BIOINSPIRED CONCEPTUAL DESIGN (BICD): CONCEPTUAL DESIGN OF A GRASSHOPPER-LIKE JUMPING MECHANISM AS A CASE STUDY

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ABSTRACT
The evolution process of nature creates *highly effective*, *power efficient*, and *perfectly structured* biological systems. These excellent systems provide an inexhaustible source for engineers and scientists who desire to inspire ideas, processes, structures, functions, and behaviors from biological domain and implement them into engineering domain. This approach is called “Bioinspired” and challenging for engineers. However, some problems of the practical approaches are observed. One of the problems is “ad hoc” nature of the process. Each bioinspired design product has resulted in a differing design process and a generalization was not possible. Another problem rises due to the terminology difference between engineers and biologists. To overcome these problems, a need for a systematic *bioinspired design (BID)* process was realized in early 2000s and since then, considerable research on the BID methodology has been progressed. Within the context of BID, this paper introduces a new approach on bioinspired conceptual design (BICD) procedure for hybrid bioinspired robots which can be inspired from multiple biological systems. An illustrative case study is given in the paper.

Keywords: bioinspired, bioinspired conceptual design, hybrid bioinspired robot

1 INTRODUCTION

Bioinspired design (BID) is a process which investigates biological analogies [1], [2] to produce highly creative and efficient products. The BID providing guideposts for creating [3] and a cross-over link between biological systems and engineering systems [4] has led to new and useful products and technologies [5] and some of them have been patented [6]. There are two approaches in BID studies with respect to starting point of the design; problem-based BID (PB-BID) and solution-based BID (SB-BID). PB-BID starts with an engineering problem in engineering domain, whereas SB-BID begins with a biological system in biology domain [7]. Some examples on both approaches these studies are given in Table 1.

It is known that there are some drawbacks in existing BID processes preventing wide-spread use. These problems are originated for two main reasons; one of them is the “technology transfer” problems [4], [8], [9] between “biological domain” and “engineering domain”, and the other is the limitations of current BID approaches. Some of these limitations are listed below;

- Current BID processes are still *ad-hoc*.
- Current BID processes rely mostly on designers’ experience.
- Although existing literature suggests tools and/or systematic methods for selection of biological systems to inspire, most of them provide only keyword translation between two domains.
- PB-BID and SB-BID approaches are similar in nature; however, they apply different steps.
- Information about a biological system should be collected, processed and adopted into engineering system in order to mimic a biological system or to inspire from a biological system. In the current studies, this process is blurred. However, this phenomenon requires a systematic, standard approach for sound application.
- Most of the published studies claim that a biological system is used to be inspired for a bioinspired product. This delimits the design variety and creativity.

Table 1. Some examples of BID models and the associated steps

BID	Author(s)	BID steps	Domains of Steps
PB	Helms, Vattam, and Goel [9]	➢ problem definition ➢ reframe the problem (biologizing) ➢ biological solution search ➢ define the biological solution ➢ principle extraction ➢ principle application	Engineering Engineering-Biology Biology Biology Biology-Engineering Engineering
	The Natural Edge Project [4]	➢ identify the real challenge ➢ translate the challenge into biology language– 'Biologise' the question ➢ define the habitat parameters/conditions ➢ re-ask 'How does nature do that function here, in these conditions?' ➢ find the best natural models (literal and metaphorical) ➢ mimic the natural model as form, process, and ecosystem ➢ evaluate the solution – nature as measure ➢ pay respect to the Inspiration	Engineering Engineering-Biology Biology Biology Biology Biology-Engineering Engineering Engineering
	Biomimicry Guild [10]	➢ distill (distill the design function) ➢ translate (translate to biology) ➢ discover (discover natural models) ➢ emulate (emulate natures strategies) ➢ evaluate (evaluate your design against life's principles)	Engineering Engineering-Biology Biology Biology-Engineering Engineering
	Anon [6]	➢ formulate the technical problem ➢ seek for analogies in biology ➢ identify corresponding principles ➢ abstract from the biological model ➢ implement technology through prototyping and testing.	Engineering Biology Biology Biology-Engineering Engineering
SB	Vakili and Shu [11]	➢ select initial information source of biological phenomena ➢ identify of synonyms for engineering functional keywords ➢ identify of suitable bridge between engineering functional keywords and synonyms and biological phenomena ➢ search for keywords and synonyms in bridge ➢ identify and find more detail on relevant biological phenomena	Biology Biology Biology-Engineering Biology-Engineering Biology
	Anon [6]	➢ identify a biological system ➢ analyze biomechanics, functional morphology and anatomy ➢ understand the principles ➢ abstract from the biological model ➢ implement technology through prototyping and testing	Biology Biology Biology Biology-Engineering Engineering
	Helms, Vattam, and Goel [9]	➢ identify of a biological solution ➢ define of the biological solution ➢ extract of a principle ➢ reframe the solution ➢ search a problem ➢ define of the problem ➢ apply of the principle	Biology Biology Biology Biology Biology-Engineering Engineering Engineering

