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# RPPR Final Report
as of 21-Jan-2020

Agency Code:

Proposal Number: 68293EG **Agreement Number: W911NF-16-1-0304**

**INVESTIGATOR(S):**


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DUNS Number: 066811191 EIN: 030179440
**Report Date:** 30-Nov-2019 Date Received: 18-Jan-2020
**Final Report** for Period Beginning 01-May-2016 and Ending 30-Apr-2019
**Title:** Morphological Plasticity for the Design, Control and Deployment of Complex Engineering Systems
**Begin Performance Period:** 01-May-2016 **End Performance Period:** 30-Apr-2019
**Report Term:** 0-Other

Submitted By: Joshua Bongard Email: Josh.Bongard@uvm.edu
Phone: (802) 656-4665

**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

**STEM Degrees:** 1 **STEM Participants:** 1

**Major Goals:** Recent advances in materials science and fabrication technology have made possible the construction of thermodynamically open, complex engineered systems: That is, systems in which not only energy but matter as well may be added, removed or changed throughout the system's lifetime. For such systems to perform useful work, their properties must not only be understood but optimized. Optimizing a system that may form a continuum of rigid and soft components—and in which this admixture may change over time—is extremely non-intuitive and underexplored. Thus, our overall scientific objective here was to imbue artificial, thermodynamically open systems with morphological and/or neurological plasticity and study the systems' resulting properties. Such a study enabled us to optimize these systems to perform useful work.

**Accomplishments:** To meet this objective, three scientific questions were addressed:

1. What is the adaptive benefit of morphological plasticity for an ATOS, compared to an equivalent system that adapts to its environment only through neurological plasticity? This question is being addressed by performing a series of A/B tests in which two sets of ATOS's are optimized: those that have access only to neurological plasticity (the control), and the other which has access to both morphological and neurological plasticity (the treatment).

2. How can an optimized ATOS capable of morphological plasticity be automatically and gradually reduced to a system of equivalent capability, but is thermodynamically closed? In all of the work in this contract, only theoretical models and simulated systems are being investigated. Until physical ATOS's are feasible, simulated, morphologically plastic ATOS's are being simulated and optimized such that they are gradually reduced to simulated, morphologically fixed systems, after which they may be manufactured as physical, morphologically fixed systems. However, this actual manufacture is beyond the scope of this project.

3. Are ATOS's more scalable than systems that lack morphological plasticity? If an ATOS is optimized to perform some useful work, and two parts of the system should grow differently in response to two different stimuli, work in theoretical evolutionary biology dictates that these two systems will gradually become independent of one another, thus yielding a modular system. Since modular systems are known to be more scalable than non-modular systems, it is here hypothesized that systems capable of "developmental modularity" can more easily be scaled up to greater complexity and competency.

Relevance to Army

# RPPR Final Report
as of 21-Jan-2020

Robots that can enter and reconnoiter spaces with arbitrarily sized- and shaped points of ingress are, and would be of great utility to Army and DoD. Soft robots exhibit much more facility to do so than traditional robots with rigid mechanical structures, as the former can deform in response to the apertures that must be traversed. However, soft robots are still in their infancy. Without exception, all physical extant soft robots are designed by hand and then manufactured. This project is aimed at automating the design of such robots to meet arbitrary performance metrics, such as their ability to deform while moving over or traversing through environmental structure. This automated design process is notoriously difficult; our work is shedding light on better ways to enable the automated design of such systems. Such technology may be useful for commercial and/or civilian use as well. There is a wide range of domains in which soft machines capable of squeezing through arbitrarily sized- and shaped points of ingress, from micromachines that can traverse blood vessels to rescue robots for searching and locating human survivors in disaster zones.

Accomplishments for Reporting Period

Below we summarize four accomplishments that were achieved through the project.

A formal definition of morphological modularity has been established, and incorporated into automated design methods for generating useful Artificial Thermodynamically Open Systems (ATOS's). In brief, morphological modularity allows an automated design method to improve the functioning of one physical component of an ATOS without disrupting the functioning of other components. Informally, morphological modularity is defined as follows: if an autonomous agent is able to actuate a subset of its actuators, and that action causes a localized repercussion detected by a small subset of its sensors, then that agent is morphologically modular. The more such feedback loops can be achieved by one agent, the more morphological modular it is.

