

Morphogenetically Assisted Design Variation

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Abstract—Current engineered systems are often brittle and hard to modify in contrast to living organisms, which adapt to structural changes in a graceful and integrated manner. We refine the concept of functional blueprints, an attempt to capture this adaptability, and present an architecture for adjusting a design through the execution of a network of functional blueprints. We then use our architecture to investigate the efficacy of the functional blueprint approach, presenting a preliminary empirical study of the convergence dynamics of random networks of functional blueprints. Convergence is both rapid and reliable for a wide range of parameters, demonstrating that even simple blueprints can provide effective design adaptation over a wide range of circumstances and pointing the way toward both a deeper theoretical understanding and practical applications.

Keywords—morphological computation, spatial computing

I. INTRODUCTION

Engineered systems tend to be brittle in their design, particularly as the complexity of a system's design increases. Once a system has been constructed, it is difficult to modify the design without a vast number of consequences that can be unpredictably difficult and costly to address. Animals, on the other hand, adapt gracefully as they grow and develop, with many feedback loops acting together to make changes that maintain the integration of the organism as a whole. Indeed, the flexibility and dynamicism of integration appears to be a key enabler of the evolution of biological life [1], [2].

We wish to enable such adaptability in the design of engineered systems, so that when a designer modifies one element of a design, the rest of the design automatically adjusts to compensate. Our approach is to specify a design using *functional blueprints (FBs)* [3], in which the design specifies behavioral goals and a method for adjusting the structure when those goals are not met. Previously, we have proven that it is theoretically possible to construct FBs that allow a system to navigate through the space of viable designs, and have demonstrated a cartoon model of tissue growth.

In this paper, we present preliminary results on the generalization of the FB framework for use in an interactive design tool. We begin with a description of the FB concept and related work, then present the Morphogenetically Assisted Design Variation (MADV) architecture for adjusting a design through the execution of a network of FBs. Finally, we present the first empirical evaluation of the convergence dynamics of FBs, by studying the perturbation response of randomly generated networks of FBs. We find that these networks disperse stress

quickly, reliably converging to an appropriately adapted set of values.

II. FUNCTIONAL BLUEPRINTS

A *functional blueprint* [3] consists of four elements: 1) a *system behavior* that degrades gracefully across some range of viability, 2) a *stress metric* quantifying the degree and direction of stress on the system, 3) an *incremental program* that relieves stress through growth, shrinkage, or other structural change, and 4) a program to construct an initial viable *minimal system*.

Graceful degradation of system behavior asserts that the core functionality of the system must not have a sharp transition from viability to non-viability. The stress metric and incremental program combine to shift a degraded system's configuration back toward viability. Finally, the minimal system makes sure there is some viable place to start.

Consider the example of a robot designed to climb stairs of a certain height. As the height of the stair increases, the robot will begin to struggle and the climbing behavior FB creates a stress to increase the robot's body length. As the robot's body grows, the additional mass strains the drive system and the robot's maximum acceleration rate decreases. A mobility related FB creates a stress on the motor configuration, which is relieved through the inclusion of larger motors. The larger motors provide the desired acceleration but also reduce battery life, and another FB for endurance creates a stress. This propagation of stress and relief via FB continues on until the system reaches a stable configuration. In this way FBs are able to capture extensive networks of dependencies in a system, not through the explicit representation of these dependencies, but through the declaration of desired behavior, and a means of adjusting parameters when the desired behavior is degraded.

A. Related Work

In recent years, observation of natural systems has led to investigation of how growable patterns might be programmed, generally focusing on geometric shape with less attention to integration of function, e.g., [4], [5], [6], [7]. Most similar to FBs is Werfel's work on distributed construction of structures adapted to environmental conditions [8].

Many projects in self-reconfigurable and swarm robotics also consider the formation of self-adapting design, e.g., [9], [10], [11]. Each of these approaches tends to focus on a particular adaptive structure algorithm, making them complementary to FBs, which could be applied to make such algorithms compose together.

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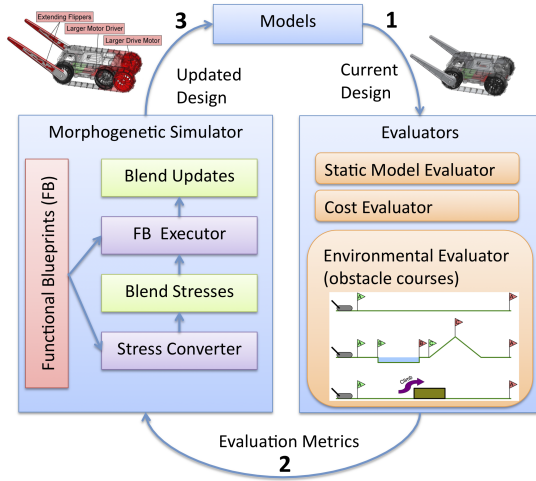


Fig. 1. The MADV architecture iteratively adapts a design against a collection of functional blueprints using a three stage loop: (1) evaluating system behavior, (2) blending action of all of the functional blueprints in a morphogenetic simulator, and (3) producing an incrementally modified model.

