EMERGENCE

Project Brief

Autonomous Systems / Planetary Construction

Monash Deep Neuron

EMERGENCE is a multi-year robotics research project investigating how a swarm of homogeneous, multifunctional robots can coordinate autonomously to perform construction tasks in challenging environments.

The initial application is lunar infrastructure, with the system focused on excavation, material transport, deposition and compaction for infrastructure such as roads, landing pads and protective berms.

The project explores whether a shared autonomous policy can allow identical robots to adapt their roles dynamically using local observations, rather than relying on fixed task assignments or a centralized controller.

1. Project Overview

Future planetary infrastructure will require substantial material handling and construction before continuous human presence is practical.

Traditional construction approaches depend heavily on large, specialized machines or centrally coordinated fleets. These systems can be vulnerable to individual machine failures, changing resource distributions and communication constraints commonly found in space environments.

EMERGENCE investigates an alternative approach:

> A decentralized swarm of homogeneous construction robots that can dynamically adapt how work is distributed across the fleet.

Rather than assigning permanent roles such as excavator, transporter or compactor, each robot is designed around the same core platform and can undertake multiple construction behaviours.

The long-term objective is for the swarm to determine how available robots should contribute to the overall mission based on local conditions and current construction demand.

2. Research Focus

The central research question is:

Can a shared reinforcement-learning policy enable a homogeneous swarm of multifunctional robots to develop adaptive role allocation across granular-material collection, transport, deposition and compaction, using only local observations, while maintaining construction performance under robot failures and changing resource distributions?

The project focuses on several interconnected research areas:

- decentralized multi-robot coordination
- multi-agent reinforcement learning
- shared-policy control
- adaptive task allocation
- robotic perception and localization
- autonomous navigation
- granular-material manipulation
- construction robotics
- system resilience
- sim-to-real validation

The project is particularly interested in whether meaningful task specialization can emerge from the interaction between shared policies, local observations and changing environmental demands.

3. System Concept

EMERGENCE uses a homogeneous robot architecture.

Each robot is based on the same core mechanical, sensing and compute platform.

Instead of building separate machines for excavation, transport, and compaction, each platform is intended to perform multiple construction roles.

The initial construction workflow consists of four core behaviours:

Excavation

Collect granular material using a robotic arm and scoop.

Transport

Move collected material between resource areas and construction zones.

Deposition

Place material according to the target construction geometry.

Compaction

Apply static pressure and vibration to increase material density and improve surface preparation.

This architecture allows the swarm to reallocate work dynamically.

For example, if one robot becomes unavailable, the remaining robots may be able to redistribute excavation, transport and compaction tasks rather than requiring a replacement specialist vehicle.

4. Robotic Platform

The current physical platform is being designed as a compact, modular construction rover.

The baseline architecture includes:

- six-wheel rocker-bogie mobility
- six independently driven geared motors
- wheel encoder feedback
- 3-DOF robotic arm
- scoop / construction end-effector
- vibratory compaction subsystem
- RGB-D perception
- 360-degree LiDAR for localization and obstacle awareness
- Jetson Xavier NX onboard compute
- STM32 low-level control

- onboard battery system
- ROS 2-based software architecture

The current CAD design is nearing completion and physical development is beginning.

The mechanical architecture prioritizes low-speed traction, stability, modularity and suitability for granular terrain.

5. Perception and Navigation

The initial sensing architecture combines multiple complementary sensors.

RGB-D Camera

Provides:

- RGB imagery
- stereo depth
- local 3D geometry
- object and material recognition
- construction-zone perception

360-Degree LiDAR

Provides:

- planar mapping
- localization
- obstacle detection
- side and rear awareness

Wheel Encoders

Provide:

- local odometry
- wheel-speed feedback
- closed-loop drivetrain control

IMU

Provides:

- orientation
- angular motion
- inertial information

These data sources will be fused to support localization, navigation and local environmental understanding.

6. Control Architecture

The system uses a layered compute architecture.

Jetson Xavier NX

Responsible for:

- ROS 2
- perception
- localization
- navigation
- world modelling
- reinforcement-learning policy inference
- inter-robot communication
- mission-level autonomy

STM32 Controller

Responsible for:

- encoder acquisition
- wheel-speed control
- motor PWM
- PID control
- current and fault monitoring
- low-level safety

This separates high-level autonomy from deterministic real-time control.

7. Reinforcement Learning Architecture

The long-term autonomy architecture is based around cooperative multi-agent reinforcement learning.

The initial development path is:

1. single-agent PPO
2. custom Gymnasium environment
3. shared-policy multi-agent learning
4. PettingZoo-based multi-agent environments
5. centralized training with decentralized execution
6. MAPPO or related shared-policy architectures
7. deployment of trained policies onto physical robots

The final architecture is intended to use the same actor policy across all homogeneous robots.

Each robot receives different local observations, causing different behaviours to emerge from the same underlying policy.

This allows the system to preserve platform homogeneity while still producing dynamic specialization.

8. Decentralized Execution

During deployment, each robot is intended to make decisions using locally available information.

Possible observations include:

- nearby material
- nearby robots
- construction progress
- current payload
- local terrain

- battery state
- robot health
- task demand

The robot may then select a high-level behaviour such as:

- gather
- transport
- deposit
- compact
- relocate
- wait

The reinforcement-learning policy is not intended to control individual wheel motors directly.

Instead, the policy selects high-level behaviours while the robotics stack executes navigation, manipulation and low-level control.

9. Centralized Training, Decentralized Execution

The project is expected to use a centralized-training, decentralized-execution approach.

