Create Adaptive Systems through "DNA" Guided Cellular Formation

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Abstract. How to design functional systems that can adapt itself to the changing operation environment is a challenge for the design community. We take a "naturalistic design" approach by exploiting the natural "design" process and mimicking its DNA based way of capturing, representing and applying "design" information pertaining to needed functions and changing operational situations. Utilizing "*design DNA"* and a "*priority distribution mapping"* technique, mechanical cells form a functional system through self-organizing.

Keywords: Design synthesis, bio-inspired design, self-organizing, cellular formation

1 Introduction

Research on design creativity has mostly been concerned with understanding how human designers create their design ideas and with developing better ways to help designers be more creative. Another drastically different way to pursue the same research is to investigate how Mother Nature created and keeps creating new creatures and novel phenomena. Bio-mimetic design is an evolving area where researchers attempt to find ways to take advantage of the "design ideas" that the nature has already created (Sarikaya 1994, Vincent and Mann 2002, Chu and Shu 2004). Furthermore, using genetic algorithms and genetic programming techniques, which somehow mimic the "idea generation" process of the nature; researchers were able to use computers to help generate novel solutions to some engineering problems.

Putting aside the philosophical discussion, we may observe that human design and natural design are very much distinct from each other: human design is more purpose or function driven and takes a top-down approach, while natural design is arguably much less purposeful and follows a bottom-up approach. These two forms of design are dictated by the difference in the ways the designs are realized. Humans can make things the way they want so that the realization can be actively pursued. The nature, however, does not "make" things happen. It "lets" things happen: the things "self-organize" themselves under given situations by following natural laws. It can be argued that the creativity in the nature exists among the "self-organizing" based option generation and "survival driven" choice making.

Our research on self-organizing based design creativity was motivated by an investigation of developing complex adaptive systems such as environment-adaptable robots. We are interested in combining the advantages of human and natural design methods and design systems that can design and build themselves by following a self-organizing strategy that on the one hand recognize the functional needs and on the other hand explore creative opportunities through self-organizing. In the following sections, we first briefly review the related work (Section 2) and then introduce the representation framework of our "design DNA", or dDNA for short, based cellular formation approach (Section 3). Case examples are discussed in Section 4 and concluding remarks drawn in Section 5.

2 Related Work

The idea of developing a naturally inspired cellular system capable of reconfiguration is not new as many research groups have been actively investigating this topic over the past 20 years. This area of research has come about because of the need for autonomous artificial systems to be capable of dynamically adapting and reacting to a changing environment while still performing their predefined tasks. The basic idea behind such systems is that given a set of simple homogenous cells that are incapable of accomplishing complex tasks alone become capable of doing so when joined together in various configurations or *gaits*. Two such examples are PolyBot (Yim et al. 2000) and SuperBot (Shen et al. 2006). The authors of SuperBot take the biological idea a step further through a hormone-inspired control algorithm (Shen et al. 2002). In (Zykov et al. 2005), Hod Lipson's group investigated and demonstrated autonomous self-replication in the context of homogeneously composed

systems comprised of cube modules. With regards to increasing a system's adaptability, the idea is that such systems have the capability if damaged to construct a detached functional copy of its non-functioning self.

In (Unsal et al. 2001) the authors of *I-Cubes* investigate a simple heterogeneous system's adaptive capability through reconfiguration. The authors developed a simplistic system composed of elements made up of passive cubes and active links capable of attaching and detaching around them. Similar to this idea the authors of (Yu et al. 2008) developed a modular heterogeneous system composed of active and passive links, surface membrane components, and interfacing cubes to achieve a Tensegrity model of cellular structure. Utilizing such a model the system is capable of contracting and expanding allowing itself to configure to various shapes capable of performing various functions. In (Rus and Vona 2001) the authors discuss their *Crystalline Robots* by approaching reconfiguration through a different means where rather than moving individual units across the surface of a structure, transformations take place internally through contractions and expansions of the entire body similar to an amoeba. In (Bongard et al. 2006), Lipson's group further investigated adaptability through means other than reconfiguration through a technique called continuous self-modeling. The group demonstrated a system with damaged extremities capability of self-discovering alternative gaits with its remaining working appendages allowing itself to continue to function. Amongst this work and the previously discussed, Lipson's group has produced many other notable innovations in this field and as such much of our work and the work of others have been significantly inspired by their visionary efforts.

