Body and Brain Quality-Diversity in Robot Swarms

TELO 2023 Supplementary Material

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Abstract

In biological societies complex interactions between the behavior and morphology of evolving organisms and their environment has given rise to a wide range of complex and diverse social structures. Similarly, in artificial counter-parts such as swarm robotics systems, collective behaviors emerge via the interconnected dynamics of robot morphology (sensory-motor configuration), behavior (controller), and environment (task). Various studies have demonstrated morphological and behavioral diversity enables biological groups to exhibit adaptive, robust and resilient collective behavior across changing environments. However, in artificial (swarm robotic) systems there is little research on the impact of changing environments on morphological and behavioral (body-brain) diversity in emergent collective behavior, and the benefits of such diversity. This study uses evolutionary collective robotics as an experimental platform to investigate the impact of increasing task environment complexity (collective behavior task difficulty) on the evolution and benefits of morphological and behavioral diversity in robotic swarms. Results indicate that body-brain evolution using coupled behavior and morphology diversity maintenance yields higher behavioral and morphological diversity, which is beneficial for collective behavior task performance in the most complex task environments. Results also indicate that such diversity maintenance produces robot body-brain couplings with neuro-morpho complexity that does not increase concomitantly with task environment complexity.

A Supplementary Material

A.1 Statistical Comparisons

Tables 1, 7, 3, 4, 5, and 6 present pair-wise statistical comparisons of *task performance*, *unique behaviors*, *behavior QD score*, *unique morphologies*, *morphology QD score*, and *neuro-morpho complexity*, respectively, of swarm behaviors evolved by the mEDEA, mEDEA-M, EDQD, EDQD-M, and Double-Map EDQD-M methods. This comparison is for each environment: *Simple*, *Medium-Low*, *Medium*, *Medium-High*, and *Difficult* (highlighted in bold). A statistically significant difference (Mann–Whitney U pair-wise statistical tests, $p < 0.05$), is indicated by a tick, and a cross indicates no significant difference between two comparative methods.

Table 1: Statistical comparisons of task performance of robot teams evolved by the mEDEA, mEDEA-M, EDQD, EDQD-M, and Double-Map EDQD-M approaches in each task environment.

Simple	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✗	✗
mEDEA-M		✓	✓	✓
EDQD			✗	✗
EDQD-M				✗

Medium-Low	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✓	✓
mEDEA-M		✓	✓	✓
EDQD			✗	✗
EDQD-M				✗

Medium	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✓	✓
mEDEA-M		✗	✓	✗
EDQD			✓	✗
EDQD-M				✓

Medium-High	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✗	✗
mEDEA-M		✗	✗	✗
EDQD			✗	✗
EDQD-M				✗

Difficult	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✗	✗
mEDEA-M		✗	✗	✗
EDQD			✗	✗
EDQD-M				✗

Table 2: Statistical comparisons of unique behaviors of robot teams evolved by the mEDEA, mEDEA-M, EDQD, EDQD-M, and Double-Map EDQD-M approaches in each task environment.

Simple	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✗	✗
mEDEA-M		✓	✓	✗
EDQD			✗	✗
EDQD-M				✗
Medium-Low	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✓	✓
mEDEA-M		✗	✓	✗
EDQD			✗	✗
EDQD-M				✗
Medium	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✓	✓
mEDEA-M		✗	✗	✓
EDQD			✓	✓
EDQD-M				✗
Medium-High	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✓	✓
mEDEA-M		✗	✗	✓
EDQD			✗	✓
EDQD-M				✓
Difficult	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✓	✗	✗	✓
mEDEA-M		✗	✗	✗
EDQD			✗	✓
EDQD-M				✗

Table 3: Statistical comparisons of behavior QD score of robot teams evolved by the mEDEA, mEDEA-M, EDQD, EDQD-M, and Double-Map EDQD-M approaches in each task environment.

Simple	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✗	✗
mEDEA-M		✓	✓	✗
EDQD			✗	✓
EDQD-M				✗
Medium-Low	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✓	✗
mEDEA-M		✗	✗	✗
EDQD			✗	✗
EDQD-M				✓
Medium	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✓	✗
mEDEA-M		✗	✗	✗
EDQD			✓	✗
EDQD-M				✓
Medium-High	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✗	✓
mEDEA-M		✗	✗	✗
EDQD			✗	✗
EDQD-M				✗
Difficult	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✗	✗
mEDEA-M		✗	✗	✗
EDQD			✓	✗
EDQD-M				✗

Table 4: Statistical comparisons of unique morphologies in each environment.

