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A SYSTEM OF MESOSCALE BIOMIMETIC ROBOSWIMMERS FOR UNDERWATER EXPLORATION AND SEARCH OF LIFE ON EUROPA

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Notice

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1. EXECUTIVE SUMMARY

Physical Sciences Inc. (PSI) in collaboration with the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) proposed in Phase I a revolutionary approach for the exploration of oceans and the search for marine ecosystems on Jupiter's moon Europa. Our concept involved biomimetic roboswimmers that collectively sensed the ice, ocean, and sea floor environment and measured its physio-chemical properties characterizing the presence of life. From the beginning we anticipated that the system would utilize technologies that would mature in the next two to three decades where the robots would incorporate microminiaturized optical and tactile sensors, acoustic communication, locomotion using microactuators, ultrafast processors, and knowledge-based/synthetic intelligence for control and for individual and collaborative decision making.

Our two premises are: the efficient exploration of the Europan ocean will require teams of small, cooperating roboswimmers; and these roboswimmers should be biomimetic, in their form (physical shape) and function (modes of operation) and also in the manner in which they are designed (evolved synthetically using Natural Selection).

In Phase I we collected and analyzed available data concerning Europa and its possible liquid ocean environment. Theories about Europa's ocean and its characteristics are many and varied. Some believe that no liquid ocean exists (the ice crust extends from the surface to the rocky core) while other believe that there may be an extensive ocean covered by only a few kilometers of ice. For those that do believe an ocean exists on Europa, many do not agree on how the ocean remains liquid or what its characteristics are. Ultimately, we are led to the conclusion that our system design must be quite flexible and able to function given that our assumptions about Europa may be far from correct.

Probably the best example of a design process that creates systems which are robust, adaptable, and efficient is Nature. Natural Selection allows a sub-optimal solution population to move toward optimality. We have chosen throughout the Phase I effort to "look to Nature" to aid us in developing our system. In Phase I we developed two Synthetic Evolutionary (SE) processes to, design the roboswimmers, and to tune a basic cooperative exploration architecture. The SE uses a Genetic Algorithm (GA) to evolve a solution population (by adjusting their defining parameters) toward the optimum. We found that this methodology works very well.

The first SE took basic roboswimmer designs (fish, eels, seahorses, crabs, and worms) and adjusted their design to optimize their performance. In some cases hybrid designs were selected which utilized characteristics of several basic roboswimmer types (a fish with crab-like legs). The second SE optimized a basic swarm exploration cooperative behavior. Here the architecture was tuned through repeated evolutionary steps until the system efficiency to explore given regions of the ocean was maximized.

In identifying the required infrastructure for Europa exploration we found several key components that must be examined in great detail. Two of the most important are: 1) techniques to communicate high-bandwidth data through ice, and 2) systems that will provide precise under-water navigation. Not surprisingly there are many organizations currently trying to develop these systems. Over the past decade there has been a resurgence in underwater exploration here on Earth. The systems necessary to perform these explorations continue to increase in performance, but, it is nearly universally held that ultra low power and highly compact underwater communication and navigation systems are the two areas where a significant advance in the state-of-the-art is sorely needed.

In Phase I we have come a long way in our understanding of the system architecture and roboswimmer designs that will be required several decades from now when NASA sends the roboswimmers to Europa in search of life. The methodology that we are developing, the Synthetic Evolution process, will certainly play an important role in designing and describing this system and in identifying technology areas that NASA and others will need to develop before this mission can be realized. The road will not be easy, but when we finally venture to this far-off world and if we do indeed discover life there, nothing will ever be the same!

2. INTRODUCTION

Our current understanding of Europa suggests that a liquid ocean is probably present under several kilometers of ice and that this ocean is probably quite deep (tens to a perhaps a hundred kilometers). Based largely on the type of life found here on Earth we suppose that Europan life will congregate near "interfaces." Interfaces of interest are those where some physical or chemical property of the environment changes dramatically – an example being the rapid increase in temperature and chemical concentration near a hydrothermal vent. While the mechanisms leading to these interfaces may be different (terrestrial hydrothermal vents are the result of volcanism while those on Europa will most likely be the result of tidal kneading of the core), the environments that they support will probably have similar characteristics.

Given that we think Europan life will inhabit areas with characteristics similar to those that exist on Earth, we have chosen to **look to nature** to aid us in developing the roboswimmer's systems architecture. Specifically, our preliminary designs will mimic terrestrial organisms (e.g., fish, eels, crabs, etc.) and we will "evolve" these design using computational techniques patterned after Natural Selection.

A key component of the design process is understanding, using the best available data and theories, Europa's ocean environment. Much of this will depend on the state of the art of our knowledge of the satellite’s geophysic properties gained from previous missions. For example, detailed mapping of Europa’s surface and global measurements of the thickness of ice layers will be available in about a decade based on the missions currently being considered by NASA. Some data on seismic activity may also become available during that time. Based on this information, potential sites of interest for exploration can be identified.

A major Phase I effort was to identify and develop designs for appropriate roboswimmers that could efficiently explore the Europan ocean. It was anticipated that a heterogeneous group, or team, of roboswimmers would be required to allow for an efficient long-term, wide-area exploration. Two particular vehicles designs were selected, a robo-eel and a robo-seahorse. These were chosen based our current understanding of Europa.

A second significant effort of Phase I was to identify roboswimmer interaction architectures that would allow them to efficiently survey Europa’s ocean. This requires that the vehicles both act as individuals and as team members. Individually, the vehicles must perform functions that bring them closer to meeting mission goals (e.g., sensing the environment, seek out and investigate interesting phenomena). As team members the vehicles also communicate with their comrades providing them with their position, what they have sensed, etc. By working together we believed that the roboswimmer system will achieve an optimize survey strategy and will be capable of performing functions impossible by a single vehicle such as a hydrobot. Finally we proposed to identify the infrastructures necessary for the development of a system of intelligent, biomimetic swimmers that could make measurements, which will characterize the existence of primitive life and the ice/ocean environment on Europa. Of particular importance is the technique that will/could be used to communicate data though potentially very thick ice. Here we utilized the expertise of the U. S. Army Cold Regions Research Laboratory (CRREL).

In the remainder of this report we will document our efforts in Phase I of this program. We will show that we have met all of the technical objectives laid our in the Phase I and in many cases have gone considerably beyond what was proposed. In many cases we have moved from the specific to the more general - developing methodologies and processes that will enable us to not only develop roboswimmer teams for the exploration of Europa but which can be used more widely for the optimization of many large complex system designs.

3. PHASE I EFFORT

3.1 Exploring the Europan Ocean

3.1.1 Introduction

In order to investigate the presence of life on Europa in Phase I we have analyzed the environment and the conditions in which living organisms could have formed. We also have determined some of the most relevant measurements that will provide evidence for present, past, or future life.

3.1.1.1 Europa's Geological Settings: Current Models and Theories

Recent interdisciplinary investigations of Europa have yielded models that explain the Jovian moon geology through tidal-tectonic processes requiring interaction with an ocean under a very thin ice crust of few kilometers thickness [Greenberg et al., 2000]. Tidal driving of strike-slip faulting indicates that cracks penetrate into a fluid layer, which is possible only with thin ice outer layer. This theory contrasts the early interpretations of the Galileo images, which theorized an icy crust about 10 km thick [Pappalardo et al., 1998], [Greeley et al., 1998]. On the basis of terrestrial analogs, the early interpretations invoked either convection in a viscous solid-state layer or volcanism as dominant geological processes. They implied a global structure in which an ocean (if present) would be isolated and disconnected from the surface by a thick crust. While the possible presence of an ocean had long motivated considerations of habitability, the thick-crust model severely constrained conditions under which life might form and survive.

If the thin ice crust model correctly represents the conditions on Europa, it describes an environment in which life could form, survive, flourish and evolve. Due to tides, liquid water regularly bathes ice crustal cracks and surfaces with heat and whatever nutrients are included in the oceanic chemistry, creating a variety of habitable environments (Figure 1). As the diurnal tides open cracks, water flows to the float line, where it boils in the vacuum and freezes owing to the cold. As the walls of the crack close a mix of crushed ice, slush and water is squeezed to the surface in between plates and is deposited on both sides of the crack. Given the frequency of the process, ridges of typical size on Europa (100 m high and 1 km wide) can form relatively quickly, in about 20,000 years. These effects operate and change over a broad range of time scales from a periodic tidal bathing of surface cracks on a daily basis, to resurfacing and global reorientation over 10^5- 10^7years, through orbital evolution that changes the fundamental conditions over ~10^8years or longer.

Because none of the two main theories - thin and thick ice crust - have yet been absolutely disproved or confirmed by actual measurements, we will design our exploration infrastructure such that we can address a range of possible ice conditions. Moreover, there is evidence that indicates that the icy crust of Europa is not uniform in thickness.

Given the current theories on Europa's geology, in Phase I we have hypothesized what sources of energy can support life on Europa (Section 3.1.1.2) and where the roboswimmers should look for life (Section 3.1.1.3).

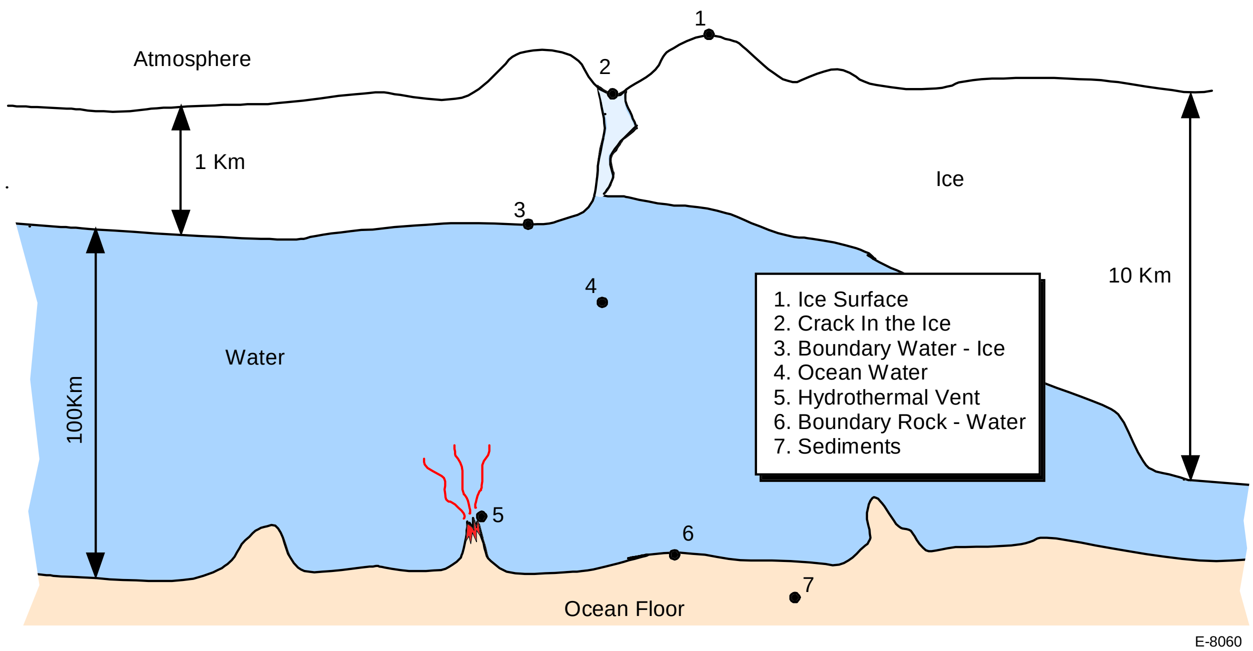

Figure 1. Possible scenarios of Europa's under-ice ocean.

3.1.1.2 Potential Sources of Energy for Life on Europa

In addressing the availability of energy to support the earliest life, specific energy sources include geochemical energy available through either hydrothermal systems, weathering of minerals, and/or tidal effects.

Hydrothermal Systems

Water that circulates through hot volcanic rock within planet's deep interior is heated to higher temperatures (e.g., > 500 C) and reacts chemically with the rock. At these high temperatures and with the oxidation state controlled by the reactions between the water and rock, carbon is stable in its oxidized form as CO_2. As the water returns to the ocean and mixes with cooler water, more-reduced forms of C will be stable. Kinetic barriers inhibit the reduction all the way to CH_4, however, and intermediate oxidation states are, for example, organic molecules. The fact that organic synthesis is energetically favored means that organisms can also construct organic compound and otherwise carry out metabolism in such an environment without additional source of energy [Shock, 1998].

However, some authors believe that Europa is likely to have had less volcanism throughout time than our Moon [Jakosky et al., 1998]. Hydrothermal systems would have been even less important than on Mars, but chemical weathering of the minerals within the rocky component at the rock-boundary and tidal effects might have provided most of the energy necessary for life to form and grow on that planet. Others believe [McCollom, 1999] that heating of the satellite's interior by friction due to tidal forces and the decay of radioactive elements may well be sufficient to generate volcanism at the Europa ocean floor, presenting the possibility that Europa may posses submarine hydrothermal systems similar to those observed on the terrestrial seafloor. The potential for the development of biological communities on Europa depends on the availability of energy sources for primary biomass production. Methanogenesis is a source of such an energy. In order for methanogenesis to be a potential source of metabolic energy for either past or present biological activities on Europa, two criteria must be satisfied. First, there must be sources for both CO_2 and H_2. Second, these compounds must be present in an environment where the reaction is energetically favorable. The calculation presented in McCollom, 1999, indicate that both of these criteria can be met in Europan hydrothermal systems. Even if Europan ocean is highly reducing with methane replacing bicarbonate as the primary form of carbon, oxidation of methane through fluid-rock interactions at high temperatures can supply a source of CO_2. In addition, fluid-rock interactions can provide sources of H_2 for either a reduced or oxidized ocean. Furthermore, methanogenesis is energetically favored during mixing of hydrothermal fluid with seawater, whether seawater is oxidizing or reducing.