During training, the learning system may access broader global information through a centralized critic.

This can include:

- global robot positions
- global construction progress
- material distribution
- joint system state

During real-world deployment, each robot uses only its own local observations and the shared actor policy.

This allows training to benefit from richer information while preserving decentralized operation.

10. Construction Research

The initial construction research focuses on granular-material infrastructure.

Target applications include:

- roads
- landing pads
- protective berms
- graded surfaces
- future foundations
- trenching and utility preparation

The first physical investigation focuses heavily on vibratory compaction.

The current compactor concept is inspired by recent planetary construction research using vibratory plate compaction.

The EMERGENCE design uses:

- robotic arm preload
- a compact vibratory plate
- dual counter-rotating eccentric masses
- adjustable vibration frequency
- controllable eccentric force
- force measurement
- vibration sensing

The aim is to experimentally characterize compaction performance across different granular materials.

11. Validation Strategy

The project will be validated progressively.

Initial testing will be conducted in simplified simulation and controlled physical environments.

Evaluation metrics may include:

- task completion time

- material throughput
- distance travelled
- energy consumption
- idle time
- collision rate
- construction accuracy
- compaction performance
- role-switching frequency
- recovery after robot failure
- performance under resource redistribution

The project will also compare reinforcement-learning approaches against simpler baselines.

These may include:

Fixed-Role Baseline

Each robot is permanently assigned to a predefined task.

Rule-Based Dynamic Baseline

Robots switch tasks according to predetermined logic.

Learned Policy

Task allocation emerges through reinforcement learning.

This allows the project to evaluate whether learned decentralized coordination provides meaningful advantages.

12. Failure and Disturbance Testing

Resilience is a major focus of the project.

Future experiments will investigate how the swarm responds to:

Robot Failure

One or more robots become unavailable.

Partial Capability Failure

A robot loses a subsystem such as its compactor or manipulator.

Resource Redistribution

Material becomes available in a new location.

Changing Construction Demand

Different stages of construction require different proportions of excavation, transport or compaction.

Congestion

Multiple robots compete for access to constrained work areas.

The objective is to determine whether the swarm can maintain useful construction performance without centralized reassignment.

13. Development Roadmap

Stage 1 — Initial Platform Development

- finalize CAD
- construct first rover
- validate mobility
- validate embedded control
- integrate sensing
- build initial construction tooling

Stage 2 — Single-Agent Autonomy

- develop PPO baseline
- create simplified simulation environment
- validate navigation and task execution
- refine reward and observation design

Stage 3 — Multi-Agent Coordination

- introduce multiple agents
- implement shared policies
- investigate emergent role allocation

- introduce task competition and cooperation

Stage 4 — Resilience Testing

- simulate robot failures
- redistribute resources
- introduce environmental disturbances
- compare against fixed and rule-based baselines

Stage 5 — Physical Multi-Robot Validation

- deploy trained policies onto physical platforms
- evaluate sim-to-real performance
- measure coordination quality
- quantify construction performance

Stage 6 — Expanded Construction Capability

Potential future capabilities include:

- site grading
- trenching
- regolith shielding
- foundation preparation
- material sorting
- ISRU integration
- modular assembly
- infrastructure maintenance
- robot recovery
- collaborative manipulation

14. Current Development Status

The project is currently in early physical and autonomy development.

Current progress includes:

- project architecture defined

- research question established
- rover CAD nearing completion
- website and public project identity established
- initial hardware architecture selected
- first reinforcement-learning environment under development
- single-agent PPO development underway
- physical component procurement beginning
- multi-agent simulation planning underway

A concept visualization of multiple robots cooperatively building lunar infrastructure is also under development.

15. Long-Term Vision

The long-term objective is not simply to build a swarm of mobile robots.

EMERGENCE aims to investigate a broader autonomous planetary construction system in which homogeneous robots can collectively prepare and maintain infrastructure with limited human intervention.

A mature system could eventually support:

- landing-site preparation
- road construction
- berm construction
- habitat-site preparation
- radiation shielding
- utility trenching
- material transport
- ISRU construction workflows
- autonomous inspection
- infrastructure maintenance
- robotic recovery and repair

The broader vision is a resilient, scalable robotic workforce capable of supporting infrastructure development in remote and hazardous environments.

16. Terrestrial Relevance

Although lunar construction provides the primary research context, the underlying technologies are also relevant to terrestrial applications.

Potential application areas include:

- mining
- remote infrastructure
- hazardous environments
- disaster response
- autonomous earthmoving
- distributed construction
- industrial material handling

The same decentralized coordination principles could be applied to terrestrial fleets operating in environments where centralized control, continuous communications or human supervision are difficult.

17. Collaboration

EMERGENCE is intended as a long-term research platform and welcomes collaboration with organizations working in:

- robotics
- autonomous systems
- reinforcement learning
- construction technology
- mining automation
- space technology
- perception
- embedded systems

- sensing
- planetary infrastructure

Potential collaboration may include:

- hardware support
- technical mentorship
- research collaboration
- simulation and software support
- testing access
- sponsorship
- industry guidance

18. Project Identity

Project: EMERGENCE
Organization: Monash DeepNeuron
Research area: Autonomous Systems / Multi-Robot Construction
Primary application: Lunar infrastructure
Development model: Multi-year research platform

EMERGENCE is currently transitioning from system design into physical development and experimental autonomy research.

The project will continue to evolve as simulation, hardware and multi-agent research converge into an integrated robotic construction system.