BIOLOGICALLY INSPIRED FAULT ADAPTIVE STRATEGIES FOR ENGINEERED SYSTEMS

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Abstract

In nature, the continued survival of a species depends on the adaptability to unexpected environmental factors. While major mutations may lead to the selection of preferred traits in the long term, in the short term there are a variety of principles found in nature which are seen across biomes which enable individual organisms and organism groups to be adaptive. For complex, human engineered systems the ability to adapt to broad environmental and mission changes is a growing research topic. This paper presents the findings of a review of biological science to identify general strategies of fault adaption. These strategies are categorized and then represented using a formal engineering model-based representation. This work demonstrates the ability to identify natural fault adaptive principles, the ability to use these principles in a guided design process, and presents a validation framework for comparing performance of biologically inspired fault adaptive technologies.

Keywords: Bio-inspired design, biomimetics, Design methodology, Product modelling, models

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1 INTRODUCTION

The ability to adapt to unexpected changes is the defining characteristic of successful organisms in nature. Nature is a laboratory where successful strategies for adaption are evident because unsuccessful ones die out. While humans cannot afford the material and time costs associated mimicking nature's random experimentation, we can learn from and use the best strategies to develop adaptive engineered systems. In this work we present initial work in developing a new concept of biologically inspired design (BID) focused on identifying the specific strategies found in nature that enable adaption.

Reliability is a key characterizing metric for engineered systems and is often determined based on the ability to maintain functionality under certain conditions (Nikolaidis, Ghiocel et al. 2005). In the design stage, engineers identify the most probable nominal and adverse conditions and build in robustness to the designed system. Natural uncertainty is generally addressed though the inclusion of margins or envelops to the design parameters (Dittmar, Hartmann 1976). There is also recognition that a fundamental behaviour or property of systems is their adaptability to change their external or internal state. Adaptability enables a novel way for systems to be robust to failures and several methods have been developed to design-in and quantify a system's adaptability (Gu, Xue et al. 2009, Ferguson, Siddiqi et al. 2007). With this focus, this paper presents our work to design adaptable engineered systems based on patterns or strategies seen in natural organisms.

Every natural organism succeeds when it can recover and continue to reproduce after experiencing a *fault*. Here we define the concept of fault as an internal or external occurrence which affects the nominal behaviour of the organism. This generalization of the concept of fault enables the identification of analogous behaviours in engineered systems. The term *failure* is similar but is used to reference the system as a whole. That is, a *fault* may lead to a system *failure* if the system or organism cannot adapt or recover from it.

There are numerous examples of designers finding successful analogues of functions or structures in nature and implementing them to create novel technologies. Further, design researchers have identified successful ways to implement BID in terms of the design process (Goel, McAdams et al. 2013, Shu, Ueda et al. 2011, Helms, Vattam et al. 2009), analogues storage and representation (Vandevenne, Verhaegen et al. 2011, Vattam, Helms et al. 2010), and catalogues of successful analogies (Spenko, Haynes et al. 2008, Hu 2006, Madangopal, Khan et al. 2005, Wang, Suda 2001). We build on this work by exploring the how to catalogue natural fault adaption strategies, how to represent these strategies in a way that could be useful for designers, and possible evaluation metrics for validating the successful use of biologically inspired fault adaption strategies. This paper represent this first step in this work to clarify the objectives of this research platform. Future work will explore how engineers can use these strategies to design engineered systems.

Specifically, in the next section we will discuss BID and design for adaptability research which form the foundation of this work. Then we present the three aspects needed for successful implementation of a BID fault adaption strategy: 1) A schema for organising and understanding the strategies found in natural systems; 2) The representation system needed to store and reuse the analogue strategies for engineering design; and 3) the possible ways to evaluate the effectiveness of implementing the desired strategy.

2 FOUNDATIONAL BACKGROUND

Here we provide some examples of the work which supports the current effort. There are numerous examples of methods and technologies that are based on the concept of adaptability or BID. Instead of being exhaustive, this section illustrates key examples of the foundational concepts.