It is apparent that the amount of biomass that could be supported by methanogenesis on Europa is small compared with photosynthetic biomass on Earth, or even compared to the amount of biomass generated by chemotrophs at terrestrial mid-ocean ridges. Nevertheless, the relatively small amount of energy available from methanogenesis in individual vent systems on Earth can and does support populations of autotrophic methanogens. The amount of energy available for methanogens in individual hydrothermal systems on Europa may well be equal to, or greater than, the energy available in analogous terrestrial systems, suggesting that Europan systems would also be capable of supporting biomass production by methanogenesis. Even though the global potential for biomass production by this mechanism is not large, it is the potential presence of life and not its abundance that is the more significant issue.

Weathering Obtained From Water-Rock Reactions

At lower temperatures and away from active volcanism, weathering of primary igneous minerals (such as olivine or pyroxene in basalt) can occur by reaction with H_2O. For example, the oxidation of ferrous iron that occurs along with the formation of H_2 from H_2O releases energy that may be utilized by organisms. In this case the oxidation of olivine provides the energy for reduction of water to H_2, and the reductive power of H_2 can support production of biomass.

An other possible reaction is the oxidation of ferrosillite in pyroxene to hematite and quartz. Typically basalt might consist of 50% pyroxene, with the Fe component being only a fraction of that. Complete weathering of a column of basalt about 10 m thick would provide sufficient energy to produce 1 g cm^{-2} biota.

One more possible reaction is the oxidation of magnetite to hematite. This reaction would provide much more energy than the previous two reactions, and there is less magnetite that ferrosillite in basalt.

Tidal Energy From Interactions With Jupiter, Io and Ganymede

Tides and orbits are intimately related, and they drive heat, rotation and stress that are the key to habitable environments on Europa. The eccentricity of the orbit causes regular variations in the height and orientation of tides raised on Europa by Jupiter. The time scale for these variations is the orbital period, ~ 3.5 days for Europa. Tides cause long-term evolution of the satellite's orbits, so that over $\sim 10^8 - 10^9$ years, the orbital resonance configuration can undergo major changes. Thus there is a strong mutual feedback loop between orbital evolution and the tidal processes on the satellite. Tidal working due to orbital eccentricity generates heat due to frictional dissipation. There might be enough heating to maintain a liquid water ocean within the layer of H_2O that constitutes the outer 100 to 150 km of Europa.

Another effect of tides that plays a key role on Europa is the rotational torque. For a satellite in a circular orbit and with a substantial permanent mass asymmetry, rotation would be expected to be locked into a synchronous state, with one hemisphere always facing the planet. The length of the day would be the same as the orbital period. Because Europa is not in a circular orbit and does not necessarily have a permanent mass asymmetry [Greenberg et al., 1984], the tidal torque can drive it to a rotation rate slightly faster than asynchronous. Voyager 2 and Galileo (17 years later) observed the orientation of Europa. The non-synchronous component of rotation observed is so slow that a day on Europa is indistinguishable from the 3.5 day orbital period, but the hemisphere facing Jupiter could turn away from the planet in as little as 6000 years.

Evidence that there has been substantial rotation even during the most recent small fraction of the age of Europa surface comes from the interpretation of three types of tectonic features that have been formed by tidal stresses:

- Global or regional lineaments that display crosscutting sequences
- Distribution of strike-slip faulting by the tidal-walking process
- Character and distribution of arcuate crack features (cycloidal lineaments).

3.1.1.3 Potential Habitats: Where to Look?

From the observations conducted by Galileo and the theories developed from the images, we can hypothesize that there is an intimate interaction between the liquid ocean and the cracked surface of the ice on Europa. A variety of environmental niches can be available with the potential for providing fairly confortable, diverse, and changing conditions for life.

Fuel and oxidants are continually produced at, and delivered to, the surface of Europa by non-equilibrium processes such as meteorite impacts, photolysis by solar ultraviolet radiation and radiolysis by changed particles. Significant reservoirs of oxygen have been spectrally detected on the surface in the form of H_2O_2, while molecular oxygen and ozone are inferred on the basis of Europa's oxygen atmosphere and the detection of these compounds on other icy satellites such as Ganymede. Impact of cometary bodies should provide also a source of organic materials and other fuels at the surface. In addition, significant quantities of sulfur and other materials may be continually ejected and transported from Europa. Such substances are being given consideration as potentially important biogenic materials.

Sub-Oceanic Volcanic Sites

If a sufficient portion of the tidal heat is dissipated within the rocky mantle, volcanism at the base of the ocean is possible. Thus, one type of habitable environment may be analogous to terrestrial sub-oceanic volcanic sites, with both heat and biologically useful substances being actively delivered. While full-scale volcanism at the silicate mantle on Europa is not considered a realistic hypothesis, however, significant hydrothermal activity is quite plausible.

Boundaries Between Rock and Water

At the interface between the ocean and the underneath rocks chemical weathering of minerals is probably a valuable energy source that create a warmer and favorable environment for life to grow.

Cracks in the Ice

Cracks are probably caused by tidal stresses, bathing their interior with warm water and pumping slush to the surface. Working of the cracks may cause much of the tidal heat to be dissipated at these locations. Within a give crack, any organism would be expected to occupy a range of depths, with individuals either moving with the flow or attaching themselves to the crack wall.

However organisms could not survive very near the surface (few centimeters depth), where bombardment by energetic charged particles in the Jovian magnetosphere would disrupt organic molecules. Organisms in a crack would probably need to stay much further down than few centimeters to survive.

3.1.1.4 Measurements to Detect Life on Europa

In Phase I we have determined some of the most important set of measurements that the roboswimmers will need to perform to find life on Europa (Section 3.1.1.4) and we have defined some sensor technologies that will need to be developed (Section 3.1.1.5).

Answers to Fundamental Questions

Confirm Presence of Liquid Water Underneath the Ice Crust

Presence of liquid water is the first requirement for the formation, growth and survival of life. There is evidence that underneath the icy crust lays liquid oceanic water. However, we need measurements that actually validate the presence of water and ice.

Determine the Ice Crust Thickness (Local and Average)

The thickness of the ice crust on Europa is a very crucial parameter that might play a key role in the presence of life. Due to tides, liquid water regularly reaches the ice cracks and surfaces with heat and the nutrients due to the oceanic chemistry, creating a possibility for habitable environments. A thick ice crust would isolate the ocean from the surface and would make it difficult for life to form and grow.

Analyze the Composition of the Dark-Brown Deposits on the Sides of the Ridges

Many scientists have speculated that, because the dark deposits on the sides of ridges derive from internal constituent that emerge from the ocean, analyzing surface samples on the sides of the ridges, might provide important information about the ocean composition and possible life signs (fossils).

Search for Favorable Habitats (Environmental Measurements)

In Phase I we have identified some of the most relevant measurements that would provide crucial information about environmental conditions favorable for life.

Measure Temperature T(s,t) and Temperature Gradients

One of the key measurements to be performed on Europa is the determination of the temperature as function of location and time. The knowledge of temperature and temperature gradients will answer many questions about the geology of Europa, and will provide important clues on where to look for life.

The activities and growth of microorganisms are greatly affected by the chemical and physical conditions of their environment. Temperature is one of the most important environmental factors influencing the growth and survival of organisms. On Europa we might look for organisms that are typical of extreme cold environments, called Psychrophiles. Because the cytoplasmatic membrane must be in a liquid state for proper functioning, Psychrophiles have membrane lipids rich in unsaturated fatty acids, which make the membranes fluid and functional at low temperature. However we cannot exclude that hydrothermal vents on the bottom of the ocean could have created Thermophiles, organisms that grow at high temperature.

Measure Pressure P(s,t)

Measurements of the underwater pressure will allow us to understand the thermodynamic processes of the water (relative water column in relation to depth). Pressure information will also be precious for understanding the solubility of the gases and the effects of different phases on the Europan ocean.

Measure Water Density

The density of a solution provides important information about the presence of dissolved salts. It helps to understand heat propagation, heat profile with depth. Moreover, tidal motion can be extrapolated from the water density and its gradients.

Acquire Water Kinematics

Motility of the water would allow nutrients and energy transfer, necessary for life. Because of the tidal effects there might be a considerable underwater movement. However, a too strong oceanic current might decrease the chances of life to have formed in certain locations on Europa.

Conductivity

The information about conductivity of the ocean will provide us with important information about the ion content of water.

Determine pH, Dissolved Gases and Inorganic Salts

It is possible at least spatially locating life phenomena by following pH gradients in aqueous environment (which is either appearance of waste or disappearance of nutrients). This might be difficult in an environment as well stirred as the Europan oceans probably are. Environmental parameters that help to understand life (i.e., possible chemistry and energy sources) can be collected with *ion selective electrodes* (redox and membrane-based). These are available for the measurement of not only pH, but also a variety of dissolved gases such as oxygen, ammonia, carbon dioxide, and also methane (O_2, NH_3, CO_2) and inorganic salts (NO_3, F, Ca_2, K, Br, I, Cl, Na, etc).

Search for Life (Biological Measurements)

The main distinction between exploring life on Europa and the previous attempts on Mars (with the Viking mission) is the presence of liquid water. In aqueous solutions it is possible to perform many assays crucial to determine weather life exists. In dry environments the number of feasible tests are very limited.

In Phase I we have identified the following two crucial experiments that would provide evidence of life on Europa:

Labeled Release Experiment

Organic materials can be present even in absence of life. In order to reliably detect life forms it is possible to measure their metabolic products. In other words we can follow the effects of living processes in the aqueous environment on Europa by monitoring the effects of uptake and waste. The experiment can be carried on by taking a sample of Europa's ocean water and expose it (inside the robot-swimmer) to organic nutrients that have been radioactively labeled. If microorganisms are present they will use these compounds as an energy source. We can detect the tagged radioactive metabolized gases using a radioactive detector. Particular attention must be paid to prevent Europa's environment from the risk of contamination during the mission.

Detection of DNA and RNA

Detecting and analyzing microbial cells present in environmental samples of Europa - such as Europan seawater - requires sensitive methods to quantify DNA yields prior to species identification analysis. The best and simplest methods employ dyes or stains that become fluorescent only when bound to nucleic acids. An example of these dyes is unsymmetrical cyanine nucleic acid stains. They have negligible intrinsic fluorescence, but large fluorescence yields when bound to DNA and/or RNA. One of the greatest advantages provided by sensitive, fluorogenic nucleic acid stain-dyes that become fluorescent only upon binding nucleic acids is that they provide one-step method with single, short incubation times. These methods are readily automatable and well suited to high-throughput analysis.

An example of fluorogenic nucleic acid stain is *Ethidium Bromide* that provides sensitivity for a double-stranded DNA detection considerably greater than that provided by ultraviolet absorbency measurements. It also exhibits significant fluorescence upon binding RNA and single-stranded DNA.

The methods used to date to detect DNA and RNA cannot be directly used for exploration of Europa: they require to release gels or powders (*unsymmetrical cyanine nucleic acid stains*) in a sample of liquid that will become fluorescent if containing DNA or RNA. We do not intend to release any material or chemical in the Europan ocean to avoid the risk of polluting the Jovian satellite and our own measurements.

We envision that in the future it will be possible to attach these powders to polymeric porous surfaces (with covalent bonds, so that would not be carried out in the environment). This solution will allow the dyes not to be released in the Europan ocean we want to analyze but be continuously flushed with water that would go in and out freely, probably just due to water kinematics or to robot-swimmer movements. When DNA (or RNA) get in contact with the dyes, it will bound with them. A large fluorescence will be yielded as sign of the captured DNA. In this way the water flowing through will still be clean water, but without the DNA (RNA) (which will be captured by the dye), that is the evidence we are searching for. Of course the development of this hypothetical combination of biotechnology and polymer sciences is not a near term objective, but might be the topic of significant researches for the next decades.

3.1.1.5 Need for Innovative Sensor Technology

All the measurements identified in this proposal require new sensor design and innovative technology. It is necessary to:

- Miniaturize and optimize the sensors size and weight
- Minimize power consumption
- Build sensors resistant to elevated pressures for use at great ocean depths
- Extend the range of measurable values that can be monitored.

Semiconductor manufacturing has allowed the computational power of a room-sized, multimillion-dollar supercomputer of the 1060's to fit neatly on everyone's desk in the 1990's. We believe that in the same way over the next 20 or 30 years the set of sensors we need for the measurements on Europa will be reality.

For instance, inertial sensors such as accelerometers and gyroscopes, are necessary for guiding and controlling the robot swimmers. Inertial sensors will be developed in the future using new technologies based on the silicon micromachine revolution. Micromachining is based upon using modern semiconductor fabrication techniques to fashion mechanical structures. This provides orders of magnitude improvement in cost, size, and power consumption, environmental survival, and lifetime as compared to conventional sensor technology.

Microfabrication techniques based on integrated circuit technology is spreading rapidly to different fields [Karube, 1993], including biology and chemistry. Micromachined chemical analysis systems, for instance, have shown many advantages over conventional ones, including fast response times, low consumption of reagents, and miniaturized sensors. These are all properties crucial for our purposes, which is carrying a complex set of sensors in dedicated small biomimetic robot-swimmers.