3 cFORE: Cellular System Formation and Representation

Answering the questions posed in section 1 requires a comprehensive representation framework that maps biological system concepts into mechanical systems. Figure 1 illustrates our cellular system formation & representation (cFORE) scheme that is being developed to facilitate synthetic DNA-based adaptive system development.

As shown in Figure 1, cFORE is developed through synthesizing system formation concepts from both the fields of biology and mechanical engineering. After an extensive review of biological literature, we have identified 16 key biological concepts and processes that are integrated into the cFORE framework together with key design concepts found in mechanical engineering. In the following, we first present the definitions of a selected set of concepts and then discuss more about them in the Simulation Study and Discussion section. Corresponding biology concepts are sometimes associated in parentheses when appropriate.

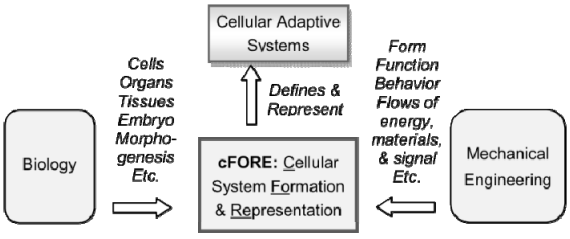

Fig 1. cFORE model and its relations with biology and mechanical engineering

Definition1-Mechanical Cell: A mechanical cell, mCell, see Figure 2, is defined as: mCell = {Cu, (f), (Φ), dDNA, Es, Ec, Mc}, where;

Cu: control unit (nucleus), *dDNA*: design information, (Φ): centroidal location, (f): 6 sides, Es& Ec: energy storage & converter (mitochondria), Mc: material converter (lysosomes).

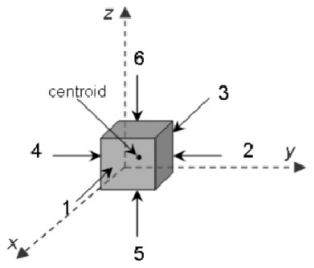

Fig 2. A simple mehanical cell model. Each cell has a centroid location and 6 sides which may perform certain functions.

Definition2-dDNA: *dDNA* is a matrix representation containing a system's genome:

$$dDNA = \begin{bmatrix} (\phi, f_c, F_p)_{1,1} & \mathsf{L} & (\phi, f_c, F_p)_{1,n-1} & (\phi, f_c, F_p)_{1,n} \\ (\phi, f_c, F_p)_{2,1} & \mathsf{L} & (\phi, f_c, F_p)_{2,n-1} & (\phi, f_c, F_p)_{2,n} \\ \mathsf{M} & \mathsf{L} & \mathsf{M} & \mathsf{M} \\ (\phi, f_c, F_p)_{m,1} & \mathsf{L} & (\phi, f_c, F_p)_{m,n-1} & (\phi, f_c, F_p)_{m,n} \end{bmatrix}, < MIS >$$

Each item in the above matrix is a mCell Gene with a Priority ID m. A realized *dDNA* matrix is a complete description of a specific system or product, which we call system genome or sGenome. Note that the mCell Genes with the same m ID's have different locations, i.e., (x, y, z)'s. Therefore, the number of rows of each column in a *dDNA* may not be the same and depends on a product's genotype-phenotype mappings. An sGenome contains information regarding, from global to local: functional priority layers, cellular locations

(Φ), cellular functions (f), and self-growth mCell instruction set (MIS) (transcribed protein sets).