Control theory also addresses problems of system integration, but generally has difficulty with large numbers of non-linearly interacting parts. A notable exception may be viability theory [12], a branch of mathematical theory which is intended to address such concerns, thought it still focuses on systems well-described by differential equations.

III. ARCHITECTURE

The Morphogenetically Assisted Design Variation (MADV) architecture is structured around a design modification loop, as illustrated in Figure 1. First, the functionality of the current design is analyzed by a set of *evaluators*, each of which returns a set of metrics. The metrics are processed by the *morphogenetic simulator* to produce a set of stresses for each FB. Each set of stresses is blended together to produce the collective stress for its blueprint, which is input to the blueprint’s update function. The outputs of the update function are changes to design attributes, which are likewise blended together and used to produce a modified design. The loop is run until the design converges. The same blending function is used for blending stresses and for blending attribute updates:

$$V = \text{sign}(\sum_i V_i) \cdot \max_i(V_i \frac{\sum_i V_i}{\sum_i |V_i|}).$$

This blending function preserves the direction of the sum of the values, resulting in a value that is a fraction of the largest value in that direction. It is designed to result in smaller values when blending values with opposite signs, but preserves the maximum value when all the values have the same sign.

A series of evaluators are used to determine how well a design accomplishes specific tasks. For example, a robot model might be evaluated in many ways including cost, component interaction complexity, and satisfaction of overall objectives. In one case that we have been considering, our environmental evaluator examines the time it takes a robot to climb a step

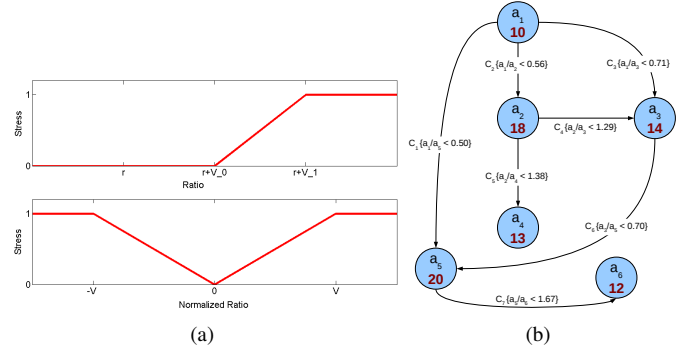


Fig. 2. (a) Stress function used in experiments for ratio functional blueprints (top) and the perturbation blueprint (bottom). (b) Example of a randomly generated functional blueprint network with 6 attributes and 7 blueprints.

in a simulated environment. This time is an evaluation metric, which is then converted into a stress value by a FB’s stress function. These evaluators help ensure that the design can accomplish the desired objectives.

A designer interacts with the MADV architecture by modifying the existing design or environment attributes, with each modification performed by introducing a “user goal” FB. This perturbs the design, and, with appropriately formulated FBs, should drive adaptation until either the designer’s intent is satisfied or the design reaches a stable partial solution from which it cannot proceed further.

IV. EMPIRICAL EVALUATION

We now have a framework for FBs and an architecture for evaluating a network of FBs in order to adapt a design. If the individual FBs are not designed appropriately, however, then the system may not be able to re-converge to a non-stressed state, and adaptation will fail. For the FB approach to become practically useful, therefore, it is important to investigate the conditions and dynamics of successful adaptation:

- Under what conditions will a network of FBs re-converge after it has been perturbed?
- When a network converges, how quickly will it do so?

We present here the results of a preliminary empirical investigation, using random networks of simple FBs.

A. Experimental Setup

For our experiments, we consider a set of n design attributes, each with a positive real number value. These attributes are linked together by k FBs, each of which constrains the ratio between two attributes. Thus, in this case the collection of attributes and FBs may be viewed as a graph, where attributes are nodes and FBs are edges.