We have found that in some cases, even a highly morphological modular ATOS is unable to perform the required task well. This is because the morphological modularity feedback loops do not support the desired behavior. Thus, we have formulated a second definition: ecological modularity. In this definition, the robot must be morphological modular with respect to relevant environmental features that are detected by the agent's sensors.

We have found that if a robot is morphologically modular and ecologically modular with respect to the task that it must perform, we can greatly reduce the number of training instances that the robot must be exposed to become robust to previously unseen combinations of environmental features. Intuitively, the idea is that an ATOS that is modular in this way, when encountering a new environment in which it must continue performing its task, does not see an unfamiliar environment, but rather an unfamiliar combination of familiar environmental local features. More specifically, non-modular machines require an exponentially increasing number of training instances, as the complexity of the environment in which it must perform increases. An appropriately modular ATOS, in theory, only requires a linear increase in training instances as its task environment complexifies.

Finally, we developed a novel automated design algorithm during this project that is efficient at automatically designing the mechanical structure, materials properties, and neural control policy of an ATOS. The way this method works is to use as its base an evolutionary algorithm. Whenever an ATOS in the evolving population spawns a child ATOS with different morphology from its own, selection pressure is decreased on the offspring of the child, giving evolution time to discover compensating control policies that exploit the potential morphological innovation in the child and its offspring.

**Training Opportunities:** Graduate Students Involved During Reporting Period

Sam Kriegman (Ph.D). Continuing studies at the University of Vermont.
Collin Cappelle (Ph.D). Research Engineer at Navisens.
Joshua Powers (Ph.D). Continuing studies at the University of Vermont.

**Results Dissemination:** 1. [Unreviewed arxiv pre-print:] Rosser, Kent, Jia Kok, Javaan Chahl, and Josh Bongard. "Sim2real gap is non-monotonic with robot complexity for morphology-in-the-loop flapping wing design." arXiv preprint arXiv:1910.13790 (2019).

2. [Journal publication:] Kriegman, Sam, Nick Cheney, and Josh Bongard. "How morphological development can guide evolution." Nature Scientific Reports 8, no. 1 (2018): 13934.

3. [Journal publication:] Cheney, Nick, Josh Bongard, Vytas SunSpiral, and Hod Lipson. "Scalable co-optimization of morphology and control in embodied machines." Journal of The Royal Society Interface 15(143) (2018): 20170937.

4. [Journal publication:] Corucci, Francesco, Nick Cheney, Francesco Giorgio-Serchi, Josh Bongard, and Cecilia Laschi. "Evolving soft locomotion in aquatic and terrestrial environments: effects of material properties and environmental transitions." Soft Robotics, 5(4) (2018): 475–495.

5. [Peer-reviewed conference publication:] S Kriegman, N Cheney, F Corucci, JC Bongard (2018). Interoceptive robustness through environment-mediated morphological development.
Proceedings of the Genetic and Evolutionary Computation (GECCO) Conference, pp. 109–116.

6. [Peer-reviewed conference publication:] Cappelle, Collin, and Josh Bongard. "Embodied Embeddings for Hyperneat." In Artificial Life Conference Proceedings, pp. 461-468. One Rogers Street, Cambridge, MA 02142-1209 USA journals-info@ mit. edu: MIT Press, 2018.

7. [Journal publication:] Bernatskiy, Anton, and Josh Bongard. "Evolving morphology automatically reformulates the problem of designing modular control." Adaptive Behavior 26, no. 2 (2018): 47-64.

8. [Peer-reviewed conference publication:] Bernatskiy, Anton, and Josh Bongard. "Choice of robot morphology can prohibit modular control and disrupt evolution." In Artificial Life Conference Proceedings 14, pp. 60-67. One Rogers Street, Cambridge, MA 02142-1209 USA journals-info@ mit. edu: MIT Press, 2017.