Definition3-mCell Gene: mCell Gene, Gc, is defined as:

$$G_c = < \phi \quad F_c \quad F_p >$$

The information inscribed per Gene is Φ cellular location, F_c cellular level functions, and F_p system level priority functions. More precisely, an mCell Gene is defined as,

$$G_c = <x,y,z,(f_1 \ldots f_{n1})_1,(f_1 \ldots f_{n2})_2,(f_1 \ldots f_{n3})_3,$$
$$(f_1 \ldots f_{n4})_4,(f_1 \ldots f_{n5})_5,(f_1 \ldots f_{n6})_6,P>$$

where (x, y, z) is the geometric location of the cell with respect to a reference *central point*; (f1.., fn) are the cellular functions per face of the cell (we assume to have 6 faces as we are dealing with a cubic mCELL as defined in figure 2), and P is the priority of that particular cell to the overall system's form and subsequent system level function. The concept of system level priority functions or simply *priority* is necessary in the context of determining a system's adaptive capability. During operation, when identifying a system's gaits or reconfiguration states, system *priority* determines the location that reconfiguring cells desire to occupy. Namely, in a system's *Priority Distribution Map,* which will be discussed in greater detail in the following section, a designer has the control to determine where certain cells may reconfigure to in order to either maintain current system level functions (such as walking, climbing etc.) or dynamically create new ones. In essence, the higher is a particular position's priority with respect to the overall system, the more desirable it will be for the cells searching for a place to reconfigure to. For our current systems we define 4 possible levels of priority: Highest, High, Middle, and Low with values of 1, 0.7, 0.5, and 0.3, respectively. Depending on the method used to implement *dDNA* and sGenome and consequently the process of design evolution may take different forms. Figure 3 illustrates the Gene of an arbitrary mCell.

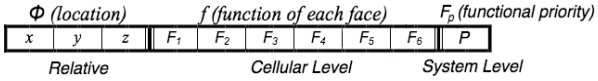

Fig 3. An example of mCELL gene that encodes location, cell level and system level functions

Definition4-mCell Instruction Set, MIS (transcribed protein set): MIS is defined as one of 2 types of instruction sets (proteins):

<mCellInstructionSet>::= <enzymes>|
<structuralInstructions>| <communicationInstructions>

<enzymes> :: =
<cellularFunctionExpressionInstructions><formationInstructions>
<cellularFunctionExpressionInstructions> ::=
<expressionActions><generalActions>
<formationInstructions> :: =
<formationActions><generalActions>
<structuralInstructions> :: =
<structuralActions><generalActions>
<communicationInstructions> ::=
<commActions><generalActions>.

In biology, amino acids are the basic structural building units of proteins. Similarly we define a group of cellular actions and group them into 4 sets.

Definition5-Cellular Actions (amino acids): a set of cellular actions is defined as:

<cellularActions> ::= <generalActions> |
<expressionActions> |
<formationActions> | <structuralActions>| <commActions>
<generalActions>:: =<(x,y,z), F1, F2, F3, F4, F5, F6, &, P>: General actions that stores centroid location (x, y, z), mCell face information F1 through F6, the "&" operation, and P priority.
<expresionActions> :: = <f1 f2 … fn>: Expression amino acid that stores cellular functional expression instructions.
<formationActions>:: =<u d l r f b A D #> formation actions that store the formation actions. u, d, l, r, f, b, A, D, # stand for up, down, left, right, forward, backward, attach, detach and an integer value respectively.
<structuralActions> :: = <cs1, cs2, …>: Structural actions that stores construction actions.
<commActions> ::= <cm1, cm2, ...>Communication actions.

An example of an instruction (protein) composition of cellular actions is:

<formationInstructions> =
(2,1,6)DF3d1AF3(1,1,5)AF1,

which states that the cell at centroid location (2,1,6) should detach face 3, move down 1 and attach at its face 3 the cell at centroid location (1,1,5) at its face 1.