A field in considerable growth is also surface polymer sensors. We envision in the future it will be possible to develop robot-swimmers whose skin is polymeric and acts as a sensory aid. The robots could also be equipped with sorts of tentacles as tactile organs and as actuators.

Miniaturized diode-lasers could be developed for chemical analysis. The purpose would be to irradiate the sample of water that flows through and use optical spectroscopy for the detection of chemicals.

3.2 Roboswimmer Design

3.2.1 Introduction

In following our "look to Nature" approach, we chose a process known as Synthetic Evolution to develop the roboswimmer's designs. Synthetic Evolution uses a Genetic Algorithm (GA) to move from an initial set of sub-optimum "individuals" (independent solutions) to an optimum set.

The process is begun by first creating a virtual environment with properties similar to what we believe will exist on Europa. The environment is then seeded with Interesting Regions. Interesting Regions are simply well defined areas containing measurable physical or chemical properties. We then identified a basic set of roboswimmer types based on terrestrial models (fish, eels, seahorses, crabs, and worms). Each roboswimmer types was parameterized so that it could be numerically manipulated within the GA. The performance of each population was assessed using a fitness measure. Here we chose as the fitness measure the count of the number of Interesting Regions a roboswimmer encounters in a given time. The more regions detected, the better its fitness. Roboswimmers with high fitness are preferentially selected for reproduction to create the next generation.

3.2.2 Virtual Environment

We chose a 2-D virtual environment (vertical slice of Europan ocean) with distinct layers: near ice, water column, near bottom, bottom, near sediments, and far sediments (Figure 2). Within each layer we assume that the bulk characteristics are homogeneous – e.g., density and chemical concentrations are constant, etc. A 2-D environment was chosen (instead of a 3 or 4-D) to simplify the development of the simulation. We believe that the process we are developing will work as well in more realistic environments.

Within the overall framework of the virtual environment the depth of each layer can be adjusted as shown in Figure 3. This allows us to explore the sensitivity of the process results with this geometric property. As our understanding of Europa increases, these relative depths can be set to more representative values to fine-tune the evolved roboswimmer's form and function.

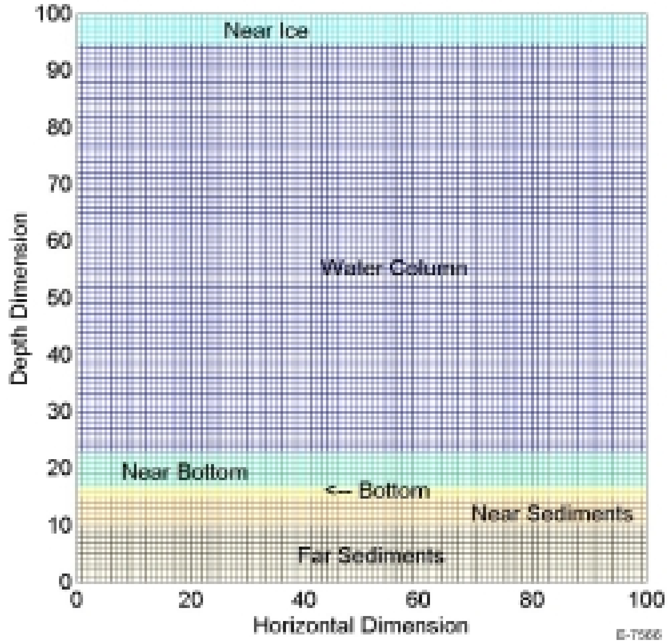

Figure 2. 2-D virtual environment used by simulation.

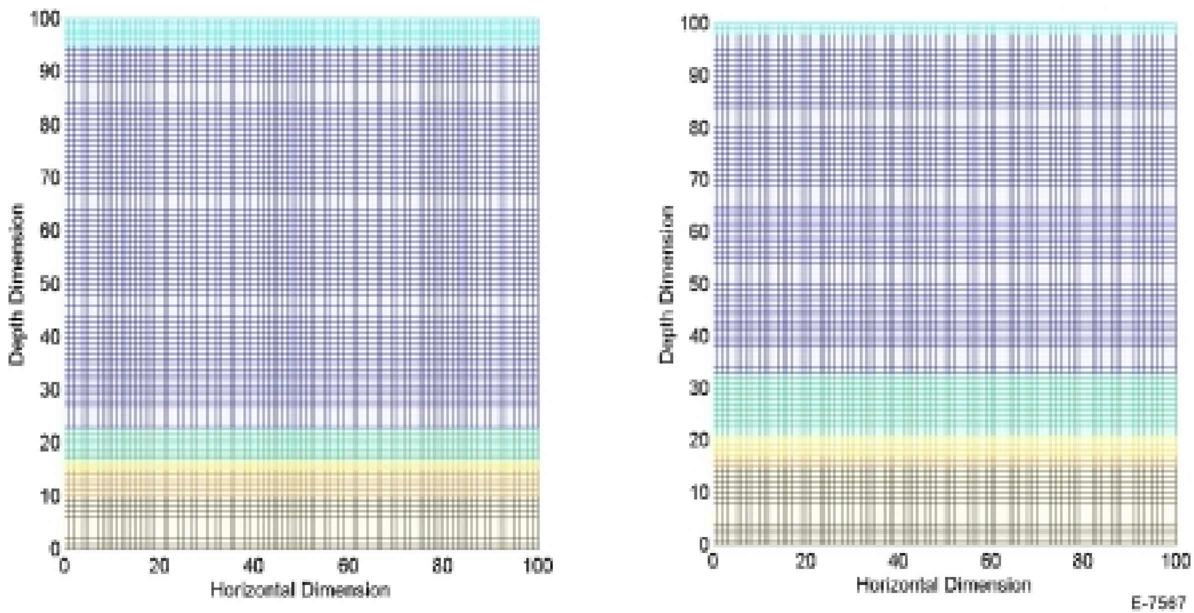

Figure 3. Two environments with different layer depths.

3.2.3 Interesting Regions

Within each environmental layer are placed regions of interesting physical or chemical properties (Interesting Regions). Without loss of generality these regions are defined to be square with enclosed areas randomly distributed between defined lower and upper limits. Once placed the regions remain fixed both in location and size.

Each Interesting Region is characterized by a set of features. Features represent observable characteristics such as temperature gradients, chemical composition, or life species. At the start of a simulation the total number of distinct characteristics is defined with each one given a different label (e.g., A, B, C, etc.). Each interesting region is given a sub-set of the total number of characteristics ranging in number from one characteristic to the total number of defined characteristics.

Figure 4 (left) shows one environment with 10 randomly placed Interesting Regions. In Figure 4 (right) we have zoomed in on one region to show how it is displayed to the user. Features are coded as different colors – in this case light green, orange, light blue, yellow, and blue. While the features are displayed as distinct patches, the simulation actually treats them as homogeneous throughout the Interesting Region.

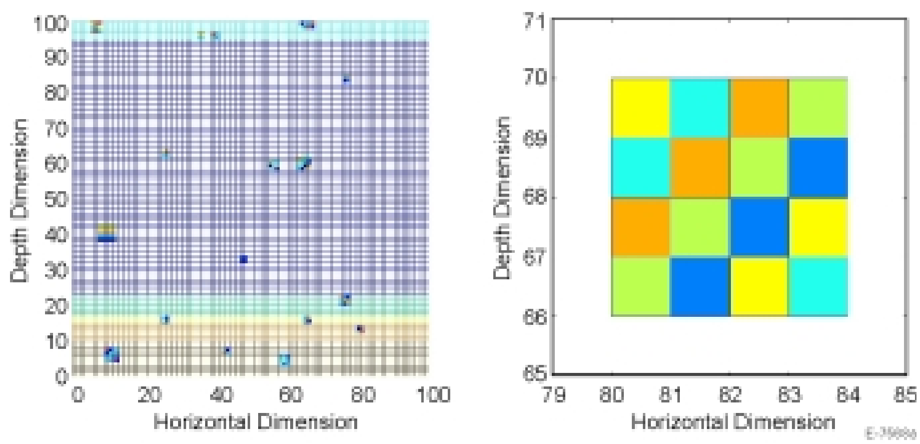

Figure 4. Virtual environment showing distribution of Interesting Regions. The different colors in these regions indicate the different characteristics found in that region (note - regions have homogeneous distribution of characteristics - separation of color is for visual purposes only).

Each observable characteristic has a prescribed residency time associated with it. This time indicates how long a roboswimmer must be in contact with the region to have detected that characteristic. The residency time simulates - in some respects - concentration levels of the particular characteristic and the bandwidth of the roboswimmer's sensor. All of the roboswimmers are assumed to have sufficient sensors to detect all of the observable characteristics.

Within each environment layer the Interesting Regions are given a weight factor that in a game theoretic sense defines a payoff. For example, Interesting Regions on the bottom or in the sediments are ‘worth’ more than similar regions found in the water column. The weighting scheme is implemented for two reasons. First, it attempts to minimize extinction (e.g., Interesting Regions in the sediments are sparse compared to those in the water column – volumetrically speaking) by giving Interesting Regions in the sediments a higher payoff, when compared to those in the water column. By doing this, worm like creatures attain a high fitness even if they only discover a few Interesting Regions.

3.2.4 Simplified Environment to Create Methodology

The virtual environment described above was chosen to aid in developing the *methodology* that will allow us to define the form and function of the roboswimmers. As part of this effort we will examine the sensitivity of the roboswimmers' design to environmental parameters – total environment area; relative depth of each layer; and the number, size, and distribution of Interesting Regions within the environment and within each layer. Again the goal is to create an intelligent process that will allow the overall system of roboswimmers to be optimized as our knowledge of Europa increases.

3.2.5 The Roboswimmers

3.2.5.1 Look to Nature

Our "Look to Nature" approach to roboswimmer development has two distinct thrusts. First, we initially select roboswimmers that have features similar to terrestrial aquatic creatures (e.g., fish, eels, etc.). We then map these characteristics into a form that is suitable for computer manipulation. Second, we use synthetic evolution to take our basic creature types and "evolve" their designs to more optimum forms. In the process each species becomes better at characterizing the environment and, most importantly, the individual species intermingle and create new species – some better explorers than either of their two parent species.

3.2.5.2 Basic Creature Types

Based on the virtual environment chosen for the Phase I effort (Figure 1) we selected the following creatures as our basic roboswimmers: fish, eels, seahorses, crabs, and worms. The attributes of these creatures are shown in Table 1.

During the synthetic evolution process we allow different species to mate. This allows, for example, fish to mate with crabs resulting in a hybrid creature that has some of the attributes of a fish and some of the attributes of a crab (e.g., a fish with legs). This has two opposing effects on the creature's performance. Hybrid creatures can potentially expand their exploration space (e.g., a fish with legs can now explore the bottom and the near sediment layers) but at the cost of increased energy usage (a fish with legs will not be streamlined and will therefore have increased drag – thus requiring more energy/unit time).

3.2.5.3 Hybridization Through Evolution

As briefly described above, our design process allows for the creation of new, hybrid creatures from a stable of conventional terrestrially inspired forms. Each roboswimmer has the capacity to acquire attributes of any other creature as a result of the Synthetic Evolutionary process. Using Natural Selection our new hybrid creatures may be preferentially selected for reproduction to form a new population of roboswimmers if they perform better in our virtual environment. If their performance is diminished they will not be selected for reproduction and the hybrid strain will not survive to the next generation.

Table 1. Roboswimmers and Their Attributes

Roboswimmer	Attribute	Defining Parameters
Fish	Able to explore the Water Column, the Near Ice layer and the Near Bottom layer. Fish size is driven by the energy (batteries) it must carry to perform its mission. Speed through water can be adjusted by fin size (with appropriate adjustment to energy consumption).	Tailfin size and body length.
Eels	Able to explore Water Column, the Near Bottom and Bottom layers (when on bottom, eel is stationary). Eel size is driven by the energy it must carry to perform its mission. Speed through water can be adjusted by fin size.	Tail size and body length.
Seahorses	Able to explore the Near Bottom, Bottom, and Near Sediment layers. Seahorse size is driven by the energy it must carry to perform its mission. Speed through water can be adjusted by fin size.	Dorsal fin size and body volume.
Crabs	Able to explore the Bottom and Near Sediment layers. Crab size is driven by the energy it must carry to perform its mission. Speed over bottom can be adjusted by leg length.	Leg length and body diameter.
Worms	Able to explore the Bottom, Near Sediments, and Far Sediments. Worm size is driven by the energy it must carry to perform its mission.	Body length and cross-sectional area.

Our belief is that this process of hybridization will allow us to identify and develop roboswimmers that optimally explore the Europan environment. This heterogeneous mix of creature types allows the system to efficiently explore the entire environment, which enhances our chances of finding life. Additionally, the process can be used to shed light on new vehicle interaction paradigms. For example, if the process leads to a vehicle that is fish and crab like, we can envision this as a single vehicle with combined fish and crab attributes or as two distinct vehicles that periodically enter into a symbiotic relationship.

3.2.5.4 Synthetically Evolved Biomimetic Roboswimmers

Figure 5 shows a simplified block diagram for Synthetic Evolution that uses a Genetic Algorithm. The computational process starts by randomly creating a population of test solutions. Very little is 'magic' about this initial solution population except that it should span – as well as possible – the parameter space of the problem.

Each individual in the population is assigned a set of solution-defining parameters coded onto a virtual chromosome. For computational purposes the parameters are converted to binary form and sequentially placed on the chromosome (Figure 6). Thus, the individual's chromosome completely defines its solution to the problem.

