenges and potentials are discussed.

1.1 Literature review

In construction, the earthmoving sector has been at the forefront of embracing sensing and information technologies [5]. This adoption aims to lower operational costs, boost productivity, and elevate standards in automation and safety practices within the industry [5]. The literature on autonomous earthmoving equipment covers technical advances, optimization of earthworks planning, and fleet monitoring with a focus on safety.

Several review papers highlight innovations in earthmoving automation [5, 6, 7]. They discuss advances in fleet tracking, safety management, and machine control technology, categorizing research into equipment tracking, safety, pose estimation, and remote control. Future opportunities, especially in remote control and autonomous operation, are identified as underdeveloped areas.

Studies on fleet size optimization emphasize the integration of field data into simulation modeling. They propose methodologies, including multimodal-process data mining, to capture operational knowledge and create realistic simulation models [8]. Optimization efforts focus on minimizing both cost and emissions, considering factors such as equipment availability and project indirect costs [9, 10, 11, 12].

Fleet monitoring and safety papers explore decision-making tools for daily field management, web-accessible simulation solutions [13], and the use of motion data for real-time activity identification [14]. The importance of Multi-Agent Systems (MAS) for fleet-level coordination and safety is highlighted [15], offering proactive and reactive measures to prevent equipment-related collisions.

These papers collectively contribute to advancing autonomous earthmoving technology, addressing challenges in optimization, monitoring, and safety for more efficient and sustainable construction practices.

2 Methods

2.1 Evaluation of observed systems

Data for the evaluation is collected by observing a series of experiments and real-world demonstrations, utilizing the autonomous earthmoving machine swarm to execute various tasks in the construction and mining sector around the world.

The evaluated systems have been chosen from those that have been within the authors' direct observation in recent years. The study focuses on systems that primarily or partially align with the defined use cases.

The results obtained from the evaluation process will contribute valuable insights into the capabilities and limitations of the autonomous earthmoving system, enabling informed decisions for its utilization in infrastructure construction machine swarms.

The observed remote-controlled and autonomous earthmoving systems are evaluated based on the following criteria.

Operational Principles:

1. Human Intervention: Quantifying the degree of human intervention required for the system to operate effectively.
2. Supported Machine Types: Identifying and assessing the machine types that have been tested and are supported by the system.
3. Simultaneously Working Machines: Evaluating the system's capacity to handle and coordinate multiple machines simultaneously.
4. Adaptability to Changes: Investigating how the system adapts to dynamic changes in the environment or the operational requirements of the construction site.
5. Incorporation of InfraBIM: Examining whether the system integrates with InfraBIM (Infrastructure Building Information Modeling) for enhanced project management and coordination.

Benefits:

1. Productivity Gain: Quantifying the reported increase in productivity achieved through the implementation of the autonomous earthmoving system.
2. Qualitative Advantages: Identifying and qualitatively describing the advantages offered by the system in terms of safety, precision, and overall operational improvements.

Figure 1. Use case vehicles in simulation.[16]

2.2 Use Case Formulation

To systematically organize the development of the autonomous earthmoving machine swarm, a practical use case has been formulated. The use case revolves around the construction of a designed road, encompassing four distinct types of machines involved in following tasks:

1. Excavator Loading: Navigation of a truck to the loading spot and excavation of soil from a designated area or pile to the dump body.
2. Dump Truck Transport: The transportation of excavated soil to predetermined locations.

3. Bulldozer Spreading: Focuses on using bulldozers to spread the transported soil evenly across the construction area.
4. Roller Compacting: Involves the use of rollers to compact the soil layers, ensuring a stable foundation for the road.

The formulated use case serves as a benchmark, allowing for a comprehensive understanding of the autonomous earthmoving system's capabilities in comparison to conventional operation. The use case will be tested both in simulation and real-world environments 1.

3 Evaluation

The first system (Figure 2) was demonstrated with a small wheel loader and 3 crawler dumps working together to transport a gravel pile [17]. The demonstration took place at Seikei University in Japan. The wheel loader featured a continuous curvature path planning algorithm and PurePursuit path tracking algorithm with dead time compensation based on Smith predictor. The path planning for crawler dump trucks featured a map creation algorithm narrowing down drivable areas. The shortest path was then generated with a grid-based search and smoothed to drivable form.

Figure 2. Vehicles used in autonomous system to transport gravel pile.[18]

As the second subject (Figure 3), an autonomous dam construction system is evaluated [19]. The demonstration took place at Naruse dam site in Japan. The system is used to build the cemented sand and gravel body of a trapezoidal-shaped dam. The control method utilizes work simulations based on operational data gathered from skilled operators. The construction process of multiple worksites around the country can be monitored and controlled from a central location. The quarrying excavator was conventionally operated, and construction included a highly laborious phase of laying steel reinforcement plates by hand.