Given an sGenome encoded in *dDNA* and its transcribing methods defined above, mCells will need mechanisms to apply this design information including instructions to grow into the desired system and reconfigure into new ones. One key process governing the self-growth from an embryo to a mature system in biology is morphogenesis, which determines the shapes, sizes, and layouts of organs, tissues and overall body anatomy (Audesirk et al. 2007). Essentially, morphogenesis is guided by a set of rules or principles followed by an embryo in its transformation into a complete system. Drawing insight from this concept we introduce a similar process for our CAS. A set of Self-formation Governing Principles, or SGP was developed to guide the self-organization of mCells in forming a bio-inspired system. It has been recognized that all biological systems follow a "minimization of energy principle" when they undergo growth,

development or preservation of life (Vincent et al. (2006)). In cFORE, the SGP is defined as follows.

Definition6- Self-formation Governing Principle, SGP (morphogenesis):

<SGP> :: = <layoutPrinciples>| <developmentPrinciples>
<layoutPrinciples> :: = [System layout is determined by dDNA genes and priority at mCell levels]
<developmentPrinciples> :: = <PriorityFormationOrder>|<celullarActionPrinciple>|<systemFormationPrinciple>
<PriorityFormationOrder> : : = [Form highest priority first, if no priority exists then form middle priority, if no such priority exists then form lowest priority, if no such priority exists then begin bonding formed priority layers together]
<celullarActionPrinciple>::= [Minimize energy needed to carry out cellular actions]
<systemFormationPrinciple>::= [Minimize total energy needed to carry out actions of all mCells]

4 Case Example and Discussion

Given the cFORE framework, two questions must be addressed in order to realize our synthetic DNA based approach to developing adaptive systems. First, *dDNA* should support system design so that a specific sGenome can be composed either by designers or through computing. Our previous research on evolutionary design has shown preliminary viability of such a *dDN*A based approach (Jin et al. 2005). Further research is being carried out to deal with this issue. Second, adaptive systems must be able to build themselves from mCells based on a given sGenome and be capable of reconfiguration based upon the system's appropriate *functional priority*. To address the second question, we conducted a computer simulation study using the cFORE model. The goals of the study are (1) to verify the effectiveness of *dDNA* and sGenome representation and (2) to test the effectiveness of the SGP based self-growth of adaptive systems based on given synthetic DNA information and reconfiguration based on the system's functional priority inscribed within it. As such the questions that we wish to address in our simulation study are: (1) can a set of individually interacting cells seeded with a particular *dDNA* self-grow into the desired system? (2) Once formed into the desired system, can it be given a task and instructed to operate in a changing environment such that the only viable means afforded to it to continue functioning and reaching its goal is through reconfiguration? Figure 4 illustrates our objective.

In figure 4, the simulation's beginning (step 1) is meant to mirror the second step after the origination of a biological system (conception) known as the Blastula Stage. Once conception has occurred, the newly

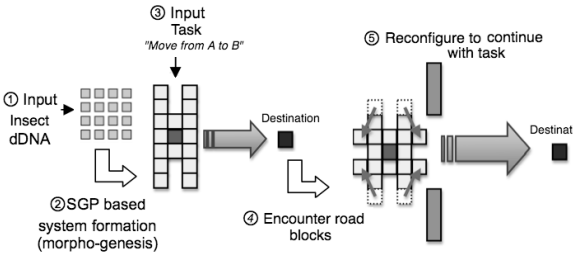

Fig 4. An adaptive reconfigurable system that reconfigure through self-organizing when encounter obstacles

formed cell containing the genetic information from both parents undergoes rapid cell division to form a collection of undifferentiated (non-specialized) cells. Since cellular division is not a viable possibility utilizing currently available technology, we have chosen to begin the simulation at Blastula with a given finite number of mCELLS. From this point forward the process of morphogenesis (*SGP*) takes over and utilizing cellular communication techniques, cells begin collaborating with one another in order to coordinate the process of forming the overall system. Through cellular communication and guidance by morphogenesis (*SGP*) the cells are able to self-organize to form the required shape of an insect-like system with a functioning torso (protecting the *central point*) and legs (used for motion). Color differentiation in the simulation is analogous to cellular functional differentiation in biology. Great care and attention has been taken to develop a system which as closely as possible mimics biology not just in form, but more importantly in function as well. Once the system has been formed (step 2), given a task (step 3), and placed in an environment with various obstacles (step 4), it is then up to the system to utilize its *Priority Distribution Map (PDM)* in order to navigate through to its goal (step 5).