2.1 Fault Adaptive Systems Design

Most fault adaptive research is based around modelling the effects of faults in systems and research in the design of adaptive systems (Samanta 2009, Isermann 1996). Modelling the effects of faults can be categorized into two subgroups. The first is to determine the fault from system information. Work in this area deals with determining the cause of a fault within a system based off of the behaviour of the system. The second subgroup is modelling the effects of any conceivable fault. These allow researchers to determine the effects or relevancy of faults in a simulated environment.

Other research has focused on making systems adaptable or reconfigurable (Olewnik, Brauen et al. 2004, Siddiqi, de Weck et al. 2006, Saleh, Hastings et al. 2003, Ferguson, Siddiqi et al. 2007). Methods of implementing fault adaption primarily use software to adapt to a fault, most likely due to the difficulty in using physical hardware to adapt. The exact nature of these methods varies primarily in the area of what goal the system is adapting toward.

2.2 Biologically Inspired Design Research

Biologically inspired systems research can be seen from two perspectives. The first research area explores methods of designing systems using biological analogues. The second area of research is validating biological analogues for a given system. Research in the first area uses a biological analogue and concentrates on the process of taking the biological analogue and getting a mechanical solution out of it (Goel, McAdams et al. 2013, Vattam, Helms et al. 2010, Vandevenne, Verhaegen et al. 2011, Nagel, Stone 2011, Shu, Ueda et al. 2011, Helms, Vattam et al. 2009, Vattam, Helms et al. 2008). For example, the roboraven uses the motion of bird wings to come up with a mechanical solution (Gerdes, Holness et al. 2014), Gecko Tape also uses a set natural analogue to develop a solution (Geim, Grigorieva et al. 2003).

The second area involves determining if the selected biological analogue is appropriate or useful to the given application (Vandevenne, Verhaegen et al. 2011, Vattam, Helms et al. 2008). These usually involve a process to compare the mechanical system to the system to the biological analogue and quantifying its goodness of fit as a solution. An example of this method is the 4 Box Method (Helms, Goel 2014) which compare the two systems in various areas to determine similarities and differences.

2.3 Biologically Inspired Fault Adaption

There has been little crossover between Ontologies, Bio-Inspired Design and Fault Adaption. One example is the BioWall (Tempesti, Mange et al. 2002), which combines fault adaptive and bio-inspired systems to create a device that mimics cell death and recreation. Researchers used cell differentiation to create a device that acted as the result of the sum of its components. As “cells” died they were replaced and the system continued to function even though damage was sustained. A second example is an ontology for bio-inspired design solutions (Wilson, Chang et al. 2009). This ontology categorized a selection of biologically inspired design solutions from the characteristics of each solution. This means that their tool is not designed to find solutions, just to categorize them in a way mechanical engineers would understand and find applicable. A model for a South East Asia rail network used bacteria to connect fault adaption with bio-inspired design (Tero, Takagi et al. 2010). In that work, a bacterium was allowed to grow between food concentrations that mimicked the layout of major cities in the region. The bacteria branched out and connected the food concentrations in such a way that if any one branch was cut the bacterium would survive. These current crossovers show that there is potential for novel insights by combining these areas.

3 A FRAMEWORK FOR IMPLEMETNING BIOLOGICALLY INSPIRED FAULT ADAPTION STRATAGIES

3.1 A Classification Schema for Fault Adaption in Nature

To understand and communicate natural strategies, a classification schema is under development to organise natural fault adaption. The design of this schema is intended to guide the exploration and assist the identification of additional strategies. We begin with four high-level strategy types and further subdivide these based on binary options. The four high-level strategy types are: **repair**, **replace**, **repurpose** and **readjust**.