The third system (Figure 4) was demonstrated in an isolated area at Ouluzone Motorsport Center where one operator remotely controlled a large wheel loader to excavate and load a dump truck [21]. The automatic transition routes were carefully recorded beforehand, and the machine repeated them during the demonstration. The operator took over with the remote control when adaption was required: for example, to excavate material from the pile and drop it into the dump body.

Figure 3. Overlook of autonomous construction of Naruse Dam in Japan.[20]

Figure 4. Control booth of retrofit remote control system.[22]

As the fourth subject (Figure 5), we evaluate a couple of autonomous haulage systems[23, 24]. The observed demonstration took place in Norway. Autonomous driving for dump trucks is attracting interest to cut costs of quarrying. Systems often include centralized traffic control, and each truck is equipped with GNSS receivers for localization and lidars and short-range radars for obstacle detection. Machines controlled by human operators have similar equipment to notify their position and for example specifying a loading position for the autonomous truck.

4 Discussion

While the demonstrations of autonomous earthmoving systems provide valuable insights into their capabilities, it is essential to acknowledge the potential bias introduced by the lack of detailed descriptions regarding the setup workload. Understanding the complexity of system setup

Table 1. Evaluation of observed remote-controlled and autonomous earthmoving systems

Principles:	1. AI swarm	2. Automated dam construction	3. Retrofit remote control	4. Autonomous haulage
Human Intervention	Demonstrated as a fully autonomous system requiring only supervision.	Conventional excavators on the material haulage phase. Autonomous construction phases require only monitoring.	Vehicles are mainly remote-controlled, can repeat actions previously recorded by the operator	Dump trucks are autonomous requiring only supervision, other machine types are remote-controlled.
Supported Machine Types	Wheel loader and dump truck (crawler)	Rollers, dozers, and dump trucks	Any, Universal retrofit	excavators, wheel loaders, dozers, and dump trucks
Simultaneously Working Machines	1 wheel loader and 3 dump trucks	4 operators control over 20 machines	2 machines per operator	not specified
Adaptability to Changes	Adaptive path planning with obstacle avoidance	Obstacle detection	No evidence of any machine vision components, relies on incessant operator supervision	Obstacle detection and automatic stopping
Incorporation of InfraBIM	No	Digital construction plans of dam	No	No
Benefits:				
Promoted Productivity Gains	Not specified	Consistent quality and speed	Enhanced operational visibility through video feed and statistical analytics	Longer operational times, lower fuel usage, extended machine life, consistent speed, reduced HR costs
Qualitative Advantages/ Disadvantages and other notes	Operational principles were discussed outright.	Special use case. Operational principles are not clear.	Adds a burden to the operator’s cognitive capacity because of the lack of comprehensive sensory.	Wide range of advanced sensory implemented in retrofit installations.

Figure 5. Autonomous dump truck at loading point.[25]

is crucial for a comprehensive evaluation, as it directly impacts the practicality and feasibility of deploying these systems in research applications.

The setup workload encompasses tasks such as calibrating sensors, configuring communication networks, and in some applications creating digital maps of the construction site. Additionally, programming machine behaviors, defining operational parameters, and integrating with existing infrastructure are critical aspects that significantly contribute to the overall complexity of systems deployment.

A notable observation in the evaluation is the discrepancy in the documentation of methodologies among commercial solutions. While the first evaluated swarm system provides a comprehensive description of the utilized methodologies, commercial solutions often lack transparency in this regard. The absence of detailed information on the underlying methodologies in commercial systems hinders a thorough understanding of their operational principles, limiting the ability to assess their potential and limitations.

The evaluation shows varying levels of human intervention. Only the first system is demonstrated as fully autonomous and requires only supervision but in commercially deployed systems all or some of the machines are controlled manually or remotely. While the commercial technologies already show promising strides in improving efficiency and reducing labor-intensive tasks, challenges persist in achieving an unambiguously beneficial autonomy level, particularly in the more complex construction phases.

Across the commercial autonomous systems there is a common theme of recording and similarly repeating work processes. For example, the third and fourth evaluated systems seemingly lack integration of a more advanced path-planning interface and adaptive autonomy. The systems still demand the majority of the operator's time to monitor and intervene in case of changes in the environment. The first evaluated system was based on algorithms capable of adapting to the current situation, but during the demonstration two of the dump trucks were stopped due to algorithm malfunction.