Functionality in this problem is seen in two facets through both system level as well as cellular level functionality. Cellular level functionality is seen through color change (cellular differentiation) while system level functionality is seen through the formation of the overall system which not only looks like an insect, but also functions like one as well. This is so because contrary to engineering design, it can be argued that in biology *form* begets *function* rather than the converse. This is one of the keys differentiating biology from engineering and is often a concept that is overlooked. If a system looks like *something*, more often than not it will function like that *something*; in biology *form* dictates *function*.

As one can note from the figure, the particular problem shown is a 2 dimensional problem.

Development of the morphogenesis-based control algorithm and the communication protocols are critical aspects of this problem. Our simulation system is built using a Java-based multi-agent simulation package, MASON. In the simulation, each mCell is treated as an agent. All mCells can move in 2-dimensional space (x, y) and for simplicity are assumed to only express a single cellular function, *attachment*. The color change of the cells in the above from grey to yellow signifies cellular differentiation.

Cellular differentiation implies a cells readiness to begin functioning as part of the complete system by expressing cellular level functions (attachment) in achieving system level functions. System level functions for this particular example are discussed in greater detail below. The mCells can communicate with each other through a shared message board. A binary method, similar to that shown in Figure 3, was used to implement the system's *dDNA*. The Φ coordinate as previously mentioned is a relative coordinate system based on the location of the *central point*, denoted in red in the above figure. The initial *dDNA* definition for the entire system and subsequent updates to its coordinates as the system moves are all with respect to the *central point*. The key in building in adaptability into the system is through the development of its *PDM* and its injection into the *dDNA* matrix through the *functional priority* element of the each of the system's mCELL Genes. The *PDM* of the above system can be seen in figure 5.

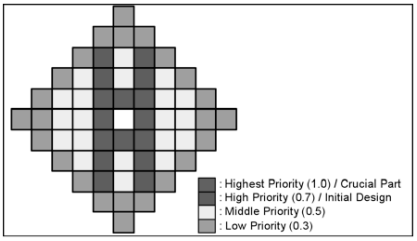

Fig 5. Abstraction of the physical states that a system, defined by dDNA, can hold

In the above *PDM* figure, the critical part of the system, i.e. the area designated in red with the highest priority is the part of the system in which the cells are responsible for maintaining the system level function of *protecting* the *central point*. This portion is critical because if this part of the system were to be damaged it would result in damage to the central point causing the system to *die*. The initial design of the system also includes the area designated by the magenta color that includes those cells responsible for expressing the system level function of *movement*. The areas in yellow and green represent possible reconfigurable states (of the magenta cells) the system can achieve if the need arises. Dependent upon the environment encountered, the cells of the system dynamically recognize the obstruction and reconfigure based upon the priority of the open spaces defined in the system's *PDM*. Control of the coordination of the system is achieved in a two-step process. Initial formation of the system (steps 1 and 2 from figure 4) is achieved through SGP (self-formation governing principles) and is implemented by following a CPM algorithm utilizing a dual control strategy incorporating both centralized and decentralized control in mimicking the biological morphogenesis process. Centralized control will come by way of DNA guidance while decentralized control will be utilized for the self-organization of the cells. The centralized control aspect of the algorithm is somewhat simpler to address than the decentralized aspect as the inclusion of the predefined *dDNA* matrix forces the emergent behavior of the self-organization of the cells to precisely that required form (function). The decentralized aspect of the control algorithm is a bit more complicated as it requires communication, collaboration, and negotiation between the cells trying to self-organize. Therefore a definition of the local rules that govern the interaction between the individual cells is a critical component of this aspect of the algorithm.