9. [Peer-reviewed conference publication:] Cappelle, Collin, Anton Bernatskiy, and Josh Bongard. "Reducing Training Environments in Evolutionary Robotics Through Ecological Modularity." In Conference on Biomimetic and Biohybrid Systems, pp. 95-106. Springer, Cham, 2017.

10. [Peer-reviewed conference publication:] Corucci, Francesco, Nick Cheney, Sam Kriegman, Josh Bongard, and Cecilia Laschi. "Evolutionary developmental soft robotics as a framework to study intelligence and adaptive behavior in animals and plants." Frontiers in Robotics and AI 4 (2017): 34.

11. [Peer-reviewed conference publication:] Kriegman, Sam, Collin Cappelle, Francesco Corucci, Anton Bernatskiy, Nick Cheney, and Josh C. Bongard. "Simulating the evolution of soft and rigid-body robots." In Proceedings of the Genetic and Evolutionary Computation Conference Companion, pp. 1117-1120. ACM, 2017.

12. [Peer-reviewed conference publication:] Cappelle, Collin, Anton Bernatskiy, and Josh C. Bongard. "Ecological modularity as a means to reduce necessary training environments in evolutionary robotics." In Proceedings of the Genetic and Evolutionary Computation Conference Companion, pp. 53-54. ACM, 2017.

13. [Peer-reviewed conference publication:] Kriegman, Sam, Nick Cheney, Francesco Corucci, and Josh C. Bongard. "A minimal developmental model can increase evolvability in soft robots." In Proceedings of the Genetic and Evolutionary Computation Conference, pp. 131-138. ACM, 2017.

14. [Journal publication:] Cappelle, Collin K., Anton Bernatskiy, Kenneth Livingston, Nicholas Livingston, and Josh Bongard. "Morphological modularity can enable the evolution of robot behavior to scale linearly with the number of environmental features." Frontiers in Robotics and AI 3 (2016): 59.

**RPPR Final Report**
as of 21-Jan-2020

**Honors and Awards:** Awards, Honors and Appointments

During the execution of this contract, PI Bongard was promoted to full professor of computer science.

The PI was also invested with the Cyril G. Veinott Chair, enacting a title change to Veinott Professor of Computer Science.

The PI was appointed director of the Vermont Advanced Computing Core (the VACC), the University of Vermont's high performance computing facility. Under his leadership, the VACC briefly enjoyed a position within the "Top500 Supercomputer Sites". During this time he was also awarded a $1M grant by the Sloan Foundation to develop the first in-browser elastic supercomputer, work on which is continuing. Much of the work completed during this contract was performed on the VACC.

**Protocol Activity Status:**

**Technology Transfer:** The work spawned the creation of several open source code repositories, new funded collaborations, and a formal collaboration with the Defense Science and Technology (DST) office of Australia.

1. https://ccappelle.github.io/pyrosim/ holds source code for creating ATOS's in a rigid-body simulator. It facilitates the creation of automated design methods that can be wrapped around the simulator kernel, and employed for automatically designing the body plans and control polices for ATOS's. It also facilitates the collection of sensor and motor data to automatically compute the amount of neural, morphological, and ecological modularity in a given ATOS.

2. https://github.com/skriegman/evosoro is a soft-bodied version of the above-mentioned code repository. It similarly facilitates the creation of soft ATOS's, which by definition have more abilities to alter their body plans to suit the demands of their task environment. To date the repository has been forked 20 times and starred 70 times, indicating the beginnings of its wide adoption by other groups.

3. Much of the work from this project forged a collaboration with Michael Levin, director of the Allen Discovery Center at Tufts University, and Sara Imari Walker of Arizona State University. Together we were awarded a DARPA contract under their Lifelong Learning Machines (L2M) program. We recently published our first manuscript from that project. The manuscript triggered a global media response, and in seven days, the source code repository associated with it (https://github.com/skriegman/reconfigurable_organisms) has garnered 135 forks and 491 stars.

4. A visiting member of the Defense Science and Technology (DST) of Australia, Kent Rosser, was involved in the later stages of this project. He has since returned to DST and is continuing a collaboration with us. In this collaboration, we are automatically designing the mechanical structure, material properties, and neural control policy for wing blades, to be used on a dragonfly-scale autonomous ornithopter.

