Paper Review

Evolving Virtual Creatures

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1. Paper Title, Authors, and Affiliations

- **Title**: Evolving Virtual Creatures
- **Published in**: Computer Graphics, Annual Conference Series (SIGGRAPH '94 Proceedings), July 1994, pp.15-22.
- **Author**: Karl Sims
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2. Main Contribution of the Paper

This paper presents a novel system for evolving virtual creatures that move and behave in simulated 3D physical worlds. The key contributions include:

- The automatic generation of both morphology and control systems of virtual creatures using genetic algorithms.
- A directed graph-based genetic representation for encoding creature structures and neural networks.
- The co-evolution of morphology and control, allowing creatures to adapt their body structure and nervous system together.
- Demonstration of emergent locomotion behaviors such as swimming, walking, jumping, and light-following, without manually designing these behaviors.
- Application of evolutionary algorithms in procedural animation and artificial intelligence.

3. Outline of Major Topics and Techniques

1. **Introduction**
   - Trade-off between complexity and control:
     - Directly animating virtual entities allows precise control but is tedious.
     - Dynamic simulation makes motions look natural but is difficult to control.
   - Optimization techniques, especially genetic algorithms, allow automated complexity generation.

- Prior work focused on evolving control systems for fixed structures, whereas this work evolves both morphology and control simultaneously.

2. **Creature Morphology Representation**
    - Creatures are represented as hierarchical articulated 3D structures.
    - Morphology is encoded using a directed graph where:
        - Nodes represent body parts.
        - Connections represent joints and attachment relationships.
    - The graph allows recursion, enabling fractal-like repeated structures.

3. **Creature Control – Neural Network Representation**
    - A virtual brain is evolved alongside morphology.
    - The control system consists of:
        - Sensors (joint angles, contact sensors, photosensors).
        - Neurons (processing units performing mathematical operations).
        - Effectors (muscle forces applied to joints).
    - The neural network functions more like a dataflow system rather than a typical biological neural network.
    - Oscillatory neurons allow rhythmic motion patterns, crucial for locomotion.

4. **Physical Simulation**
    - Rigid-body dynamics with articulated parts.
    - Collision detection and response: Uses bounding box hierarchies to optimize performance.
    - Friction, elasticity, and fluid resistance: Creatures can move on land or water with different physics settings.
    - Energy conservation is enforced to prevent exploits in the physics engine.

5. **Evolution and Behavior Selection**
    - Fitness evaluation guides evolution towards desired behaviors.
    - Different fitness criteria lead to different behaviors:
        - Swimming: Distance traveled in a simulated water environment.
        - Walking: Horizontal distance covered on land.
        - Jumping: Maximum height reached.
        - Light-following: Ability to track a moving light source.
    - Elimination of unfit creatures: Creatures with collisions, excessive parts, or unrealistic structures are discarded.

6. **Evolutionary Process**
    - Population-based approach: Each generation consists of 300 creatures, with the top 20% surviving.
    - Genetic operations:
        - Mutation: Randomly alters parameters, connections, or structure.
        - Crossover: Combines parts from two parents.
        - Grafting: Connects a node from one creature to another.

- Parallel implementation: Runs on a Connection Machine CM-5, with each processor testing different individuals.

7. **Results**
   - Evolved creatures exhibit diverse locomotion strategies:
     - Swimming creatures: Snake-like undulations, tail wagging, flipper motions.
     - Walking creatures: Bipedal or multi-legged locomotion, hopping behaviors.
     - Jumping creatures: Spring-like appendages for high jumps.
     - Light-following creatures: Steering mechanisms to track light sources.
   - Unexpected emergent behaviors: Some creatures evolved rocking movements or oscillations to move forward efficiently.
8. **Future Work**
   - More complex tasks: Evolve creatures to perform multiple behaviors.
   - Competitive evolution: Introduce population-based selection pressures.
   - Real-world robotics: Constrain morphologies to buildable robotic designs.
   - Aesthetic selection: Allow users to guide evolution based on appearance.
9. **Conclusion**
   - Demonstrates that morphology and control can co-evolve.
   - Provides a practical approach for generating autonomous virtual creatures.
   - Suggests that evolutionary methods could play a role in developing intelligent behavior in virtual entities.

4. Two Things I Liked or Found Interesting

1. **Emergent Behaviors Without Manual Design**
   - The creatures developed naturalistic locomotion strategies without explicit programming. I especially adore the idea of applying the concept of evolution and fitness into artificial life generation, this combines the beauty of genetic algorithm with the complexity of natural selection.
2. **Directed Graph Representation for Morphology & Neural Networks**
   - Using graph structures for both body morphology and neural control enables scalable and modular designs. Also, the approach allows recursive self-similarity, leading to biologically plausible body structures.

5. What Did You Not Like About the Paper?

- **Limited Complexity in Behaviors**
  - While locomotion was well-evolved, there were no high-level behaviors like predator-prey interactions or adaptive learning. I think this can be a great extension to the current work.
- **Lack of Robustness in Neural Control**

  - The neural system is not biologically realistic and is more like a data-processing system.Rather, it is unclear if the evolved behaviors generalize well beyond specific tasks.

6. Questions for the Authors

1. How could this system evolve creatures with more complex and adaptive behaviors?
2. Could reinforcement learning be combined with genetic evolution to improve decision-making? This could be helpful in providing more biological-plausible lookings of the creatures that we might not be able to generate with current approach.