Through our investigation into biology and attempting to understand the process of morphogenesis it was clear that the foundation of the algorithm should be rooted in energy minimization. Since cellular movement with regards to system formation accounts for the prime source of energy dissipation, minimization of the total number of cellular steps would be desired for the algorithm. Therefore the primary goal of this demonstration besides obviously the formation of the system defined by the system *dDNA*, is its formation through the least number of steps possible, i.e. minimum energy.

The name of the algorithm *CPM* comes from Calculate, Plan, and Move. Just as in biology, communication is vitally important in morphogenesis and is achieved through the use of growth factor proteins. In the programming domain, the messages sent back and forth between the cells in effect mimic this biological protein. Communication is important, as the cells are required to know where they are going relative to one another while organizing. If no communication exists, a collective goal between all the cells can never be achieved. Planning and coordination is the result of communication. Every element in the *dDNA* matrix defines a unique cellular location and priority relative to the entire system, hence not every cell can move to the same location. Furthermore, cells need to determine *on their own* which position they should move to based on the energy minimization principle. Once the cells have an

idea of where their final locations should be, they should begin to move to that location. The beauty of this algorithm is that this process can be done in real-time so that the cells at each time step can recalculate their relative distance to those defined in *dDNA* and re-determine whether or not they are heading to the position with the highest priority and minimum energy; if so they continue, and if not they re-adjust. A schematic of the CPM algorithm used in system formation can be seen in the figure 6.

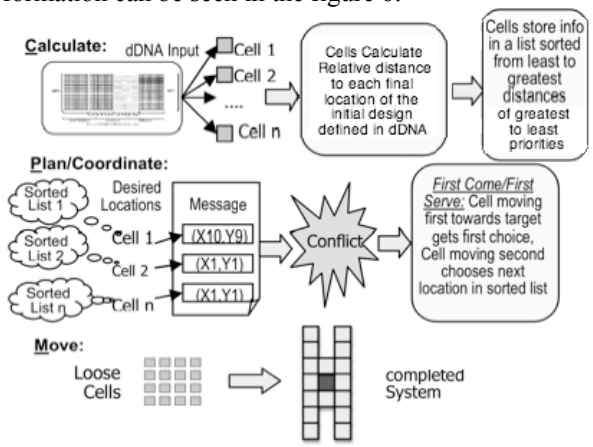

Fig 6. An illustration of the CPM (Calculate, Plan, Move) control algorithm.

The above figure shows that the first step in the process is that the desired system DNA (*dDNA*) must be seeded into each of the available cells (with cell IDs from 1 to n). In biology this step is not necessary as each dividing cell simply gets a copy of the system's DNA. The cells then use this information to calculate their relative distances to each of the final locations defined by the system DNA. The cells store this information in a list sorted from the least distance to the greatest based on priority. Planning and coordination occurs through communication whereby the cells following <layoutPrinciples>, <Priority FormationOrder> and <cellularActionPrinciple> send messages about their first choice of final DNA destination to a communal message board accessible by all other cells. In the case two cells calculate the same minimum DNA final location a conflict arises and the cells must coordinate and negotiate to see who gets that final position. Looking to utilize a simple solution to this problem, we create what we call a "First Come First Serve" <systemFormationPrinciple> used for resolving conflicts whereby the cell (defined by its ID tag) moving first towards the desired target location gets the first choice and the cell moving second must settle for its second choice. But this may lead to a further conflict as this second choice may be a first choice for another cell. In that case "First Come First Serve" gets applied again to resolve the matter and so on until all conflicts have been settled and each cell has a unique final DNA position. Once all cells have a tentative final location the simulation is taken through a single time step and the *CPM* process is repeated for each successive time step in order to optimize the minimization of the overall system energy.

Control of the reconfigure aspect of the system (steps 4 and 5) follows 4 basic rules of the System State Rule Set or *SSRS*: (1) Cells can only connect to one another at their respective cellular faces. (2) Cells must always avoid collisions with environmental obstructions. (3) Cells continuously communicate with one another about movement preferences (priority) and decisions using a communal message board. (4) System must always properly configure (dictated by environment) to a state with the highest overall system priority.