5. Work from this project spawned a collaboration with Rebecca Kramer-Bottiglio, Yale School of Engineering and Applied Science. This collaboration has recently grown into a funded collaboration through the National Science Foundation Emerging Frontiers in Research Innovation (EFRI) program's Continuum, Compliant, and Configurable Soft Robotics Engineering (C3 SoRo) sub-program. In that project, we are adapting the simulation tools developed in this project to rapidly design robot skins, and rapidly-deployable, low cost soft robots built from macroscale, hollow voxels of Dragonskin silicone,.

6. Work from this project also contributed to a crowd-based robotics platform now continuously running on Twitch.tv. "Twitch Plays Robotics" (twitch.tv/twitchsplaysrobotics) allows non-experts to collaborative direct the direction of evolution for populations of autonomous machines, some of which are more neurally, morphologically, and/or ecological modular than others in the population. Users interact with the robots by issuing commands to them using natural language. Those natural language commands are translated into word embeddings using word2vec, and fed directly into the input layer of the machines' neural control policies. The platform has now been in continuous operation for 18 months, has attracted over 18K viewers and over 5000 participants.

7. Work from this project also informed the development of a proposal put to The Alfred P. Sloan Foundation, to develop the first in-browser, elastic supercomputer. The proposal was awarded for $1M in 2017, and work on this project continues to date.

**RPPR Final Report**
as of 21-Jan-2020

**PARTICIPANTS:**

**Participant Type:** PD/PI
**Participant:** Josh Bongard
**Person Months Worked:** 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Sam Kriegman
**Person Months Worked:** 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Collin Cappelle
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Joshua Powers
**Person Months Worked:** 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**CONFERENCE PAPERS:**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** ALife
Date Received: 25-Aug-2017 Conference Date: 01-Jul-2016 Date Published: 01-Jul-2016
Conference Location: Cancun, Mexico
**Paper Title:** Material properties affect evolution's ability to exploit morphological computation in growing soft-bodied creatures
**Authors:** Francesco Corucci, Nick Cheney, Hod Lipson, Cecilia Laschi, Josh Bongard
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** ALife
Date Received: 25-Aug-2017 Conference Date: 01-Jul-2016 Date Published: 01-Jul-2016
Conference Location: Cancun, Mexico
**Paper Title:** On the difficulty of co-optimizing morphology and control in evolved virtual creatures
**Authors:** Nick Cheney, Josh Bongard, Vytas SunSpiral, Hod Lipson
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** GECCO
Date Received: 25-Aug-2017 Conference Date: 01-Jul-2017 Date Published: 01-Jul-2017
Conference Location: Berlin, Germany
**Paper Title:** A minimal developmental model can increase evolvability in soft robots
**Authors:** Sam Kriegman, Nick Cheney, Francesco Corucci, Josh Bongard
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** Genetic and Evolutionary Computation COnference
Date Received: 31-Aug-2018 Conference Date: 22-Jul-2018 Date Published: 22-Jul-2018
Conference Location: Kyoto, Japan
**Paper Title:** Interoceptive robustness through environment-mediated morphological development
**Authors:** Sam Kriegman, Nick Cheney, Francesco Corucci, Josh C. Bongard
Acknowledged Federal Support: **Y**

**WEBSITES:**

**URL:** https://ccappelle.github.io/pyrosim/
Date Received: 25-Aug-2017
**Title:** The Pyrosim Simulator
**Description:** This site contains all documentation, code, and installation instructions for Pyrosim, the Python Robot Simulator.
**URL:** https://github.com/skriegman/evosoro
Date Received: 25-Aug-2017
**Title:** The EvoSoRo simulator
**Description:** This site contains all the documentation, code, and installation instructions for EvoSoRo, the Evolving Soft Robots simulator.