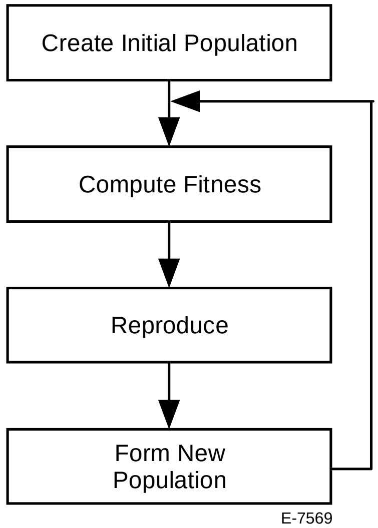

Figure 5. Block diagram of a simple Genetic Algorithm.

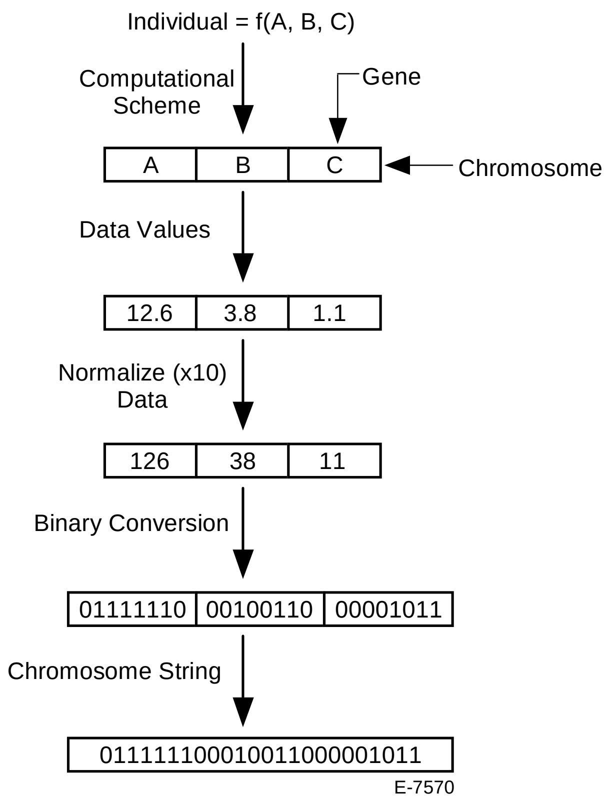

Figure 6. Parameter coding onto a virtual chromosome.

For each individual in the initial population a “fitness” value is computed. This simply quantifies how well the individual solved the optimization problem. For example, if the problem were to find the best straight line through a set of data, a good fitness measure would be the sum of the squares of the errors. In this case 'good' implies a small fitness value.

A new population is created from the existing one by reproduction and mutation. Here members with “good” fitness measures are preferentially selected and mated. Reproduction involves the process of crossover where the child inherits part of its genetic material from parent A and part from parent B (Figure 7). The chromosome of a child solution can undergo mutation. Here a bit within the chromosome is randomly selected and its value reversed (Figure 8).

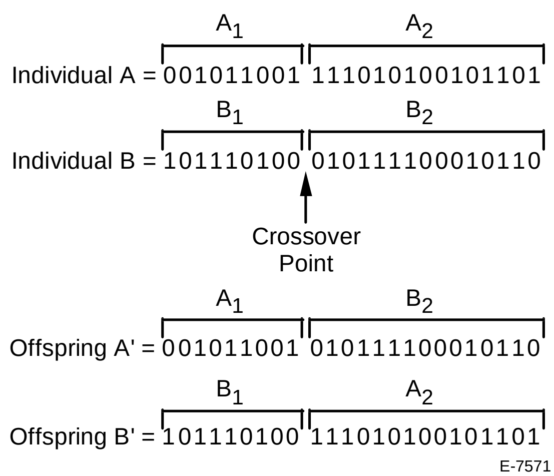

Figure 7. Exchange of genetic material during reproductive crossover.

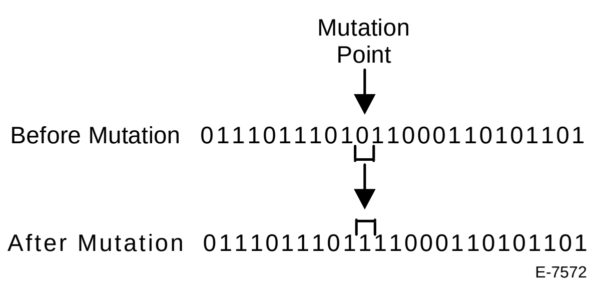

Figure 8. Single-point mutation on a virtual chromosome.

After a new population has been created from a previous one by reproduction and mutation, each member's fitness is computed and the process repeated. As in Natural Selection this process preferentially selects individuals with superior fitness and efficiently explores the entire solution space (through mutation). The result is an optimized population – one that best solves the problem.

3.2.5.5 Description of Numerical Simulation

The Genetic Algorithm as implemented in our simulation is shown in Figure 7. As described above the initial population is comprised of distinct aquatic roboswimmers, fish, eels, seahorses, crabs, and worms. Each of the roboswimmer types has a set of attributes that describe its dynamics and functional behaviors. These attributes are given in Tables 2 and 3.

Within each environmental layer the nominal roboswimmer consumes a given amount of energy at each time step (shown in Table 2). For example, a seahorse will use 1.6 energy units/time interval when it operates in the Near Ice layer, 1.4 energy units in the Water Column, etc. For roboswimmers that have evolved to hybrid types (characteristics of several basic roboswimmers – fish + crab = fish with legs), the simulation uses the maximum energy consumption figure from among the active type. For example, a roboswimmer operating in the water column with characteristics of a fish, an eel, and a seahorse will consume 1.4 energy units/time interval.

From Table 3 we see that discrete roboswimmers have functional attributes that are in many cases distinct from other types of roboswimmers and other functional attributes that overlap those of other roboswimmers. For example, fish and eels are nearly identical except that eels can modulate their speed in the Near Bottom Layer. If life should exist in this layer and require some finite time to sense it, eels will be better adapted to explore there.

The last column in Table 1 identifies each roboswimmer's defining parameters. For example, in our simulation a fish is defined by its tailfin size (specifies survey speed) and its body length (amount of energy available for survey). During the evolutionary process these parameters are adjusted in an attempt to optimize the individual creature's ability to explore the environment and detect Interesting Regions. For all roboswimmers these parameters have offsetting effects. Again, using the fish as an example, a larger tailfin will allow the fish to explore the environment more quickly but at the cost of increased energy consumption. Additionally, the Interesting Regions require a certain residency time (virtual sensors do not have infinite bandwidth) for it to be detected. A fish that can move very quickly may miss Interesting

Table 2. Energy Used (Nominally) by Roboswimmers at Each Time Step
Within Each Environment Layer

Environment Layer	Fish	Eels	Seahorses	Crabs	Worms
Near Ice	1.1	1.4	1.6		
Water Column	1.0	1.2	1.4		
Near Bottom	1.2	1.0	1.0	1.4	
Bottom			1.0	1.0	1.1
Near Sediments				1.2	1.0
Far Sediments					1.2

Table 3. Behavioral Characteristics of Roboswimmers

Environment Layer	Fish	Eels	Seahorses	Crabs	Worms
Near Ice	Swim - constant speed	Swim - constant speed	Swim - constant speed Stationary - short periods of time (1 to 5 time intervals)	Can't operate in this region	Can't operate in this region
Water Column	Swim - constant speed	Swim - constant speed	Swim - constant speed	Can't operate in this region	Can't operate in this region
Near Bottom	Swim - constant speed	Swim - variable velocity	Swim - constant speed Stationary - short periods of time (1 to 5 time intervals)	Swim - constant speed	Can't operate in this region
Bottom	Can't operate in this region	Can't operate in this region	Stationary - long periods of time (1 to 100 time intervals)	Crawl - variable speed	Stationary - long periods of time (1 to 200 time intervals)
Near Sediments	Can't operate in this region	Can't operate in this region	Can't operate in this region	Stationary - short periods of time (1 to 20 time intervals)	Stationary - long periods of time (1 to 200 time intervals)
Far Sediments	Can't operate in this region	Can't operate in this region	Can't operate in this region	Can't operate in this region	Stationary - long periods of time (1 to 200 time intervals)

Regions (not in contact with the region for sufficient time) and will require large energy reserves to explore the entire environment. As the fish's energy requirements increase, its body length must also increase (it will require more batteries). This results in increased drag, which causes the energy consumption/unit time to increase. Table 4 shows the system level effect of varying the roboswimmer's defining parameters.

As before, hybrid roboswimmers have characteristics of different basic roboswimmer species. A hybrid roboswimmer will have a nominal speed that is the minimum of its constituent species and an energy storage capacity that is a maximum of its constituent species. Physically this suggests that a hybrid roboswimmer has less efficient mobility but enhanced energy storage capability.

Table 4. Roboswimmer Parameter Effects on System-Level Performance

Fish	Tailfin Size	• The fish's speed is proportional to tailfin size. The fish's nominal tailfin size is 1 and its nominal speed is 1 distance unit per iteration. An increase in tailfin size of 10% results in an increase in speed of 10%. The maximum tailfin size is 100% larger than the nominal size. The tailfin size can go to zero (fish can't move). • Increased speed causes an increase in drag that results in an increased rate of energy consumption. The increase in energy consumption rate goes as the square of the speed - doubling the fish's speed results in a four-fold increase in energy consumption.
	Body Length	• As the fish's body length increases, so too does its drag. We have chosen this to be a linear relationship, a 10% increase in body length results in a 10% increase in energy consumption rate. The fish's nominal body length is 1. The maximum length attainable by a fish is 2 and the minimum is 0.5. • The stored energy of the fish is proportional to its body length. Increasing the body length by 10% increases the stored energy by 10%. The nominal stored energy of the fish is 1000 units.
Eel	Tail Size	• The eel's speed is proportional to tail size. The eel's nominal tail size is 1 and its nominal speed is 0.5 distance unit per iteration. An increase in tail size of 20% results in an increase in speed of 10%. The eel can quadruple its tail size. Minimum tail size is zero. • Increased speed causes an increase in drag that results in an increased rate of energy consumption. The increase in energy consumption rate goes as the square of the speed - doubling the eel's speed results in a four-fold increase in energy consumption.
	Body Length	• As the eel's body length increases, so too does its drag. We have chosen this to be a linear relationship, a 20% increase in body length results in a 15% increase in energy consumption rate. The eel's nominal body length is 1. The eel can be as long as triple its nominal length or as short as half its nominal length. • The stored energy of the eel is proportional to its body length. Increasing the body length by 10% increases the stored energy by 10%. The nominal stored energy of the eel is 2000 units.
Seahorse	Dorsal Fin Size	• The seahorse's speed is proportional to dorsal fin size. The seahorse's nominal tailfin size is 1 and its nominal speed is 0.2 distance unit per iteration. An increase in tailfin size of 30% results in an increase in speed of 10%. The seahorse can quadruple its tail size. Minimum tail size is zero. • Increased speed causes an increase in drag that results in an increased rate of energy consumption. The increase in energy consumption rate goes as the square of the speed - doubling the seahorse's speed results in a four-fold increase in energy consumption.
	Body Volume	• The drag on the seahorse is proportional to its body volume. A linear relationship has been chosen where a 10% increase in body length results in a 25% increase in energy consumption rate. The seahorse's nominal body length is 1. The seahorse can be as long as double its nominal length or as short as one quarter its nominal length. • The stored energy of the seahorse is proportional to its body volume. Increasing the body volume by 10% increases the stored energy by 15%. The nominal stored energy of the seahorse is 500 units.

Table 4. Roboswimmer Parameter Effects on System-Level Performance (Continued)

Crab	Leg Length Body Diameter	• The crab's speed is proportional to its leg length. The crab's nominal leg length is 1 and its nominal speed is 0.1 distance units per iteration. An increase in leg length of 10% results in an increase in speed of 10%. The crab can triple its leg length. Minimum leg length is zero. • Increased speed causes an increase in drag that results in an increased rate of energy consumption. The increase in energy consumption rate goes as the square of the speed - doubling the crab's speed results in a four-fold increase in energy consumption • The drag on the crab is proportional to its body diameter. A linear relationship has been chosen where a 10% increase in body diameter results in a 10% increase in energy consumption rate. The crab's nominal body diameter is 1. The crab can have a maximum body diameter of 3 and a minimum of 0.1. • The stored energy of the crab is proportional to its body diameter. Increasing the body diameter by 10% increases the stored energy by 10%. The nominal stored energy of the seahorse is 5000 units.
Worm	Body Length Cross-sectional Area	• The worm's speed is constant (when in motion) at 0.01 distance units/iteration. • The worm has two energy consumption levels. At rest the worm consumes 10% its nominal in-motion rate (see Table 2). • Since the primary drag mechanism of the worm is friction, its drag is proportional to its surface area. Doubling the cross-sectional area quadruples the energy consumption rate. The worm's nominal cross-sectional area is 1. Its maximum cross-sectional area is 3 and its minimum is 0.5. • The stored energy of the worm is proportional to its cross-sectional area. Increasing the cross-sectional area by 10% increases the stored energy by 20%. The nominal stored energy of the worm is 1000 units.

3.2.5.6 Roboswimmer Dynamic Behaviors

During a simulation run the roboswimmers explore their virtual environment searching for Interesting Regions. At this stage the roboswimmers do not employ sophisticated search strategies, instead they randomly swim/walk/slither through the environment for 20,000 time steps. As they encounter and detect Interesting Regions (they remain in contact with the region for more than the minimum residency time) they collect points that go toward their Fitness Measure (discussed below). Each roboswimmers can only collect points for a given region once - they cannot return to that region later in the simulation and collect more points for rediscovering it.