The development of an intuitive interface for planning and monitoring is principal to the successful integration of autonomous earthmoving systems. Regardless of the control paradigm, it is necessary to provide operators with user-friendly tools that allow for efficient task planning, real-time monitoring, and intervention when necessary. This interface should have a balance between comprehensive oversight and machine-level control, ensuring that operators can easily understand and influence the swarm's behavior.

One prevailing trend observed across the evaluated autonomous earthmoving systems is the reliance on centralized control architectures. While this approach facilitates coordination and monitoring, especially in scenarios involving multiple machines and complex tasks, it raises questions about scalability and adaptability. In a conventional construction environment, centralized control aligns with the hierarchical organization of tasks and the need for coordinated actions. However, the paradigm shifts when considering the dynamics of a robot swarm, where decentralized control mechanisms may offer distinct advantages.

A notable revelation is the absence of any form of InfraBIM incorporation within most of the evaluated systems. Only the second evaluated system had digital plans of automatically constructed material layers. The benefits of InfraBIM, such as enhanced communication and streamlined data transfer, seem to be overlooked. Incorporating InfraBIM principles could pave the way for more intelligent and intuitive interactions between the modeled design and the autonomous systems, gaining a new level of efficiency and precision in construction operations.

The efficient handling of data poses a challenge in the context of autonomous earthmoving systems, with centralized systems often facing higher data processing and communication costs. As the scale of construction projects increases, the challenge of data scalability becomes more pronounced. Decentralized control systems, by distributing data processing among individual units, may offer a more scalable solution, potentially lowering the costs associated with the handling and transmission of large datasets.

5 Conclusion

The formulated use case, covering excavator loading, dumper transport, bulldozer spreading, and roller compacting, serves as a foundational framework for developing methods and concepts for autonomous earthmoving systems. Valuable insights are gleaned from evaluated systems and existing literature. The initial system offers tangible methods and functions for individual machines, while others present refined user interfaces and comprehensive hardware solutions.

The study's evaluation predominantly relies on qualitative assessments due to the limited availability of quantitative data, particularly for commercial solutions where such information may not be publicly accessible. Furthermore, the study's emphasis on formulated use cases inherently lends toward subjective evaluations, as the aim is to identify systems or components adaptable to own research and development endeavours.

While the study's criteria ensure a comprehensive assessment of Earthmoving swarm technologies, it's essential to acknowledge the limitations of qualitative evaluation in fully capturing aspects like economical feasibility, operator skills, and potential time and cost savings. Future research needs to address these areas to delve into the quantitative aspects and provide a more holistic understanding of autonomous earthmoving systems' effectiveness and practical implications. As autonomous swarm technologies are advancing in the construction sector and data becomes more available, there is also a need for systematic analysis of the social and environmental aspects of using autonomous Earth-moving equipment, particularly in terms of benefits and impact evaluation.

The ongoing phase of the swarm project aims to set up the use case machines with the necessary equipment and control systems. The subsequent step involves establishing a secure yet dynamic connection across all robots and monitoring systems, allowing authorized units to seamlessly join the swarm.

The future objective is to demonstrate the use cases first individually and then collectively. The aspiration is to eliminate all manual intervention, with a transitional phase focusing on creating a user interface concept. This concept should empower a minimal number of human operators to instruct multiple machines, allow designing detailed tasks swiftly and intuitively, and need manual control only for exceptional circumstances.

The ultimate goal for InfraBIM-based automation development is to achieve machine readability for the models, enabling autonomous machines to directly comprehend their intended tasks from modeled designs without intermediary software[26]. With appropriate infrastructure, AI-powered methods could be implemented to take control of task execution, as already demonstrated for some machine types, especially in the transportation field.

References

[1] J. S. Lee, Y. Ham, H. Park, and J. Kim. Challenges, tasks, and opportunities in teleoperation of excavator toward human-in-the-loop construction automation. *Automation in Construction*, 135:104119, 2022. doi:10.1016/j.autcon.2021.104119.

[2] S. N. Naghshbandi, L. Varga, and Y. Hu. Technologies for safe and resilient earthmoving operations: A systematic literature review. *Automation in Construction*, 125:103632, 2021. doi:10.1016/j.autcon.2021.103632.

[3] S. Ali, W. Saad, N. Rajatheva, K. Chang, D. Steinbach, B. Sliwa, C. Wietfeld, K. Mei, H. Shiri, H-J. Zepernick, et al. 6g white paper on machine learning in wireless communication networks. *arXiv preprint arXiv:2004.13875*, 2020. doi:10.48550/arXiv.2004.13875.

[4] M. Rath, A. Darwish, B. Pati, B.K. Pattanayak, and C.R. Panigrahi. Swarm intelligence for resource management in internet of things. pages 21–45, 2020. doi:10.1016/B978-0-12-818287-1.00005-X.