**Final Project Report - Grant #W911NF1610304**
**Reporting Period: November 2015 – November 2019**

# Morphological Plasticity for the Design, Control, and Deployment of Complex Engineering Systems


PI Josh Bongard
Department of Computer Science
University of Vermont, Burlington, VT, 05405


## Objective

Recent advances in materials science and fabrication technology have made possible the construction of thermodynamically open, complex engineered systems: That is, systems in which not only energy but matter as well may be added, removed or changed throughout the system's lifetime. For such systems to perform useful work, their properties must not only be understood but optimized. Optimizing a system that may form a continuum of rigid and soft components—and in which this admixture may change over time—is extremely non-intuitive and underexplored. Thus, our overall scientific objective here was to imbue artificial, thermodynamically open systems with morphological and/or neurological plasticity and study the systems' resulting properties. Such a study enabled us to optimize these systems to perform useful work.

## Approach

To meet this objective, three scientific questions were addressed:

1. What is the adaptive benefit of morphological plasticity for an ATOS, compared to an equivalent system that adapts to its environment only through neurological plasticity? This question is being addressed by performing a series of A/B tests in which two sets of ATOS's are optimized: those that have access only to neurological plasticity (the control), and the other which has access to both morphological and neurological plasticity (the treatment).

2. How can an optimized ATOS capable of morphological plasticity be automatically and gradually reduced to a system of equivalent capability, but is thermodynamically closed? In all of the work in this contract, only theoretical models and simulated systems are being investigated. Until physical ATOS's are feasible, simulated, morphologically plastic ATOS's are being simulated and optimized such that they are gradually reduced to simulated, morphologically fixed systems, after which they may be manufactured as physical, morphologically fixed systems. However, this actual manufacture is beyond the scope of this project.

3. Are ATOS's more scalable than systems that lack morphological plasticity? If an ATOS is optimized to perform some useful work, and two parts of the system should grow differently in response to two different stimuli, work in theoretical evolutionary biology dictates that these two systems will gradually become independent of one another, thus yielding a modular system.

Since modular systems are known to be more scalable than non-modular systems, it is here hypothesized that systems capable of “developmental modularity” can more easily be scaled up to greater complexity and competency.

**Relevance to Army**

Robots that can enter and reconnoiter spaces with arbitrarily sized- and shaped points of ingress are, and would be of great utility to Army and DoD. Soft robots exhibit much more facility to do so than traditional robots with rigid mechanical structures, as the former can deform in response to the apertures that must be traversed. However, soft robots are still in their infancy. Without exception, all physical extant soft robots are designed by hand and then manufactured. This project is aimed at automating the design of such robots to meet arbitrary performance metrics, such as their ability to deform while moving over or traversing through environmental structure. This automated design process is notoriously difficult; our work is shedding light on better ways to enable the automated design of such systems. Such technology may be useful for commercial and/or civilian use as well. There is a wide range of domains in which soft machines capable of squeezing through arbitrarily sized- and shaped points of ingress, from micromachines that can traverse blood vessels to rescue robots for searching and locating human survivors in disaster zones.

**Accomplishments for Reporting Period**

Below we summarize four accomplishments that were achieved through the project.

1. A formal definition of morphological modularity has been established, and incorporated into automated design methods for generating useful Artificial Thermodynamically Open Systems (ATOS’s). In brief, morphological modularity allows an automated design method to improve the functioning of one physical component of an ATOS without disrupting the functioning of other components. Informally, morphological modularity is defined as follows: if an autonomous agent is able to actuate a subset of its actuators, and that action causes a localized repercussion detected by a small subset of its sensors, then that agent is morphologically modular. The more such feedback loops can be achieved by one agent, the more morphological modular it is.

2. We have found that in some cases, even a highly morphological modular ATOS is unable to perform the required task well. This is because the morphological modularity feedback loops do not support the desired behavior. Thus, we have formulated a second definition: ecological modularity. In this definition, the robot must be morphological modular with respect to relevant environmental features that are detected by the agent’s sensors.