Simple	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓
Medium-Low	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓
Medium	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓
Medium-High	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓
Difficult	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓

Table 5: Statistical comparisons of morphology QD score in each environment.

Simple	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓
Medium-Low	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓
Medium	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓
Medium-High	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓
Difficult	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✓

Table 6: Statistical comparisons of neuro-morpho complexity in each environment.

Simple	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✗
EDQD-M		✗
Medium-Low	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✗
EDQD-M		✗
Medium	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✗
Medium-High	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✓
EDQD-M		✗
Difficult	EDQD-M	Double-Map EDQD-M
mEDEA-M	✗	✗
EDQD-M		✗

Table 7: Statistical comparisons of unique behaviors in each environment.

Simple	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✗	✗
mEDEA-M		✓	✓	✗
EDQD			✗	✗
EDQD-M				✗
Medium-Low	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✓	✓	✓
mEDEA-M		✗	✓	✓
EDQD			✗	✗
EDQD-M				✗
Medium	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✓	✓
mEDEA-M		✗	✓	✓
EDQD			✓	✓
EDQD-M				✗
Medium-High	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✗	✗	✓	✓
mEDEA-M		✗	✗	✓
EDQD			✗	✓
EDQD-M				✓
Difficult	mEDEA-M	EDQD	EDQD-M	Double-Map EDQD-M
mEDEA	✓	✗	✗	✓
mEDEA-M		✗	✗	✗
EDQD			✗	✓
EDQD-M				✗

A.2 Evolved Behavior Quality Diversity

Figures $1 - 10$ present behavioral *Quality Diversity* QD representations of the behavioral QD score calculated for highest task-performance swarms evolved by mEDEA, mEDEA-M, EDQD, EDQD-M, and Double-Map EDQD-M in each environment. Note that swarm behavior is defined by distance covered (Y axis) and resource type gathered (X axis), and thus behavioral QD score in this case is defined by the quality (task-performance) given specific combinations of values for these behavioral characteristics (distance covered, resource type gathered). For each behavioral cell (distance explored, resource type), darker cell shading indicate a value closer to 1.0, meaning close to the maximum possible distance was explored or close to the maximum number of resources was gathered. Whereas, lighter cell shading indicates a value closer to 0.0, meaning a low distance was explored and a low number of resources gathered.

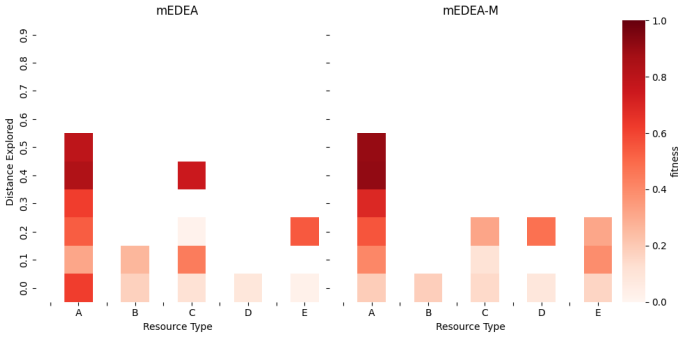

Figure 1: Behavioral QD of highest task-performance swarms evolved by mEDEA and mEDEA-M in the *simple* environment.

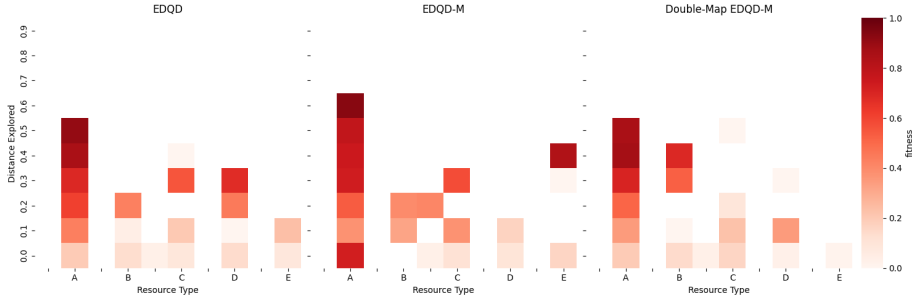

Figure 2: Behavioral QD of highest task-performance swarms evolved by EDQD, EDQD-M and Double-Map EDQD-M in the *simple* environment.