Basic or hybrid creatures that can operate with more than one form of locomotion (swim and crawl, etc.) will randomly select which locomotion type to use when they encounter an interface. For example, a hybrid roboswimmer that is a combination of a fish and a crab can select either to swim or to crawl when it encounters the bottom. While in contact with the interface it will, at each time step, randomly select if it crawls or swims.

3.2.5.7 Our Fitness Function

The Fitness Function chosen is simply the sum (over the 20,000 iterations) of the payoffs of each Interesting Region detected by a roboswimmer. The more regions detected the higher the individual's Fitness.

During reproduction the individuals with the higher relative Fitness are preferentially selected to mate and create the next generation of roboswimmers. Crossover allows similar species to explore different regions of their parameter space and different species to form hybrid roboswimmers.

3.2.6 Preliminary Results

3.2.6.1 Baseline Experiments

To ensure that the simulation produced logical results, a baseline experiment was conducted. Here Interesting Regions are only placed in the Water Column and left the other layers devoid of life. Based on Table 3 we can see that the only roboswimmers that have a chance of surviving are, fish, eels, and seahorses. Crabs and worms cannot survive in this environment because there is no possibility that they will encounter Interesting Regions.

The simulation was started with 10 roboswimmers of each type for a total population of 50 individuals. In the initial population the individual's parameters were selected randomly from within the limits defined in Table 4. A total of ten Interesting Regions of random size (between 1 and 4 length units) and random location were placed within the Water Column. At each evolutionary iteration the total number of each species (including hybrids) were counted (see Figure 9).

Several interesting results were found from this experiment. As expected, crabs and worms perished immediately. Due to mutation we see that at the 4th iteration a single crab reappears and at the 8th iteration a worm reappears. While the fate of the lone worm at the 8th iteration is unknown, the crab that appeared in the 4th iteration disappears immediately.

Because fish are the most efficient explorers in the Water Column they proliferate quickly (observe the jump in the number of fish from iteration 1 to 2). While eels are the next most efficient Water Column explorers their number initially decline as fish take over. Interestingly by examining the hybrid roboswimmers more closely it was revealed that most of them have fish characteristics combined with characteristics of all of the other roboswimmer types. There are fish+eels, fish+crabs, fish+crabs+worms, etc. Because there is no penalty for a fish to have characteristics of the other roboswimmer types when operating in the Water Column, hybrid roboswimmers with at least fish characteristics will still maintain a high Fitness.

By the fifth iteration the only roboswimmer types are fish and hybrids where the hybrids all have fish characteristics. At the sixth iteration we again see eels reemerging. This occurred because the fish’s tails began to increase in size, which made some eels slightly more efficient when compared to these fish. By the seventh iteration the eels are on a rebound and the fish population is diminishing. At the eighth iteration many of the fish have reduced their tail size and have become more efficient when compared to the eels.

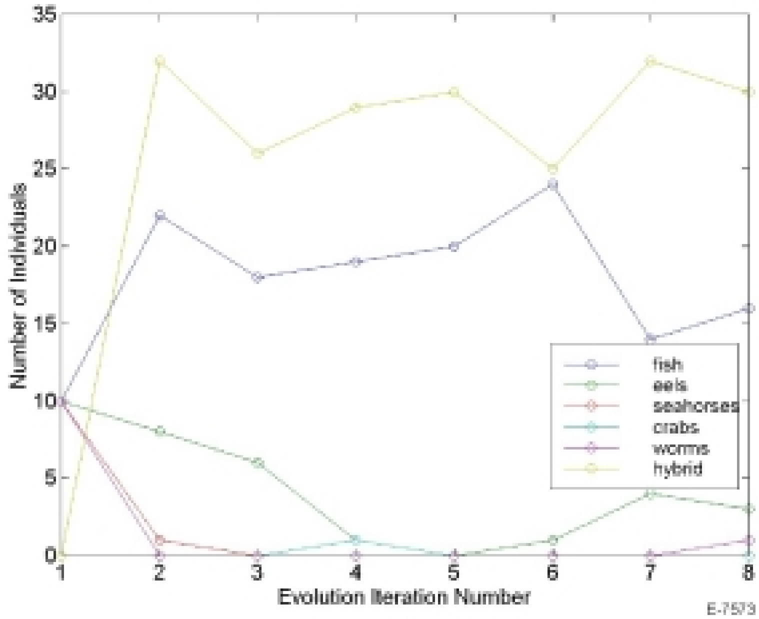

Figure 9. Results of baseline experiment. Here Interesting Regions were placed only in the Water Column. Synthetic evolution selected only fish and fish+other as the most suitable roboswimmers for this environment. Because the additional characteristics given to hybrid fish will not enhance its ability to explore this environment, the other characteristics can be deleted without affecting the optimized solution. Thus synthetic evolution selected fish type roboswimmers which is the expected result.

This experiment provides a preliminary validation of our approach. Given an environment that clearly favors one type of roboswimmer, the simulation indeed selects that roboswimmer. Additionally we see that because of parameter drift in the fish population eels reemerged for a brief period. Although not conclusive it appears that the simulation has uncovered a sensitivity to small parameter shifts in the fish. A small increase in average tail size caused the eels to reappear, an indication that in parameter space a steep solution gradient exists between fish and eels.

3.2.6.2 Preliminary Hybridization Experiments

In this experiment we placed Interesting Regions in the Water Column (60%-12 regions) and the Near Sediments (40% - 8 regions). Regions in the Water Column had a payoff of 1 while those in the Near Sediments had a payoff of 10. As before we created an initial population with 10 roboswimmers of each type for a total population of 50 individuals. At each evolutionary iteration the total number of each species (including hybrids) were counted (see Figure 10).

Given the distribution of Interesting Regions we expected the simulation to preferentially select fish and worm type roboswimmers. Instead what we found was that fish and crab roboswimmers were selected with hybrids being predominantly crabs+worms and fish+crabs. The reason crabs were selected over worms is that they have more energy reserves and are much more swift (10 times as fast). Even though they consume 20% more energy each step, their speed and extra energy allow them to explore the Near Sediments more efficiently than worms.

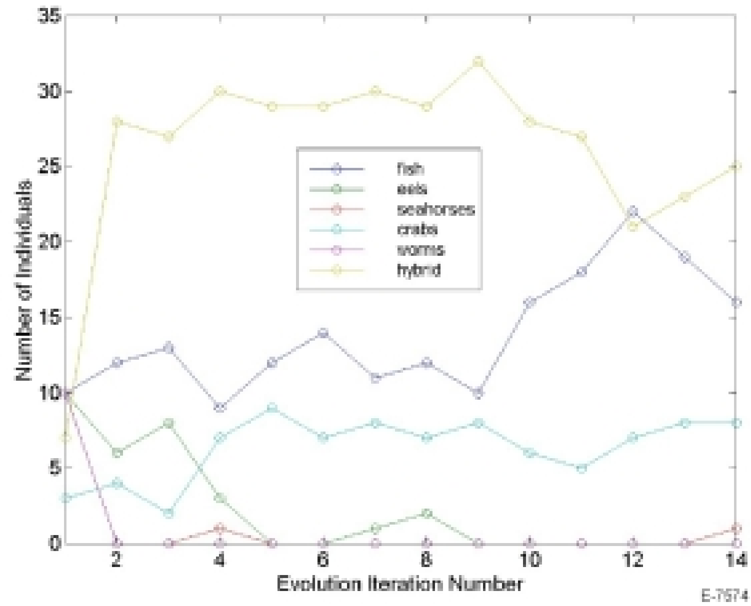

Figure 10. Results of first hybridization experiment. Here Interesting Regions were placed in the Water Column and in the Near Sediments. Synthetic evolution selected fish, crabs, fish+crabs, and fish+worms as the most suitable roboswimmers for this environment.

For this type of environment it appears that the most suitable set of roboswimmers would include, fish, crabs, and hybrids such as fish+crabs and crabs+worms. As mentioned above, an even better solution may be a symbiotic relationship between fish and crabs and crabs and worms. Here crabs could request fish to carry them to different locations along the bottom and crabs could carry worms placing them in the sediments at potentially interesting locations.

3.3 Collaborative Exploration

3.3.1 Introduction

In Subsection 3.2 we described the approach taken to synthetically evolve a group of roboswimmers using a Genetic Algorithm. We showed that in a homogeneous virtual ocean the "optimal" roboswimmer is a fish. For more complex environments other creature types (fish, eels, seahorses, crabs, and worms) are preferentially selected. The GA architecture that we developed provides a mechanism for hybridization (vehicles with attributes of more than one discrete type) and it was shown that these multi-mode vehicles are chosen in certain assumed environments.

Previously the roboswimmers acted as individuals, unaware of the existence of other roboswimmers. In this section we expand their capabilities by allowing them to interact with their siblings. Specifically we have implemented a form of sematectonic communication. Typically this term is used to describe the swarm intelligence of insects like termites. It refers to a behavior in which the action of an individual cause a global behavior modification. For termites this occurs during nest building. When a single termite places a small pellet of masticated earth, other termites will then place their pellets at the same location (instead of randomly walking about with the pellet). The action of a single termite altered the behavior of many other individuals.

3.3.2 Approach

In our approach to roboswimmer collaboration we have devised a mechanism similar to that employed by the termites. Instead of altering the environment (termite placement of pellets) we have the roboswimmers announce to the world that they have found something interesting. Each roboswimmer then decides, individually based on a set of rules, if it will act on this information.

As a first step in developing a process to identify, tune, and evaluate communication and collaboration architectures, we have chosen to limit our simulation to a homogeneous environment (water column) and a single type of roboswimmer (fish). Once the process have been validated we are certain that it can be extended to include more complex environments and teams of roboswimmers – where the word "team" implies that individual may have unique characteristics.

The goal of the *group* of cooperating fish is to completely characterize the environment in the shortest possible time. As before we allow the simulation to place Interesting Regions throughout the environment where each region is defined by a set of characteristics. The group of fish explore the environment as individuals, only being interrupted when a sibling announces that it has found an Interesting Region. At this point the fish decides if it will modify its trajectory or will ignore the announcement. Characteristics of the rules that each fish follows after the reception of an announcement is what the GA attempts to optimize.

Once the environment has been completely characterized (all of the Interesting Regions have been found and each has been fully explored) the simulation is stopped and the total number of time steps counted. This represents the fitness of the fish group.

3.3.3 Virtual Environment

The environment used here is very similar to that used to evolve the roboswimmer's *form* as presented in Subsection 3.2. Here the environment is simpler in that it only includes the water column – the near ice, near bottom, bottom, near sediments, and far sediments layers have been removed. As before, Interesting Regions are placed randomly throughout the environment at the start of a run.

Figure 11 shows several environments used during the simulation results that will be presented later in this report. Here the Interesting Regions range in size from 2-by-2 blocks to 4-by-4 blocks.

As before, Interesting Regions are areas of interesting physical or chemical properties. Once placed the regions remain fixed both in location and size.

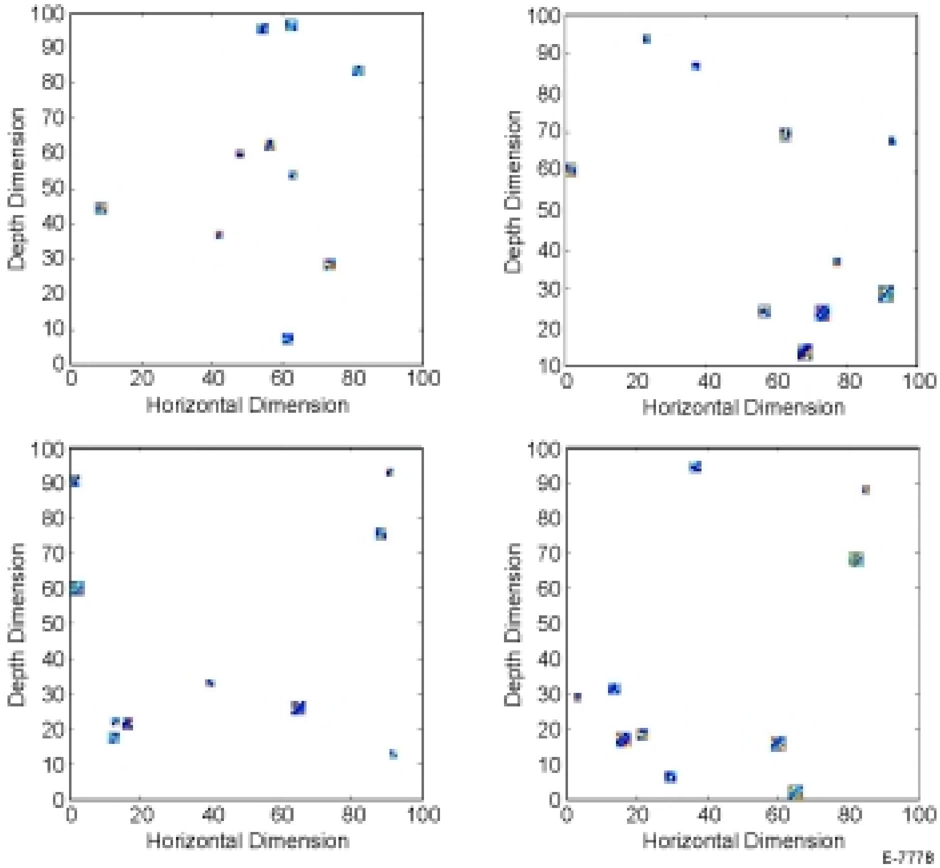

Figure 11. Several virtual environments.