Figure 7 shows the result of one simulation run in which initial undifferentiated mCells receive insect *dDNA* and a task to move the red *central point* to the blue destination point. Upon receipt of the *dDNA* information, the undifferentiated cells form about the *central point* and proceed to move through the environmental terrain to the destination point. Once the system encounters the first roadblock, it reconfigures based on the *PDM* inscribed in the system's *dDNA*. We assume of course that the system cannot simply travel above or below the roadblocks. Upon fulfilling rule 4 of *SSRS*, the system continues towards its target where it encounters another roadblock, repeats the process until reaching its final destination point. Figure 7 is summarized below:

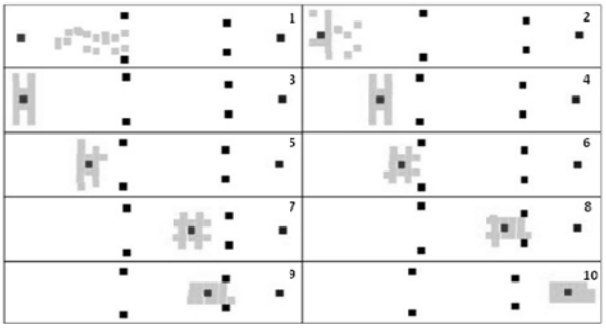

Fig 7. Simulation results, progression of time from left to right and from top to bottom

Step1: After DNA seeding has occurred, the cells move towards the red *central point* guided by *SGP*.

Step2: After reaching the desired location defined by *dDNA*, mCELLS begin forming the desired system.

Step3: mCELLS successfully form the desired system.

Step4: The system moves towards blue target point.

Step5: Encountering the first environmental roadblock the system first senses the obstruction and then begins formulating a solution by self-organizing.

Step6: The system continues trying to find the adequate reconfiguration state.

Step7: The newly modified system, which is no longer an insect-like system continues moving.

Step8: Again the system attempts to reconfigure per defined system *PDM*.

Step9: Reconfiguration continues until is it able to go through the narrower blocks.

Step10: The system reaches its final blue destination point.

Summarizing the results of the multiple simulation runs, we found that (1) system growth can be realized through a *dDNA* controlled and decentralized cellular self-organizing formation strategy; (2) as in biology, cellular self-organizing for self-growth of mechanical systems can be achieved through the use of *dDNA* and SGP (morphogenesis) principles, and cellular actions including <commActions>; and (3) Mechanical system reconfiguration as a means of modifying or attaining new functionality is primarily a result of the priority inscribed in a system's *dDNA*. Moreover, the simulation design and results also have pointed us to some important and otherwise unidentified issues.

Conflict Resolution: Since each mCell applies <cellularActionPrinciple> that demands minimization of cellular energy usage (i.e., travel distance in this simulation), it is likely that multiple mCells may desire to fulfill the same cellular location. Hence the "First Come First Serve" conflict resolution technique was needed to overcome the arising conflicts between the mCells. Essentially the cells may be regarded as selfish entities with very little consideration for their neighbors or the global system in which they are a part of. The world in which they are operating in is strictly numerical as the primary algorithm that guides their behavior is based strictly on mathematics. As such, removing "First Come First Serve" altogether from the algorithm produced systems in almost all of the simulation runs with "holes" in their morphology. The undeveloped system occurs because more than one cell has chosen to occupy the same final DNA position because the cells have no means of resolving the conflict of selecting the same final DNA location with one another. Therefore if they cannot resolve the conflict, they simply ignore it and move to the same location.

Cellular Communication: Cellular communication is another important factor that affects the outcome of dDNA based self-growth and subsequent reconfiguration process. Again, the chief issue is conflict between or among mCells. Cell division (mitosis) based bio-cell creation eliminates tremendous needs for cellular communications. But in the mechanical world where cellular coordination replaces cellular division, the case often arises where two or more cells select the same final DNA location. Therefore without proper communication between the cells, no negotiation and coordination can occur between them, i.e. "First Come First Serve" never gets enacted because such a technique is heavily based upon communication. Hence the outcome of eliminating cellular communication entirely is again an undeveloped system with "holes" because cells simply move to the location of minimum energy and highest priority without any regard for who has already moved there first.