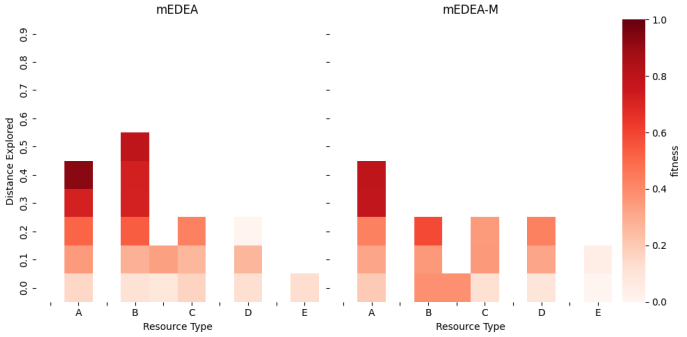

Figure 3: Behavioral QD of highest task performance swarms evolved by mEDEA and mEDEA-M in the *medium-low* environment.

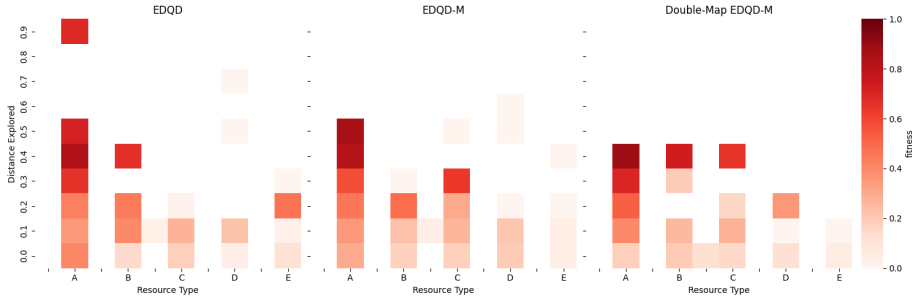

Figure 4: Behavioral QD of highest task-performance swarms evolved by EDQD, EDQD-M and Double-Map EDQD-M in the *medium-low* environment.

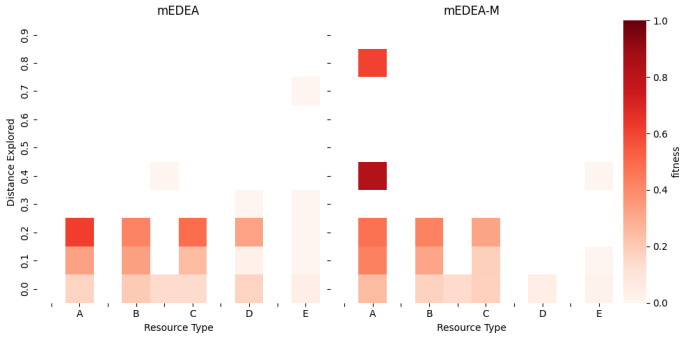

Figure 5: Behavioral QD of highest task-performance swarms evolved by mEDEA and mEDEA-M in the *medium* environment.

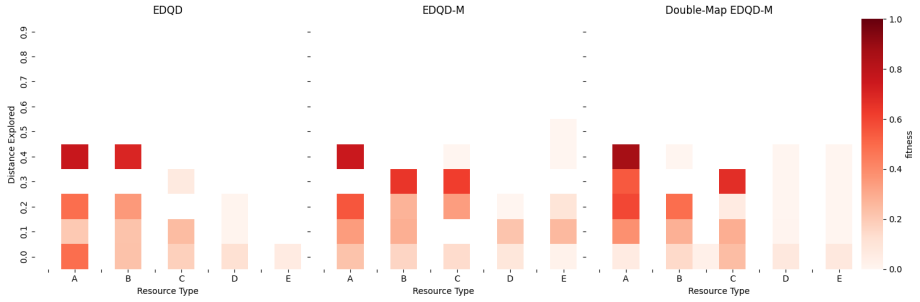

Figure 6: Behavioral QD of highest task-performance swarms evolved by EDQD, EDQD-M and Double-Map EDQD-M in the *medium* environment.