3. We have found that if a robot is morphologically modular and ecologically modular with respect to the task that it must perform, we can greatly reduce the number of training instances that the robot must be exposed to become robust to previously unseen combinations of environmental features. Intuitively, the idea is that an ATOS that is modular in this way, when encountering a new environment in which it must continue performing its task, does not see an unfamiliar environment, but rather an unfamiliar

combination of familiar environmental local features. More specifically, non-modular machines require an exponentially increasing number of training instances, as the complexity of the environment in which it must perform increases. An appropriately modular ATOS, in theory, only requires a linear increase in training instances as its task environment complexifies.

4. Finally, we developed a novel automated design algorithm during this project that is efficient at automatically designing the mechanical structure, materials properties, and neural control policy of an ATOS. The way this method works is to use as its base an evolutionary algorithm. Whenever an ATOS in the evolving population spawns a child ATOS with different morphology from its own, selection pressure is decreased on the offspring of the child, giving evolution time to discover compensating control policies that exploit the potential morphological innovation in the child and its offspring.

**Collaborations and Technology Transfer**

The work spawned the creation of several open source code repositories, new funded collaborations, and a formal collaboration with the Defense Science and Technology (DST) office of Australia.

1. https://ccappelle.github.io/pyrosim/ holds source code for creating ATOS's in a rigid-body simulator. It facilitates the creation of automated design methods that can be wrapped around the simulator kernel, and employed for automatically designing the body plans and control polices for ATOS's. It also facilitates the collection of sensor and motor data to automatically compute the amount of neural, morphological, and ecological modularity in a given ATOS.

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[1] Kriegman, Sam, Douglas Blackiston, Michael Levin, and Josh Bongard. "A scalable pipeline for designing reconfigurable organisms." Proceedings of the National Academy of Sciences (2020).

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6. Work from this project also contributed to a crowd-based robotics platform now continuously running on Twitch.tv. "Twitch Plays Robotics" (twitch.tv/twitchsplaysrobotics) allows non-experts to collaborative direct the direction of evolution for populations of autonomous machines, some of which are more neurally, morphologically, and/or ecological modular than others in the population. Users interact with the robots by issuing commands to them using natural language. Those natural language commands are translated into word embeddings using word2vec, and fed directly into the input layer of the machines' neural control policies. The platform has now been in continuous operation for 18 months, has attracted over 18K viewers and over 5000 participants.

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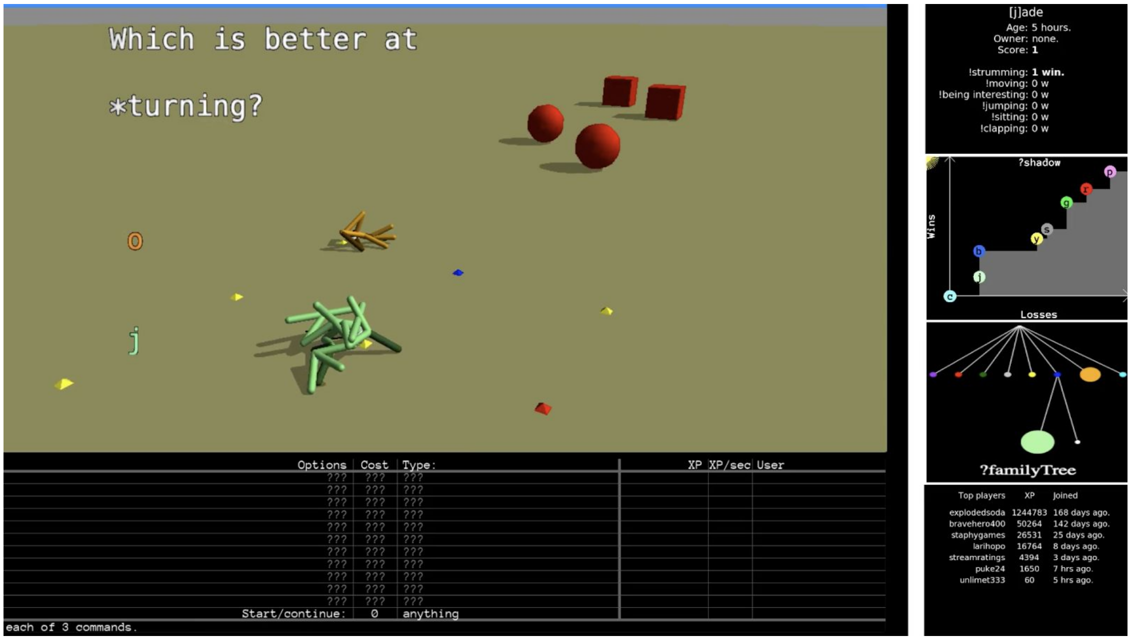
[2] Kriegman, Sam, Amir Mohammadi Nasab, Dylan Shah, Hannah Steele, Gabrielle Branin, Michael Levin, Josh Bongard, and Rebecca Kramer-Bottiglio. "Scalable sim-to-real transfer of soft robot designs." ***arXiv*** preprint arXiv:1911.10290 (2019).