Repair is when the system attempts to return to full functionality by fixing the fault in the existing component. A natural example is how organisms heal broken bones. The system (the organism) attempts to return to full functionality by fixing the fault (the break) in the component (the bone). The second is **replace**, which is when a system attempts to return to full functionality by removing the damaged component and putting an undamaged one in its place. For example a salamander replaces a damaged tail by removing the old one and growing a new one. The system (the salamander) makes an attempt to return to full functionality by removing damaged component (old tail) and replacing it with a new one (new tail). Third is **repurpose**, which occurs when a system attempts to return to full functionality by using an existing component or set of components to fulfil the role of the damage component. An example of repurpose is when an organism injures a leg, it learns to walk with the reduced number of legs. The system (the organism) attempts to return to full functionality by using an existing set of components (other legs) to fulfil the roll of the damaged component (injured leg). The final is **readjust**, which is when a system changes its mission and does not attempt to return to full functionality. For example, if an organism loses its sense of smell and does nothing to regain or get the effects of it. The system (the organism) changes its mission (live without smell) and does not attempt to regain it.

After this classification, a series of binary questions identify distinct differences which enable the particular strategy to be effective. Our initial set includes:

1. Staggered vs. Immediate Change (With respect to the time scale of the organism, how long does the strategy take from beginning to completion.)
2. Active vs. Inactive (Does the damaged part of the organism continue to carry on function or is it unused during the strategy.)
3. Mass Required vs. No Additional Mass Required (Are additional non-nominal resources external to the organism needed to complete the strategy.)
4. Return to Nominal vs Return and Learn (After the strategy is complete, is the organism still as vulnerable to the fault as before the first fault.)
5. Living vs. Non-living (Does the strategy require the use of supported elements such as living cells.)

These specifications of the strategy support how engineers will be able to implement the analogue strategy as well as evaluate the similarity and usefulness of the BID example.

Using the above approach we have begun to build a database of biological examples through literature review. This approach has led to interesting findings in the similarity and differences between natural strategies in various organisms. For example, three strategies are classified and compared in Table 1.

Table 1. Comparing the Classification of Some Example Strategies

Name	**Axolotl Limb Regeneration**	**Zebra Fish Heart Regeneration**	**General Limb Loss**
Type	*Replace*	*Repair*	*Repurpose*
Q1 Temporal	Staggered	Staggered	Staggered
Q2 Active	Inactive	Active	Inactive
Q3 Resources	No External Resources	No External Resources	No External Resources
Q4 Learn	Return to Nominal	Return to Nominal	Return to Nominal
Q5 Support	Supported	Supported	Unsupported

3.2 Model-Based Representation of Fault Adaptive Strategies for Design

While traditional approaches to BID have focused on identifying and mimicking either functions or structures found in nature to achieve a desired property, our approach requires a broader perspective of the analogue. A strategy contains three distinct components: 1) The functional principal or mechanism the strategy will use (e.g. cellular mitosis), 2) The physical manifestation of that function (e.g. cells, hormones, etc.), and 3) time-based sequence of behaviours (e.g. hormone 1 released then hormone 2 released). Simply mimicking the function or structure will not be enough to achieve the desired fault adaptive strategy.

These three aspects of the fault adaptive strategy were identified and map well to the concepts found in systematic design and model-based systems design. Namely, representing systems using functional,

structural, and time-based behavioural relationships and diagrams. This similarity is used as the basis for storing and retrieving the natural strategy to be an effective tool in the design stage for engineered systems. For this work we have begun to build a SysML database of fault adaptive analogues for design (Weilkiens 2011, Friedenthal, Moore et al. 2011). This allows for a searchable database of solutions as well as identifying additional patterns within the natural strategies. SysML include multiple diagram representations and the storing and reuse of model elements. For this work we use the Block Diagram to describe the strategy. The Internal Block Diagram describes the relationship between the physical elements of the strategy. The Activity Diagram describes the functional mechanisms of the strategy and associates those with the physical elements. Finally, the State Machine Diagram is used to describe the behavioural sequence of steps needed to achieve the strategy. A sequence diagram could also be used for this last objective, however, methods of converting and simulating SysML state machines are more refined and can be used later to evaluate the effectiveness of the chosen strategy.
Figure 1 describes the relationship between the structures used by the Axototl salamander to regrow limbs while Figure 2 illustrates the relationship between the functional mechanisms used by that strategy.