The FBs for the k ratio constraints have piece-wise stress functions as shown in the top part of Figure 2(a). If the ratio between two attributes is less than the desired ratio plus 0.05 then there is no stress ($V_0 = 0.05$). If it becomes more than ratio plus 1 ($V_1 = 1$) then the system is not viable anymore. When stress is non-zero (in $(0, 1]$), the incremental adjustment prescribed by the FB is to shift both attribute values

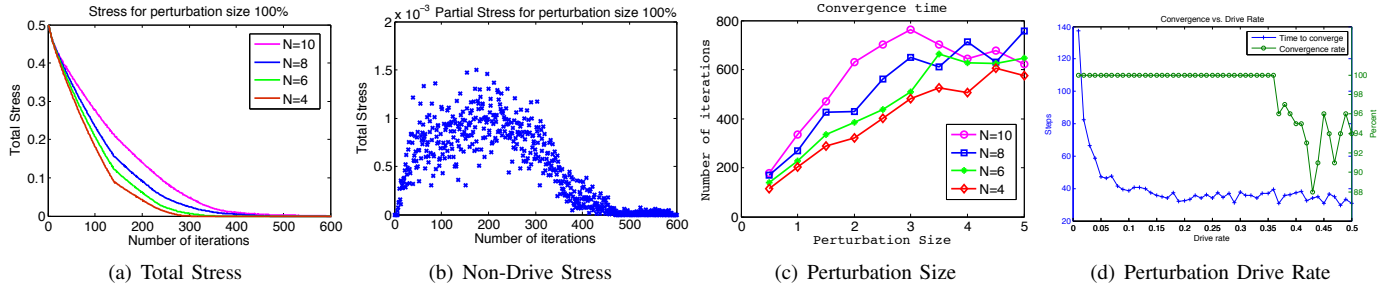


Fig. 3. The main component of the mean total stress (a) is the driver used to inject the perturbation: the network of ratio constraints rapidly adapts, keeping the mean stress over all experiments extremely low (b). Convergence is robust against a wide range of perturbation sizes (c) and drive rates (d).

by $stress * 2$ in the direction that will reduce stress, e.g., if the ratio is high, the numerator attribute will be lowered and the denominator attribute raised.

To generate a random network of k FBs and n attributes, we first assign each attribute to a random integer in the range $[10, 20]$. Each FBs is then assigned to a random pair of attributes (with no duplication allowed), and its desired ratio set to the ratio between the attributes values. A typical example is shown in Figure 2(b).

Perturbations are injected with a FB which prescribes an increase at rate d towards a desired value of $1 + P$ times its original value. This perturbation is applied to the $(n/2)^{th}$ attribute. The stress function is shown in the bottom part of Figure 2(a). The input to this function is the normalized difference, $\frac{desired - current}{current}$, where $current$ is the current value of the attribute and $desired$ is the value set by the user. When the normalized difference is non-zero, the system is stressed and becomes non-viable if it varies more than $V = 2 * P$. The incremental update when stress is non-zero is either $|desired - current|$ or $current * d$ whichever is smaller. We call d the *drive rate*. Except where otherwise mentioned, we use a drive rate of $d = 0.005$, a goal of $P = 1$, and run each parameter configuration 20 times, each time running at most 1000 iterations of the design modification loop.

B. Results and Discussion

We begin by examining the behavior of stress over time, considering four different random network sizes: (n, k) equal to $(4, 4)$, $(6, 7)$, $(8, 12)$, and $(10, 20)$. In these experiments, the FBs always converge, leaving the perturbed attribute at its new value and all other attributes at adjusted zero-stress values. Figure 3(a) and 3(b) show the total stress over time and stress only in the ratio constraint network, respectively. For the latter, we see a “spiky” pattern of small amounts of stress appearing and rapidly vanishing, showing that these FBs are rapidly adapting to the driving perturbation across a wide range of sizes. These figures show highly effective adaptation, where stress from the perturbation is dispersed as quickly as it is injected into the network.

This rapid and robust adaptation behavior holds across a wide range of perturbation sizes and drive rates. Figures 3(c) and 3(d) show the variation in convergence time with perturbation size ranging from $P = 0.5$ to 5 and for perturbation

drive rate ranging from $d = 0.01$ to $d = 0.5$ (100 iterations per d value), respectively. Only when we set d to extremely high values, changing the value of an attribute by more than 35% in a single iteration, does the system fail to converge.

V. CONCLUSION

Building on the previously developed concept of FBs, we have presented the MADV architecture for adjusting a design through the execution of a network of FBs. We then used this architecture to conduct a preliminary empirical study of the convergence dynamics of random networks of FBs, finding that convergence is both rapid and reliable for a wide range of networks and parameters. Although the empirical results presented here are limited in scope, they are an important step toward validating the approach, as they demonstrate that even simple blueprints can provide effective adaptation across a wide range of designs. Future work includes a broader empirical investigation and a theoretical investigation of FBs. We also aim to apply the MADV architecture to the redesign of an entire mobile robot.

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