The choice for the use of a communal message board with access to all cells was made as it was the easiest means of keeping track of all the required cellular information. But in the case of increasing the amount of cells from 17 to 100, 500, 1000 or more, the information becomes extremely difficult to handle. We envision that successful cellular communication is a key for effective *dDNA* and mCell based system formation and reconfiguration.

Information of *dDNA*: A third important parameter is DNA and the information it stores. As in biology, the need for the inclusion of *dDNA* into each mechaniCELL is required to give each cell knowledge of the greater picture of which it comprises only a small portion. Contrary to biology though, which seeds each cell with DNA through cellular division, the computer model required individually seeding each cell with the appropriate *dDNA*. As in biology, without DNA, the cells comprising the system would simply function as independent cells never expressing system level genes. Hence system level forms and functions can never be expressed and the resulting system is simply a collection of cells with cell divisions occurring out of necessity rather than requirement. Furthermore, if the cells are seeded only with information regarding the initial formation of the system (i.e. the insect) with no information relating to the system's *PDM*, the resulting system would not be capable of reconfiguring and hence navigating through the various environmental terrains (Steps 4 and 5).

Adaptability through Priority: With regards to the adaptability, more specifically reconfiguration, the priority information inscribed in *dDNA* reflecting the *priority distribution map* is crucial. Testing the importance of priority to the adaptability of the system in the mechanical world, we observe that without this information, the resulting system simply stops upon encountering the first roadblock. It is only through the system's *PDM* that the system can navigate through the varying environmental terrain. The limitation of the *PDM* technique is rooted in the fact that

irrespective of the size of the *PDM*, if the roadblock encountered impedes upon the system's critical area (i.e. red zone in figure 5), the system will fail.

5 Concluding Remarks

Bio-inspired design is not a new area. But unlike other bio-mimetic engineering research that mimic mechanical mechanisms of specific animals or plants (Shu et al. 2003, Dickinson 1999), our approach uniquely attempts to mimic the *biological process* of creating, storing, and applying *design* information. Again, self reconfiguration is not a new idea, but our work differs from previous ones at a fundamental level with the incorporation of DNA and morphogenesis. Through the incorporation of *dDNA*, our work is unique in that it simply defines what the final system should be through *dDNA* and allows the cells to independently self-organize through communication protocols and local interaction rules (morphogenesis rule set) to achieve it. There is a great deal of robustness in this process and algorithm in that any desired system can be formed as long as it can be defined by *dDNA*. Furthermore, reconfiguration or alteration of the system is easily achieved through the incorporation of *priority*. In order to build a true *mechanical lifelike cellular adaptive system* for the purposes of increasing a system's adaptability and robustness, fundamentally the artificial system must not just be formed using a concept of "cells", but to be represented by *dDNA* and grown using a morphogenesis-based process whereby both the forms and functions of the system are emerged.

From a design creativity perspective, we attempted to take a nature's way of creating designs by exploring how a system should be formed, meaning how design information should be represented, stored and applied so that natural "creativity" can be realized. Although at this stage we have not stepped into the realm of letting systems evolve by themselve, the representation scheme we proposed has demonstrated its robustness to achieve adaptability. Next step is to make it evolve.

From a system design point of view, our work thus far is limited in several ways. First it is only tested in a 2D setting. Moving to 3D and going beyond moving-boxes will yield more challenges. Secondly, our work is limited by the method of computer simulation. Physical or mechanical issues such as communication, docking between cells, and physical movement of cells have not been addressed. Lastly, there has not been any exploration of "best dDNAs" and "best rule sets" that may lead to "better functionality and adaptability." Despite these limitations, our simulation-based case studies demonstrated the effectiveness of our cFORE framework and led us to a better understanding of the key issues related to *dDNA* based adaptive system development. Our future work will address the above mentioned issues.

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