[5] E. R. Azar and V. R. Kamat. Earthmoving equipment automation: A review of technical advances and future outlook. *Journal of Information Technology in Construction (ITcon)*, 22(13):247–265, 2017. ISSN 1874-4753.

[6] P. G.P.S. Fernandes, E. F. N. Júnior, and B. A. Prata. Optimization of earthworks planning: a systematic mapping study. *Canadian Journal of Civil Engineering*, 49(12):1781–1795, 2022. doi:10.1139/cjce-2022-0185.

[7] H. A.D. Nguyen and Q. P. Ha. Robotic autonomous systems for earthmoving equipment operating in volatile conditions and teaming capacity: a survey. *Robotica*, 41(2):486–510, 2023. doi:10.1017/S0263574722000339.

[8] R. Akhavian and A. H. Behzadan. Knowledge-based simulation modeling of construction fleet operations using multimodal-process data mining. *Journal of Construction Engineering and Management*, 139(11):04013021, 2013. doi:10.1061/(ASCE)CO.1943-7862.0000775.

[9] S. A.R. Kaboli, M. Bahaaddini, and S. M. Kaboli. Optimal earthmoving fleet size for minimising emissions and cost. *Journal of Mining and Environment*, 11(4):949–965, 2020. doi:10.22044/jme.2020.9910.1918.

[10] D. Morley, T. Joseph, and M. Lu. In search of the ideal truck-excavator combination. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, volume 30, page 1. IAARC Publications, 2013. doi:10.22260/ISARC2013/0045.

[11] C. Yi and M. Lu. A simulation-based earthmoving fleet optimization platform (sefop) for truck/excavator selection in rough grading project. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, volume 35, pages 1–7. IAARC Publications, 2018. doi:10.22260/ISARC2018/0133.

[12] M. Marzouk and O. Moselhi. Multiobjective optimization of earthmoving operations. *Journal of construction Engineering and Management*, 130(1):105–113, 2004. doi:10.1061/(ASCE)0733-9364(2004)130:1(105).

[13] Y. Mohamed and M. Ali. A simplified online solution for simulation-based optimization of earthmoving operations. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, volume 30, page 1. IAARC Publications, 2013. doi:10.22260/ISARC2013/0040.

[14] K. M. Rashid and J. Louis. Automated activity identification for construction equipment using motion data from articulated members. *Frontiers in Built Environment*, 5:144, 2020. doi:10.3389/fbuil.2019.00144.

[15] F. Vahdatikhaki, S. M. Langari, A. Taher, K. El Ammari, and A. Hammad. Enhancing coordination and safety of earthwork equipment operations using multi-agent system. *Automation in construction*, 81: 267–285, 2017. doi:10.1016/j.autcon.2017.04.008.

[16] M. Hiltunen. Test environment for autonomously operating swarm developed at the university of oulu. agx dynamics for unity -simulation software, 2023. URL `https://www.algoryx.se/agx-unity/`.

[17] T. Takei, K. Ichikawa, K. Okawa, S. Sarata, T. Tsubouchi, and A. Torige. Path planning of wheel loader type robot for scooping and loading operation by genetic algorithm. In *2013 13th International Conference on Control, Automation and Systems (ICCAS 2013)*, pages 1494–1499, 2013. doi:10.1109/ICCAS.2013.6704123.

[18] M. Hiltunen. Autonomously working system of small equipment excavating and transporting gravel in japan, 2023.

[19] A4csel construction production system. On-line: `https://www.kajima.co.jp/english/tech/c_a4csel/index.html`, Accessed: 07/12/2023.

[20] M. Hiltunen. Autonomously working dam construction cite at naruse dam in japan., 2022.

[21] Teleo's full-stack solution. On-line: `https://www.teleo.ai/technology/`, Accessed: 07/12/2023.

[22] R. Heikkilä. Remote control booth of retrofit system for wheeloader manufactured by teleo, 2023. URL `https://www.teleo.ai/`.

[23] T. Hamada and S. Saito. Autonomous haulage system for mining rationalization. *Hitachi Rev*, 67(1):87–92, 2018.

[24] Steer autonomous. On-line: `https://www.steer.no/`, Accessed: 07/12/2023.

[25] R. Heikkilä. Autonomously driving dump truck at loading point. retrofit control system manufactured by steer, 2023. URL `https://www.steer.no/`.

[26] M. Hiltunen, R. Heikkilä, I. Niskanen, and M. Immonen. Open infrabim for remote and autonomous excavation. *Automation in Construction*, 156, 2023. doi:10.1016/j.autcon.2023.105148.