Each region is characterized by a set of features – for the simulation results shown below there are a total of 11 different features, and any single Interesting Region can have at most 5 different features. Features represent observable characteristics such as temperature gradients, chemical composition, or life species.

In this simulation the roboswimmers are assumed to have sensors with infinite resolution and bandwidth. Simply put this means that when a roboswimmer enters an Interesting Region containing a feature that it can sense (i.e., the roboswimmer is equipped with a sensor able to measure yellow and the Interesting Region contains a yellow feature) it detects it immediately.

3.3.4 Performance Metric

The goal of the population of roboswimmers is to *completely* explore the virtual environment in the least amount of time. For each run of the simulation several parameters are recorded, status of environment characterization at each time step, and total time required to fully characterize environment.

The status of the environmental characterization is accomplished in the following way. At the start of a run an array is created that identifies the features defining each Interesting Region. As features are identified in Interesting Regions a note is made in the array to indicate that this feature is now known. This data is not communicated to the fish which causes multiple fish, each having similar sensors, to rediscover a given region. This represents a baseline collaborative scheme, one in which the fish have no memory of previous discoveries.

At each time step the total number of fully characterized Interesting Regions is displayed and stored. In this simulation there are 10 Interesting Regions. After the 10^{th} region is characterized the simulation ends and the total time required to characterize the environment is stored – this is the measured performance metric.

3.3.5 The Roboswimmers

To demonstrate our approach to roboswimmer collaboration and cooperation we have chosen to focus on one type of vehicle – fish. We believe that our approach is scalable and can incorporate more complex environments and different 'species' of roboswimmers.

3.3.5.1 Sensor Suite

Each roboswimmer fish used in this simulation is equipped with a compliment of sensors, each sensor assumed to have infinite resolution and bandwidth. At the start of the simulation the fish are randomly given a set of sensors – here four sensors per fish. For each fish the sensors do not need to be unique, i.e., a single fish can have four of the same type of sensor. In the simulation there are a total of 11 different feature types and thus a total of 11 different types of sensors. After all of the fish have been equipped with sensors a software routine is run to ensure that the population's sensor complement is complete – i.e., the population of fish contains sufficient sensor types to ensure that all environmental features can be detected.

3.3.5.2 Collaboration Mechanism

As mentioned above, we have implemented a form of sematectonic communication within the fish population. Each fish upon entering a detectable Interesting Region announces to all of the other fish that it has found a feature. Each of the other fish then decide (using an internal set of rules), individually, if they will act on this information. If a fish decides to investigate it alters its trajectory and heads for the Interesting Region. The block diagram of the collaboration architecture is shown in Figure 12.

The rule (act/ignore) block diagram is shown in Figure 13. Contained within a fish's announcement are the fish's current position (we have assumed perfect navigation) and its compliment of sensors. No information is given regarding what the fish sensed, as this is implicit in the announcement. After receiving an announcement the receiving fish computes both its relative range to the announcing fish and the number of sensors it has that are different than from announcing fish. Using this data the fish decided if it will act on or ignore the message.

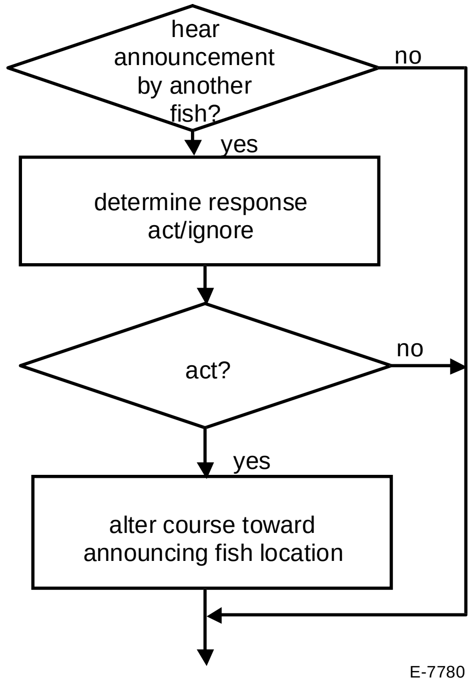

Figure 12. Block diagram of fish collaboration.

The act/ignore determination is the result of two virtual coin flips. First the fish decides, based on the number of different sensors it carries relative to the announcing fish, if it will act on the announcement. This is done using the probability distribution shown in Figure 14. In Figure 14 are plotted a series of curves relating the number of different sensors and the probability of the fish acting on the announcement. The shape of each curve is determined by a parameter we have called "convexity." As the convexity increases the apparent slope of the line decreases (all curves are piecewise linear and start at 100% probability). For example, with a convexity = 5.11 the probability that the fish will act if it has two sensors that are identical to the announcing fish’s and two that are different is approximately 47%. Flipping a biased coin makes the actual decision. If the result is positive the fish then checks a range-gated probability distribution.

One possible range-gated probability distribution that a fish could use is shown in Figure 15. Here there are two parameters that define the distribution, the relative range to peak probability (range_max = 65 in figure) and the width of the distribution curve (dist_width = 10 in figure). For a relative range between the receiving and announcing fish less than 55 or greater than 75 the receiving fish will not act on the announcement. For relative ranges between 55 and 75 there is a finite probability that the receiving fish will act. In the figure an example is shown where the relative range is 60 resulting in a probability of acting equal to 50%. As before a bias coin toss is used to determine if the fish will act whenever there is a non-zero probability. If the two coin-flips described above are positive, the receiving fish alters its course to head directly for the announcing fish.

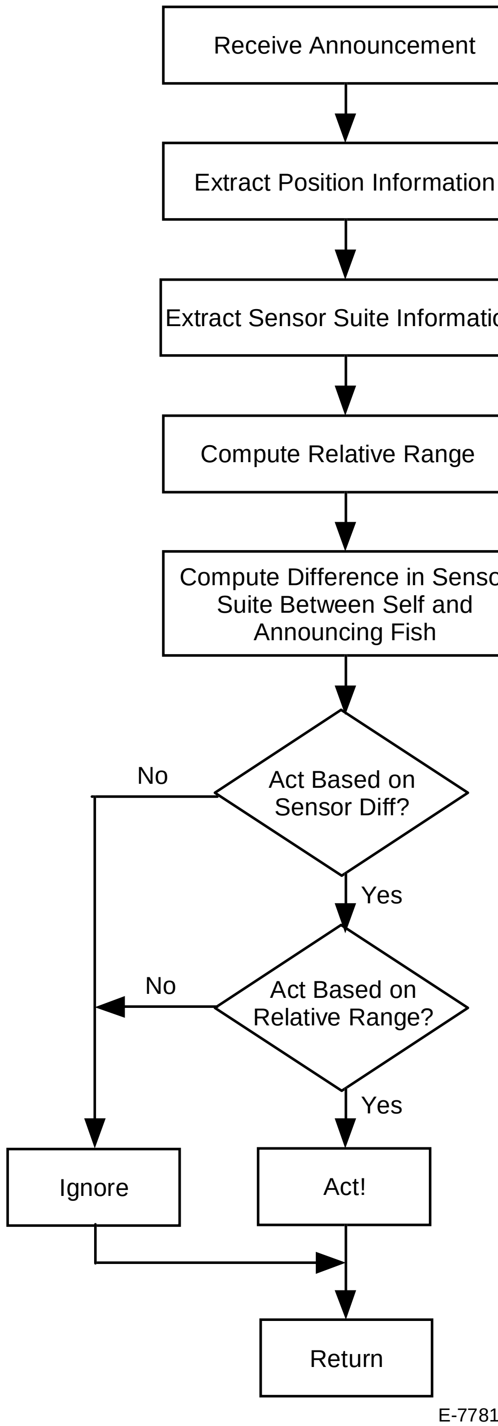

Figure 13. Block diagram of the rule base used to determine if fish will act or ignore announcement.

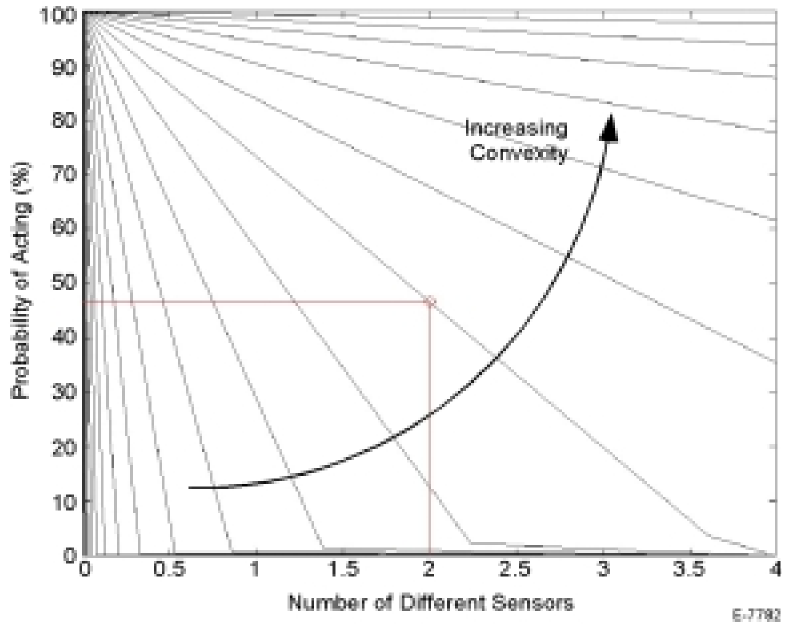

Figure 14. Potential probability distributions used by a fish to decide if it will act on a received announcement. For a convexity = 5.11 and given that the receiving fish as two different sensors (compared to the announcing fish), there is a 46.638% probability that the receiving fish will act.

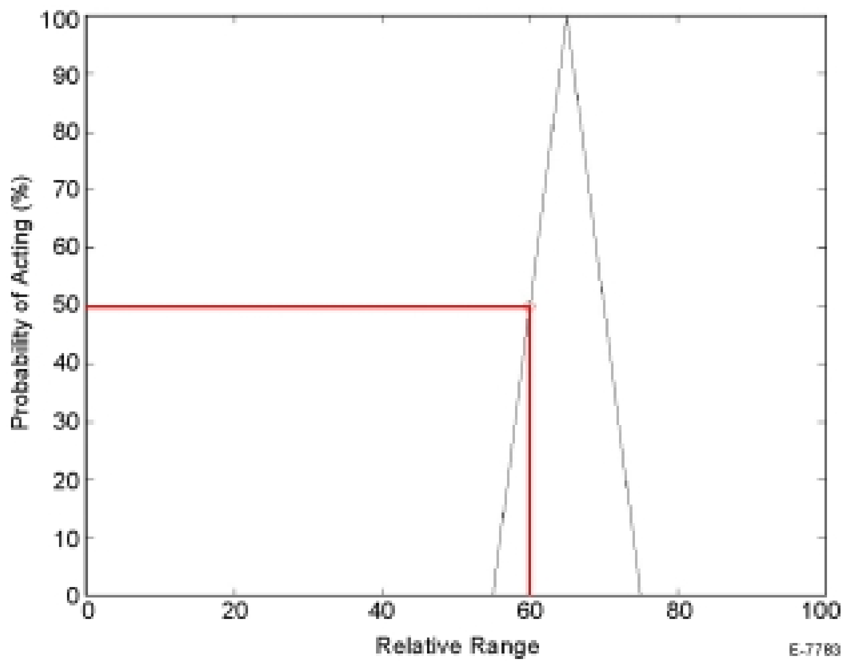

Figure 15. One possible range-gated probability distribution utilized by a receiving fish. If the relative range between the announcing and the receiving fish is 60, then there is a 50% probability that the receiving fish will act on the announcement.

One difficulty that was encountered using the rule-base above was a local trapping of fish at Interesting Regions. Because the fish can turn instantaneously they can be recalled to an Interesting Region by a second fish after just leaving it. The more fish trapped in an Interesting Region the more stiff the solution becomes (Interesting Regions act as sinks in the simulation - see Figure 16). To eliminate this problem a turning rate limit was imposed on the fish to reduce their agility. For each time-step the fish is constrained to only turn a prescribed amount - say 20 deg. Thus to make a 180 deg turn will take 9 time steps. In that amount of time the fish is able to move sufficiently far away from the Interesting Region so that it will not return immediately.

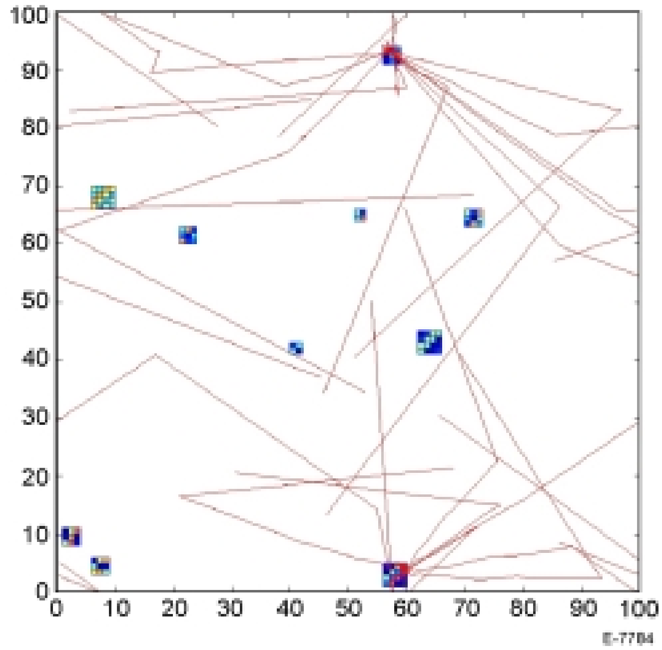

Figure 16. Fish trajectories showing that over time the fish can become trapped at Interesting Regions.