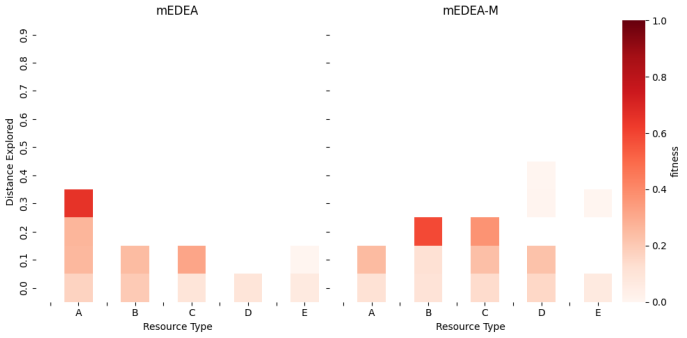

Figure 7: Behavioral QD of highest task-performance swarms evolved by mEDEA and mEDEA-M in the *medium-high* environment.

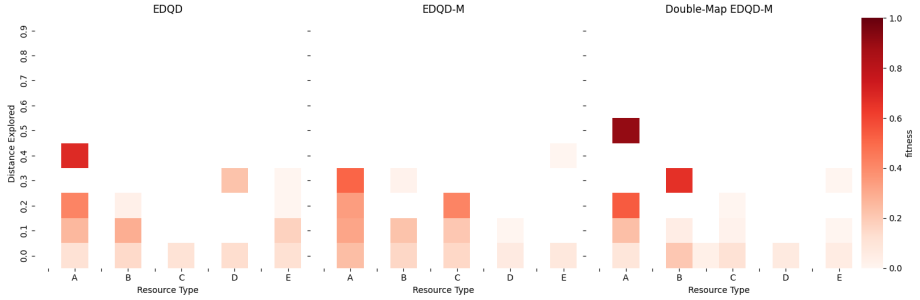

Figure 8: Behavioral QD of highest task-performance swarms evolved by EDQD, EDQD-M and Double-Map EDQD-M in the *medium-high* environment.

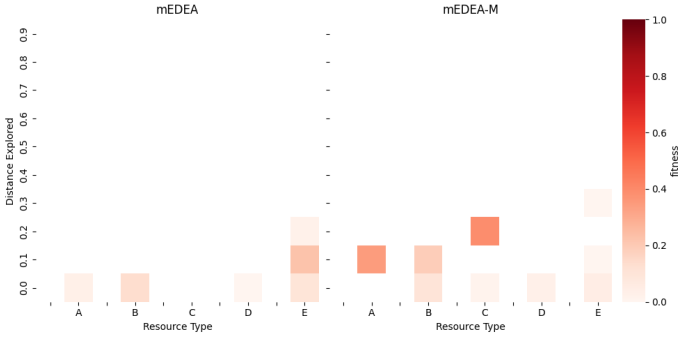

Figure 9: Behavioral QD of highest task-performance swarms evolved by mEDEA and mEDEA-M in the *difficult* environment.

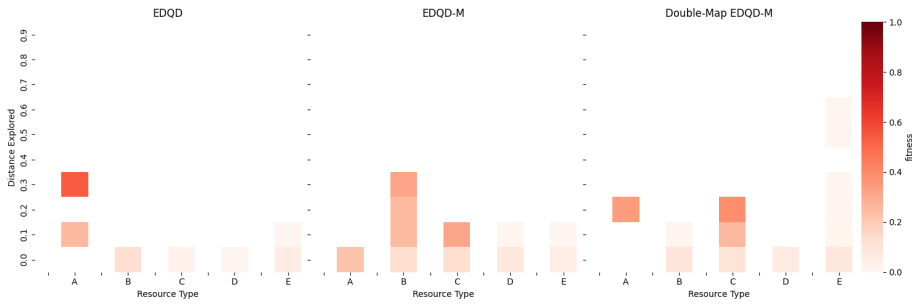

Figure 10: Behavioral QD of highest task-performance swarms evolved by EDQD, EDQD-M and Double-Map EDQD-M in the *difficult* environment.