3.3 Evaluation of Implemented BID Fault Adaptive Strategies

There are two critical aspects of evaluating the effectiveness of using natural fault adaptive strategies in engineering design. The first is from a designer's perspective and the later on the effectiveness of the solution itself. To address the first portion, we have developed a manual guide which leads designers through a series of questions that explore the applicability of different strategies. In the initial stages this is a simple flow chart, however, future work may look at automating this process. To evaluate the effectiveness of this flowchart approach we will organise an experiment comparing usage of this tool as compared with using AskNature.org and no BID aid.

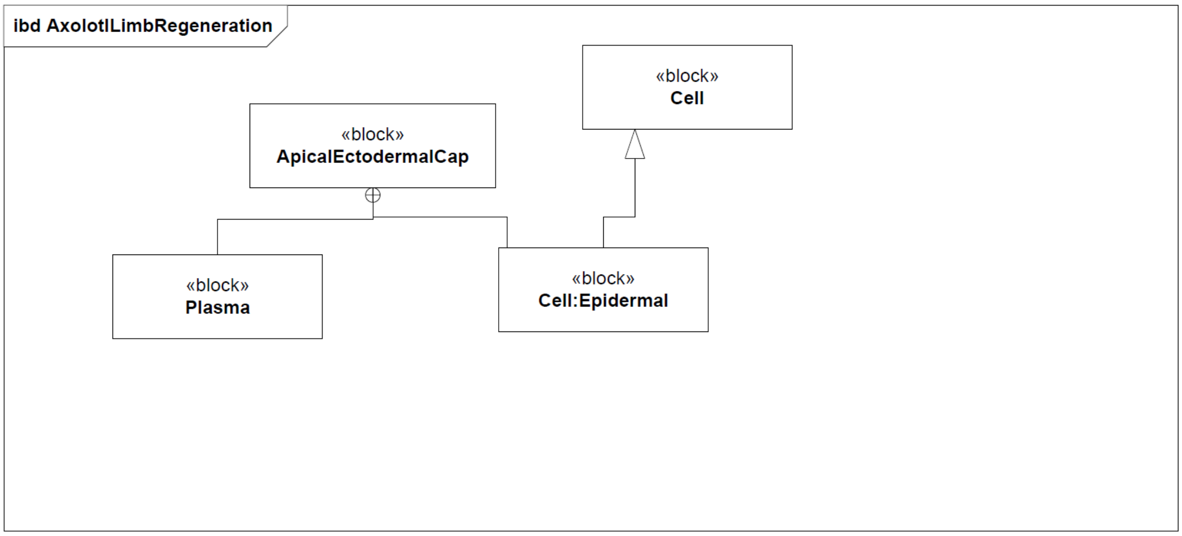

Figure 1. SysML Internal Block Diagram for the Axolotl limbr regeneration strategy.