From the discussion above we can see that there are four parameters that define the fish's collaboration dynamics: the sensor probability distribution defined the “convexity” parameter; the range-gated probability distribution defined by the two parameters, range_max and dist_width; and the maximum turn rate parameter. These parameters, once prescribed, are used by all of the fish in a population and are time invariant. The focus of the synthetic evolution process, described below, is to find the set of parameters that minimize the exploration time required for a group of fish to completely explore the environment.

3.3.6 <u>Synthetically Evolved Roboswimmer Exploration Collaboration</u>

A Genetic Algorithm was used to "evolve" the roboswimmer's collaborative interaction. The parameters space of this problem is four-dimensional where the parameters are described above. Similar to the coding process described in last months report, the four parameters were mapped onto a virtual chromosome in binary form. Through synthetic evolution each parameters was allowed to vary between prescribed limits (shown in Table 5).

Table 5. Parameter Limits Used in this Simulation

Parameter	Minimum Allowable Value	Maximum Allowable Value
Convexity	0	4 (for this simulation)
range_max	0	100 (for this simulation)
dist_width	0	1/2 of range/max
Maximum Turn Rate	0	180 deg/time step

3.3.6.1 Description of Numerical Simulation

The solution population is composed of 20 individuals where an individual is defined to be 20 identical fish (each of the 20 fish utilize the same act/ignore parameters). At the start of a simulation run the fish are randomly placed within the environment and given a random initial heading. Each fish will move along a straight line (wrapping at edges) until they receive an announcement and decide to act on it. At that point the fish will begin a turn toward the announcing fish's position. If during this turn the fish receives another announcement and decides to act on it, it will start turning towards the new announcing fish's position. As mentioned previously, each fish is assumed to be capable of navigating in its environment perfectly. The simulation continues until the environment is completely explored.

Because of the statistical nature of the simulation, five independent runs are made for each individual in the population with the resulting exploration times averaged together. This results in a total of 100 runs being made (20 groups of 5) for each iteration of the Genetic Algorithm.

3.3.6.2 Genetic Algorithm

Like the GA described in last month report, this GA seeks to optimize a population through synthetic evolution. Here the fitness measure is the total time required to completely explore a virtual environment. The goal is to find the set of parameters (which define the population) that will minimize this time.

To start the process 20 individuals were created each having a randomly selected set of parameters. The fitness of each individual was found by allowing that individual to explore the environment and measuring the time it required to complete the task. Individuals with superior fitness (lower times) are preferentially selected for reproduction (crossover and mutation).

3.3.7 Results

3.3.7.1 Evolutionary Optimization

Figure 17 shows the fitness measure (discrete data points) of each individual in a population for a total of 36 evolutionary steps. The mean of the data at each step was computed and is shown by the solid red line. We can see that initially the ensemble population required

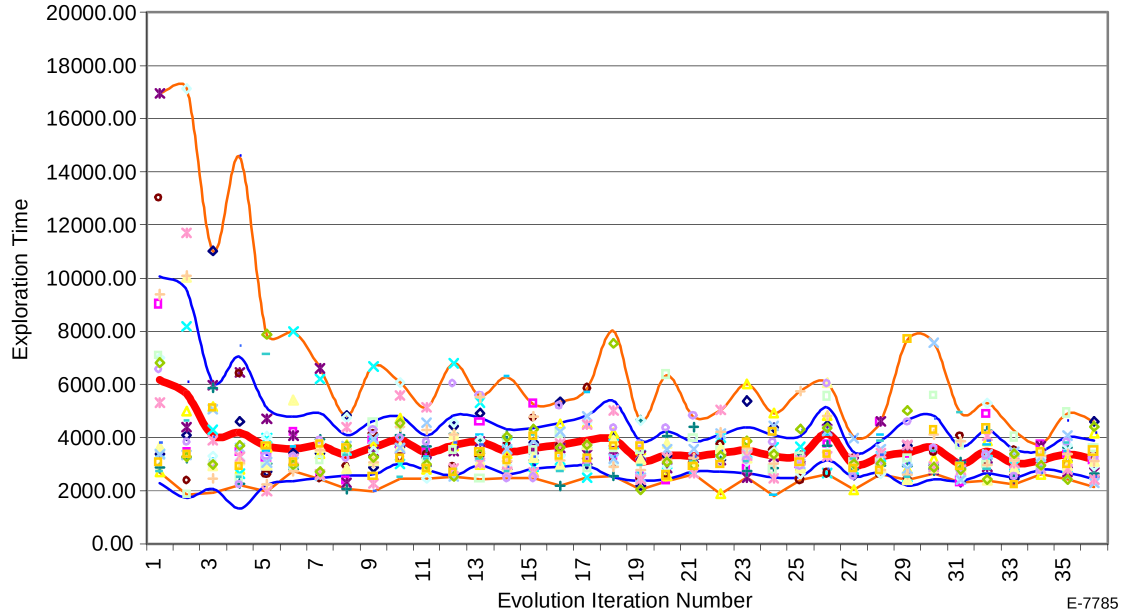

Figure 17. Fitness of population individuals at each iteration of evolutionary process. The solid red line shows the ensemble average, the dashed orange lines show the maximum and minimum values at each iteration, and the dashed blue lines define the 1-sigma envelope.

over 6,000 steps to completely characterize the environment. Very quickly the mean drops below 4,000 and at step 36 the mean is approximately 3,100. Computing the piecewise linear slope of the mean indicates that the evolutionary process is not yet complete (slope is still negative).

Also plotted are the data bounds (maximum and minimum shown by the dashed orange lines) and 1-sigma lines (dashed blue) above and below the mean. As expected the 1-sigmal envelope shrinks during the evolutionary process (entire population is optimized) but remains finite due to mutation. Mutation ensures that the optimum reached is global but maintaining genetic diversity at each iteration.

3.3.7.2 <u>Parameter Optimization</u>

During the evolutionary process we expect the algorithm to search parameter space looking for the optimum *set* of parameters. As the optimum is approached the range of each parameter should diminish - possibly approaching a single value. Histograms were computed for each parameter, at each iteration. These plots are shown and described below.

Figure 18 shows the variation of the convexity parameter at each iteration. Initially the parameter value is evenly distributed over the allowable range (one or two fish having any one parameter value). As the evolutionary process continues we see instances where a particular parameter value will emerge, become dominant, and then disappear. Finally a single parameter value emerges as dominant (in this case that value is approximately 0.14) and nearly all of the fish utilize this value (by iteration 36 all 20 fish are using convexity = 0.14).

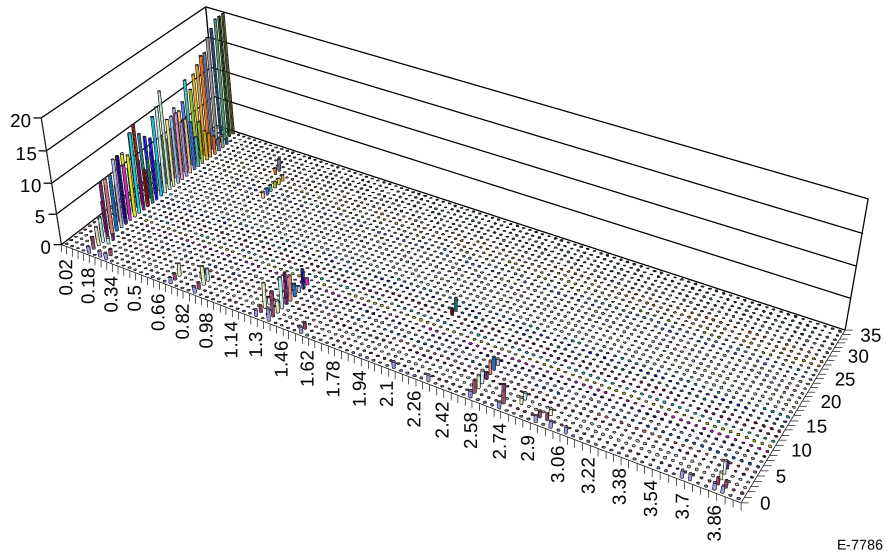

Figure 18. Variation in convexity parameter during evolution.

Figure 19 shows the variation of the max_range parameter at each iteration. As before, the parameter value is initially evenly distributed over the allowable range and as the evolutionary process continues a distinct value emerges. By iteration 36 nearly all of the fish are using max_range = 41.5.

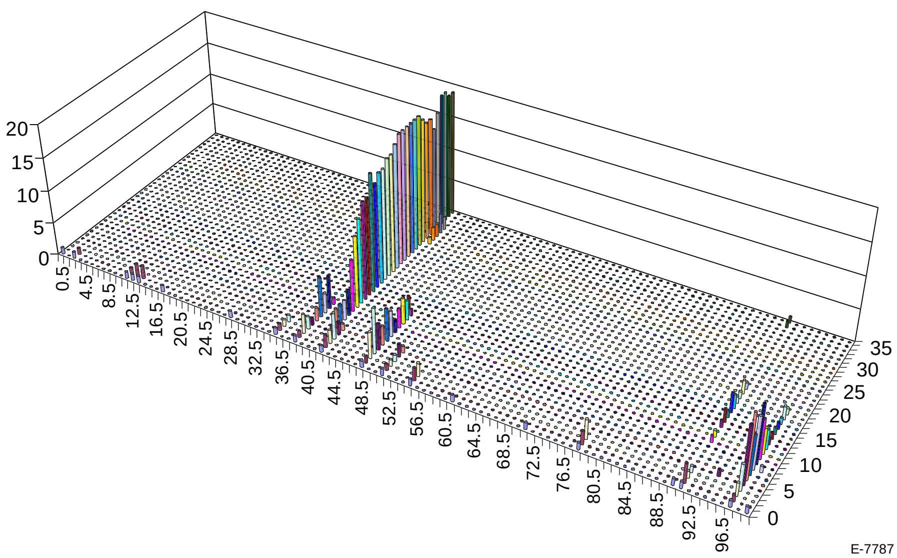

Figure 19. Variation in max_range parameter during evolution.

The dist_width parameter (Figure 20) during evolution behaves in a similar way as the previous two parameters. Ultimately nearly all of the fish are using a value of approximately 10 for dist_width.

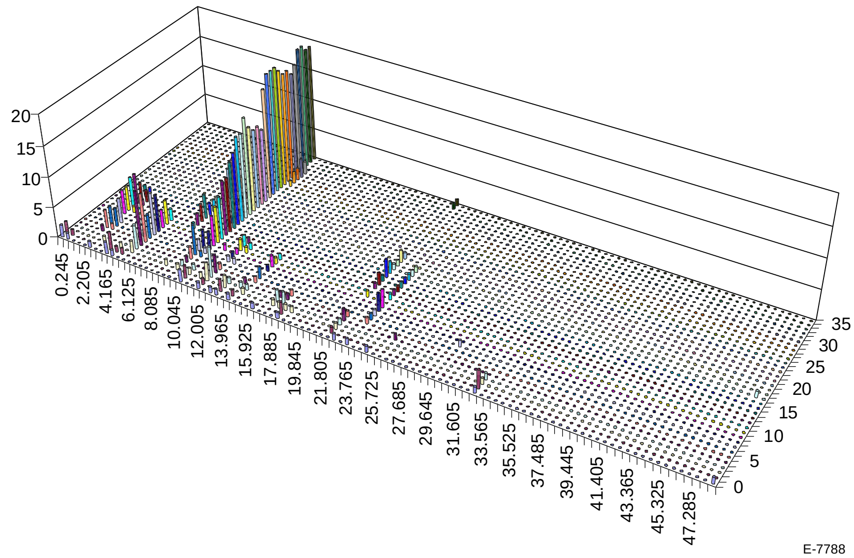

Figure 20. Variation in dist_width parameter during evolution.

The most interesting parameter behavior during the evolutionary process is that of the maximum turn rate parameter (Figure 21). As before the parameter is initially evenly distributed across the allowed range of 0 to 180 deg per iteration. During the evolutionary process values emerge and disappear just like in the previous three parameters. What is interesting is that this parameters does not settle down quite as quickly as the previous three. At iteration 36 there are 12 fish using a value of 168.5 deg/iteration, 5 fish using 170 deg/iteration, 2 using 146 deg/iteration, and 1 using 125 deg/iteration. While the first two groups are close together and will probably converge to a single value, it is the emergence of the other two groups that is most revealing. There are potentially two explanations. Either the evolutionary process

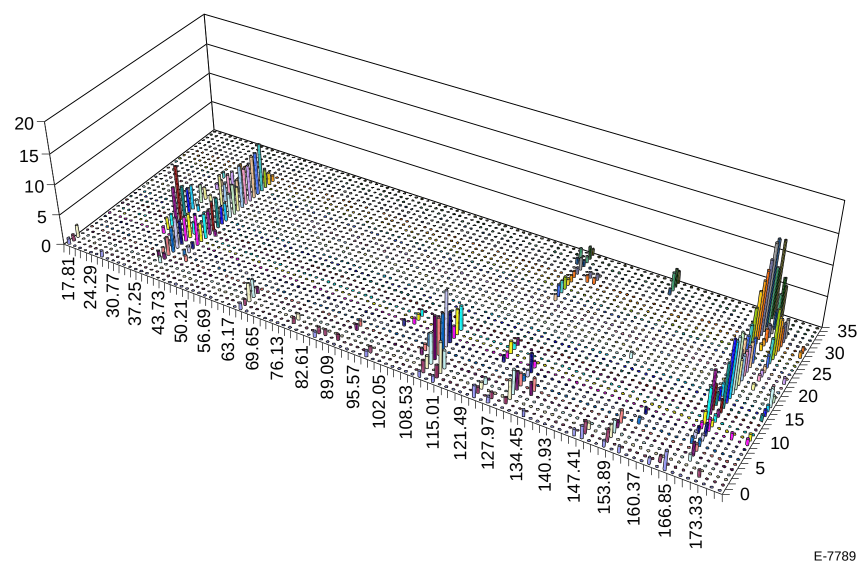

Figure 21. Variation of the maximum turn rate parameter during evolution.

has not yet finished (supported by the mean trend in Figure 9) or this parameter has more than one optimal solution. The later possibility is the most intriguing. This would imply that the GA can identify multiple optimal solutions simultaneously - something that few other optimization techniques can claim.