[3] Kriegman, Sam, Stephanie Walker, Dylan Shah, Michael Levin, Rebecca Kramer-Bottiglio, and Josh Bongard. "Automated shapeshifting for function recovery in damaged robots." ***Proceedings of the Robotics: Science and Systems (RSS) Conference*** (2019).




A snapshot from the Twitch Plays Robotics platform. At this point, users may indicate whether the [o]range or the [j]ade robot is better at obeying the command ‘turning’.

**Resulting Publications During Reporting Period**


1. [Unreviewed arxiv pre-print:] Rosser, Kent, Jia Kok, Javaan Chahl, and Josh Bongard. "Sim2real gap is non-monotonic with robot complexity for morphology-in-the-loop flapping wing design." ***arXiv*** preprint arXiv:1910.13790 (2019).

2. [Journal publication:] Kriegman, Sam, Nick Cheney, and Josh Bongard. "How morphological development can guide evolution." ***Nature Scientific Reports*** 8, no. 1 (2018): 13934.

3. [Journal publication:] Cheney, Nick, Josh Bongard, Vytas SunSpiral, and Hod Lipson. "Scalable co-optimization of morphology and control in embodied machines." ***Journal of The Royal Society Interface*** 15(143) (2018): 20170937.

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109–116.

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7. [Journal publication:] Bernatskiy, Anton, and Josh Bongard. "Evolving morphology automatically reformulates the problem of designing modular control." ***Adaptive Behavior*** 26, no. 2 (2018): 47-64.

8. [Peer-reviewed conference publication:] Bernatskiy, Anton, and Josh Bongard. "Choice of robot morphology can prohibit modular control and disrupt evolution." In ***Artificial Life Conference Proceedings*** 14, pp. 60-67. One Rogers Street, Cambridge, MA 02142-1209 USA journals-info@ mit. edu: MIT Press, 2017.

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13. [Peer-reviewed conference publication:] Kriegman, Sam, Nick Cheney, Francesco Corucci, and Josh C. Bongard. "A minimal developmental model can increase evolvability in soft robots." In ***Proceedings of the Genetic and Evolutionary Computation Conference***, pp. 131-138. ACM, 2017.

14. [Journal publication:] Cappelle, Collin K., Anton Bernatskiy, Kenneth Livingston, Nicholas Livingston, and Josh Bongard. "Morphological modularity can enable the evolution of robot behavior to scale linearly with the number of environmental features." ***Frontiers in Robotics and AI*** 3 (2016): 59.

**Graduate Students Involved During Reporting Period**

- Sam Kriegman (Ph.D). Continuing studies at the University of Vermont.
- Collin Cappelle (Ph.D). Research Engineer at Navisens.
- Joshua Powers (Ph.D). Continuing studies at the University of Vermont.

**Awards, Honors and Appointments**

- During the execution of this contract, PI Bongard was promoted to full professor of computer science.
- The PI was also invested with the Cyril G. Veinott Chair, enacting a title change to Veinott Professor of Computer Science.
- The PI was appointed director of the Vermont Advanced Computing Core (the VACC), the University of Vermont's high performance computing facility. Under his leadership, the VACC briefly enjoyed a position within the "Top500 Supercomputer Sites". During this time he was also awarded a $1M grant by the Sloan Foundation to develop the first in-browser elastic supercomputer, work on which is continuing. Much of the work completed during this contract was performed on the VACC.