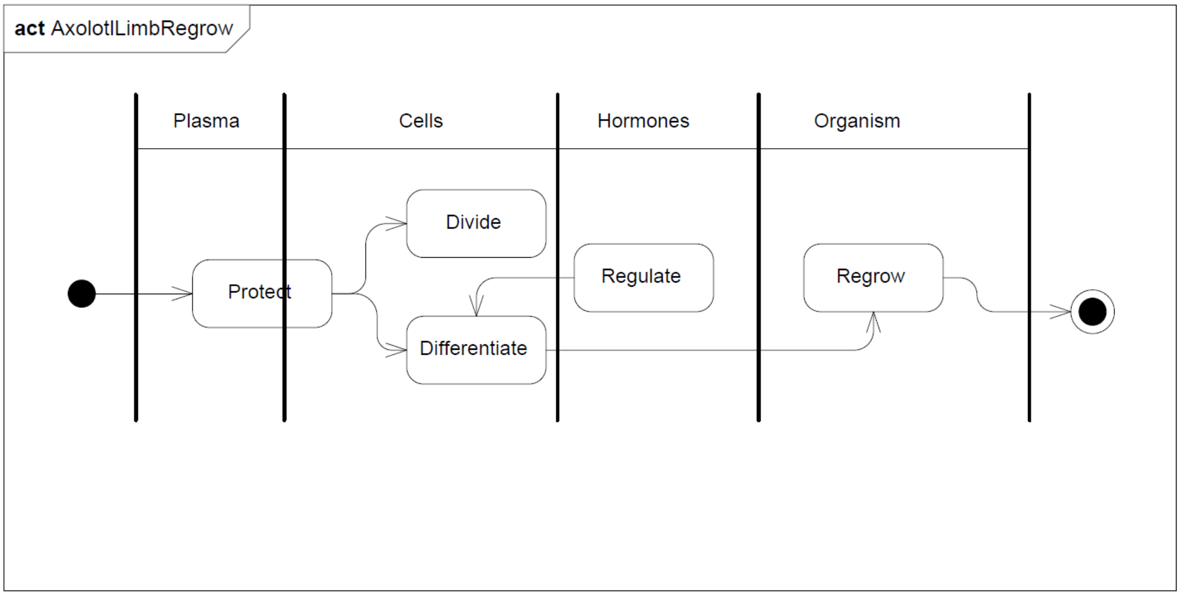

Figure 2. SysML Activity Diagram describing the functional mechanisms of the Axolotl Limb regeneration strategy.

While this will not provide definitive answers regarding the effectiveness of the flowchart it will enable us to compare the method and refine future automation based on designer's needs and preferences. This approach is based on the foundation of other researchers who have used designer experimentation for method validation (O'Rourke, Seepersad 2013, Zahedi, Guité 2013, Nagel, Stone 2011).

The second aspect of evaluating the effectiveness of BID fault strategies is the successfulness of the engineered solutions. This can be considered in two parts, simulated success and field success. By using state machines to describe the behavioural relationships we can simulate numerous fault scenarios for engineered systems following design-stage fault propagation analysis methods (Kurtoglu, Tumer et al. 2010, Sierla, Tumer et al. 2012, Papakonstantinou, Sierla et al. 2011, Papakonstantinou, Sierla et al. 2012, Papakonstantinou, Sierla et al. 2012, Jensen, Hoyle et al. 2012). This work can give a comparative score of the system's functional robustness to the space of potential faults.

Field validation requires extensive use of the engineered system in comparison to non-adaptive systems to overcome any unexpected or un-simulated fault scenarios. This will require implementation of an engineered solution and time in operation. Thus, this aspect will be fulfilled in much later work.

4 CONCLUSSIONS

This paper presented a novel concept for biologically inspired design (BID) which looks to the strategies used by natural organisms to achieve fault adaptive behaviour. Traditional approaches to building robust engineered systems utilizes margins on design parameters to account for uncertainty. Some novel systems express fault adaption behaviour to overcome uncertain operating environments and random internal failures. This work is based on the concept of using the natural laboratory to aid designers in identifying what type of fault adaptive strategies may be effective.

While some researches have been able to develop examples of fault adaptive systems that mimic nature (notably electrical systems patterned after cellular structures), there is a need for a fundamental design theory and methods which support finding and using BID fault adaption. This paper presented our initial findings of an effective classification schema for identifying natural strategies, our approach to represent the strategy using SysML diagrams of the function, structure, and behaviour needed to implement the strategy, and developed a framework for how to evaluate the effectiveness of that BID for fault adaption.

The next stages of this work will be to automate the existing flowchart-based approach to finding natural analogues, expanding the repository and representation of those strategies, and formal validation of the approach. This research also opens exploration into identifying patterns in the model-based representation and automation of the analogue model building processes.

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