3.3.8 Wrap-up of Collaboration Design

As we stated early in the program, it was our desire to create a process that would allow us to identify and develop teams of roboswimmers that could efficiently explore Europa. During this Phase I effort we have created and utilized advanced techniques that mimic Nature in the way they identify, select, and tune a complex system to best solve the optimization problem. Our process allows us to use Natural Selection to identify the best form for a team of roboswimmers given a particular environment. It allows these simple creature types to interact at a fundamental level and create hybrid types that are even better at efficient exploration. While our collaboration technique is relatively simple, our approach to optimization is not. The process we have created is scaleable and will allow us to combine the two similar but independent simulations into one thus allowing us to identify the roboswimmers *form* and *function*.

While our focus is on exploring Europa, we feel that the system we are developing will have application across a broad spectrum of problems.

3.4 System Infrastructure

In Phase I, CRREL performed an evaluation of the infrastructure requirements for a Europa exploration mission using roboswimmers. The main infrastructure issues are delivery of the hardware to Europa, penetration through ice, and communication through ice layers to transfer the data acquired by the roboswimmers to an orbiting spacecraft or to earth. We decided to concentrate in Phase I on the most challenging issue that would require development of new technologies over the next two decades. Low power, robust communications through moving layers of Europan ice represents the toughest challenge. (We felt that delivery of exploration hardware to Europa presents more of an engineering challenge than a technological challenge. Penetration of roboswimmers and associated hardware through hundreds of meters of ice is difficult but it requires further development of existing technologies, and NASA organizations such as JPL possess the necessary expertise. Additionally, low power, robust communications among the roboswimmers is also a very difficult problem requiring development of new technologies, but we consider it under roboswimmer development and not infrastructure development.) For purposes of Phase I, we evaluated the state of the art of through-ice communications using the expertise at CRREL. For many years, CRREL has participated with the U.S. Navy in work on submarine communications through near-polar ice. This work considered acoustic as well as microwave technologies. While much of the work is not available in open literature, we were able to learn that little success resulted from these efforts. The main problems were high power requirements and salinity of the ice. Therefore, these approaches may not be applicable to the Europa environment. We considered optical fibers or even wires through ice, laid in place by a descending penetrator. The difficulty with this approach is mechanical integrity in the dynamic ice environment. A series of small microwave repeaters sown in the ice as the penetrator descends is another possibility, but again, this approach may not work due to continual movement of ice. Thus, the through-ice communications is a difficult problem requiring more concerted effort not possible within the resources of Phase I. We will address the problem in much greater depth and identify future technology developments under Phase II, Task 5.

3.5 Conclusion and Next Steps

3.5.1 The Phase I Program

This report documents our efforts identifying the characteristics of Europa's ocean that should be sensed, developing a methodology that will allow us to design efficient roboswimmers, and developing an architecture that allows us to evolve communication and collaboration techniques between the roboswimmers.

Thus far the tools and techniques that we have developed are essentially independent – designed to focus on a particular problem parameter. The next step is to understand how each individual tool can be combined to provide a unified design approach, one that will allow us to develop each roboswimmer as a system. Specifically we wish to develop an integrated design tool – one that will select and adjust each roboswimmer's compliment of sensors, will identify the optimum vehicle *form*, and will identify the best techniques for roboswimmer communication, collaboration, and cooperation.

3.5.2 Increasing Simulation Fidelity

In this month's report we will describe the steps required to achieve a unified design approach. We will describe the structure of the virtual environment and the integration of the roboswimmer's sensor selection, form, and sibling interactions. As before we plan to use a Genetic Algorithm to evolve the "system" toward an optimum solution.

3.5.2.1 Virtual Environment

In Phase I we developed a simple 2-D environment to demonstrate our approach. This environment represented a vertical slice of an ocean space – one that contained delineated regions with randomly placed Interesting Regions. Interesting Regions are areas containing measurable features such as temperature gradients, chemical plumes, or detectable organisms. In the simulation we did not specifically define the features, instead we assumed that the roboswimmers carried sensors that could measure the feature – whatever it was. For simplicity we assumed that the sensors were perfect – they could measure instantaneously and with perfect precision. We also assumed that the Interesting Regions, once placed, were static. They did not move within the environment nor did they change in size.

To bring the simulation closer to reality we must significantly increase the fidelity of the virtual environment. Again a good choice is to look to Nature and create models that mimic terrestrial environments.

The first change that we envision making is to create a 4-D virtual environment – three spatial dimensions and one temporal dimension. Because the Europan ocean is presumably not a static environment we must anticipate temporal variability. Not only can the environment be in motion, but the Interesting Regions can also change with time, becoming more disperse, changing their shape, disappearing (become immeasurable).

In the Phase I simulations we placed Interesting Regions within the environment randomly. No effort was made to cluster the regions or to assume a driving rationale behind their position. In a real environment – a hydrothermal vent for example – these regions would typically cluster in zones around some interface region. Temperature gradients would be associated with thermal plumes – being carried by convection and the currents. If there is life present it would cluster near specific interfaces – along a specific thermal zone or near other organisms (food source). To increase the fidelity of our simulation we will create environmental features that either enhance or diminish the probability of finding Interesting Regions. For example we can create a hydrothermal vent structure within the environment and cause Interesting Regions to cluster near it. These regions would include thermal plumes, chemical plumes, and inhabited areas. These regions would evolve temporally, changing their location, shape, and concentration based on simple models developed from terrestrial samples.

3.5.2.2 Realistic Sensors

The sensors used in Phase I were assumed to be perfect. Each was sensitive to, and able to measure, only one parameter. The sensors were assumed to be noise-free and have infinite bandwidth – clearly they do not represent real-world sensors (even in 20 years!).

Because the performance of a roboswimmer's sensors has a direct effect on its form (what it looks like) and how it interacts with its siblings, realistic sensor models will need to be used. Specifically these sensor models must include parameters such as, energy consumption, size and mass, dynamic range, sensitivity, intelligence, and robustness. As a start we should consider sensors that are available today and compare them to similar sensor technology that was available one to two decades ago. This will provide trend information that will allow us to extrapolate into the future and guess at what the sensors may look like decades from now.

One of the results that we would like to obtain is a list of technology thrust areas that must be addressed to **enable** the roboswimmer technology we are proposing. Specifically we would like to identify those technology areas that will require significant advances. For example, we may require a temperature sensor which consumes two orders-of-magnitude less power and is 50 times smaller than the state-of-the-art. This is an important result! It will create a roadmap for mission success.

To accomplish this we will not only "evolve" the sensor selection (i.e., different roboswimmers are given different sensor suites) but will also select their functional attributes. Figure 22 shows an example of this process. Here a temperature sensor is used to measure the local water temperature. For simplicity let's assume that the sensor is defined by three parameters, its size, its power consumption, and its speed of response. Based on first principles (physics) we can bound the limits of sensor size, power consumption, and reaction time (as shown in the figure). As the system evolves these parameters will be adjusted until the entire system (roboswimmer, sensor suite, and collaboration architecture) is optimized. By looking at each sensor we can determine if a focused technology push will be required to meet the design goals.

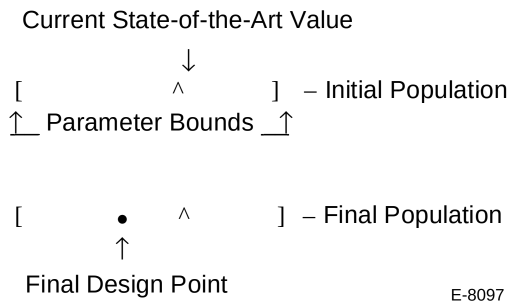

Figure 22. Each sensor will be defined by a set of parameters. For each parameter we will define realizable bounds on its range of values (including foreseeable technological advances over the next few decades). As the system evolves (optimizes its fitness) these parameters will be varied within the prescribed bounds. The end result will be a set of discrete parameter values that define the performance of the sensor.

We can also determine the sensitivity of the entire system to specific parameters by moving their boundaries. For example, we may want to know if the architecture of the roboswimmer system is tightly coupled to temperature sensor size. To investigate this we can limit the acceptable size of a temperature sensor and see what roboswimmer system evolves (Figure 23).

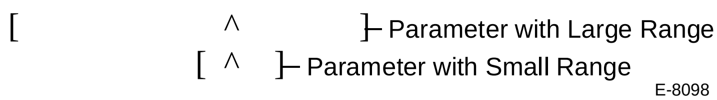

Figure 23. The range on individual parameters can be reduced to investigate the sensitivity of the final solution to these parameters.

As discussed before our approach to Europan exploration is based on teams of roboswimmers. We have specifically chosen the word "team" to highlight the fact that the individual roboswimmers are in many cases not identical, they may have different forms (e.g., fish and crabs) and different sensor suites (e.g., some fish may measure temperature while others measure a chemical concentration). To create these teams our methodology specifically allows the sensors selected for an individual to be optimized. Each roboswimmer is given the capability to carry and use all available sensors. During synthetic evolution the sensors selected by an individual will be varied along with its form and collaboration scheme. In this way the **system –** sensor suite, vehicle form, and collaboration scheme - is optimized.

3.5.2.3 <u>Collaboration and Cooperation</u>

In Phase I a relatively simple communication and collaboration scheme was devised and implemented. The important features of this scheme are, each roboswimmer is autonomous, the scheme does not require complex algorithms or large computing power, and simple individual behaviors result in a desired global behavior. In the next phase of this research this methodology will be significantly expanded and enhanced.

One aspect that we will focus on is that of collaboration. Here we wish to develop techniques that will allow multiple roboswimmers to act together to achieve a specific goal. This can include simple request-response scenarios where an individual can request assistance from other roboswimmers with differing capabilities (e.g. a thermal gradient has been detected and it is important to determine if there are also chemical gradients).

Collaboration is enhanced by the team architecture. Allowing vehicles of differing types to interact (communicate and cooperate) will enable strategies that would be impossible for a homogeneous set of roboswimmers. For example, a slow moving roboswimmer like a seahorse can request that a swift vehicle (a fish perhaps) pre-survey and area to identify the most promising locations for a detailed exploration. This has some very clear benefits. Teams allow for very efficient search strategies. Because different vehicles can explore in widely different modes (slow, close inspections to fast, coarse surveys) the team can be deployed in a very efficient manner. Faster vehicles can pre-survey an area and select likely targets for the slower vehicles to explore.

Another interesting approach that will be investigated is that of short-term symbiotic relationships between roboswimmers of different form. In Monthly Report 3 we showed that for certain assumed environments new vehicles types (hybrids) were preferentially selected. These roboswimmers had characteristics of several discrete types, for example a fish with crab-like legs. This hybrid was selected because it was able to explore and identify Interesting Regions more quickly than other vehicle types. Another way of considering this result is not as a hybrid vehicle type, but as a symbiotic relationship. A fish with crab legs could also be created by having a fish carry a crab. When the crab wishes to move to a new area quickly it could request a "ride" from a fish. This would allow the slower crab to explore over a larger area than if it only walked.

3.5.3 Unified Design Approach

Simply stated, our Unified Design Approach takes the individual design efforts of Phase I and combines them into a single roboswimmer system design tool. While in Phase I the individual characteristics of the system were optimized, in the next phase they will be integrated and optimized together.

The approach is very similar to that developed in Phase I. The system will be parameterized and the parameters assembled onto a virtual chromosome. A fitness metric will be created and used to asses the performance of each population. Individuals with superior fitness will be preferentially selected and allowed to reproduce to create the next population. This process will be continued until the system is optimized. The result of this process will be a system design that optimally explores the Europan environment search for life. The number and type of roboswimmers will be identified and the scheme they employ to collaborate and cooperate will be described. An additional important result of this design process is the identification of the technology areas that will have to mature to enable our system design. This has the benefit of providing to NASA not only a final system design but also a technology development roadmap.

3.5.4 Summary

The enhancements described above are certainly not exhaustive but represent some of the important improvements we feel would significantly improve the fidelity of our Synthetic Evolution approach to roboswimmer form and function design. The simple models we have developed in Phase I are a good start and have certainly shown that the approach is feasible. In the next phase our aim is to create realistic environments and allow our system to evolve roboswimmer teams from a systems standpoint. Because of the complexity of the interaction between the environment, the sensor suite, the vehicles form, and the collaboration and cooperation architectures we feel that unified design approach described above is potentially the only feasible methodology.

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