The above limitations on BID show that a systematic and sound BID methodology used both for a single biological system and for multiple biological systems is required. In this paper, a *bioinspired conceptual design (BICD) process model* is introduced for the design of hybrid bioinspired robots. It is well known that the main goal of any BID is to provide creative and innovative products and ideas; most of them are emerged during the conceptual design phase. In addition, the literature on BID studies show that the main difference between BID methods and systematic engineering design methods are only observed in the conceptual level. Thus, the study presented in this paper is focused on the conceptual design and hybrid bioinspired robots. The term of "hybrid bioinspired robot" is used to represent bioinspired robots which are combination of parts, features and/or ideas inspired from a single biological system or multiple biological systems. A hybrid bioinspired robot includes diverse functions, structures, and behaviors which are provided by multiple biological systems. A hybrid bioinspired robot with a grasshopper's leg for jumping and a bee's eye for vision may be integrated in the same design product.

The novelty of this BICD process model is that it includes an appropriate mapping between the biological and engineering domains, a clear representation model for the analysis of biological systems and identical steps for both SB-BICD and PB-BICD approaches. The paper is organized as follows; Section 2 introduces the new BICD procedure. Section 3 illustrates the application of BICD on a grasshopper-like jumping mechanism as a case study. Finally, the BICD procedure and the case study are summarized and discussed in Section 4.

2 BIOINSPIRED CONCEPTAUL DESIGN (BICD) PROCEDURE

BID is a branch of an engineering design and it has four phases [12] in design process of an artifact [13], [14]; clarifying the problem, conceptualizing, embodiment in layouts, and elaboration and detailing [15]. A BID model is developed as Bioinspired Conceptual Design (BICD) and the other phases can be implemented on BID. In this study, a BICD procedure was established by combining analogical reasoning between engineering and biological domains, and stages of engineering design. Process flow for the suggested systematic BICD procedure is represented in Figure 1.

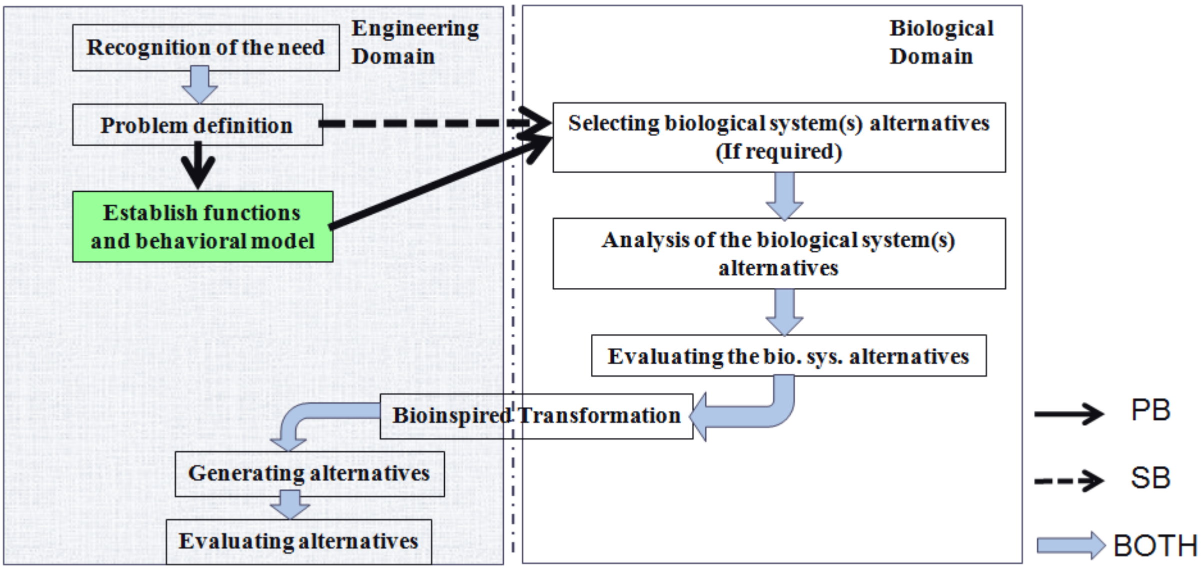

Figure 1. The process flow and related domains in the BICD approach

The BICD steps are realized in engineering and biological domains with an additional a transformation step. Engineering domain steps are similar to well-known systematic engineering design steps [12], [13], whereas biological domain steps and the transformation step are new in BICD methodology.

Figure 1 shows that both PB-BICD and SB-BICD start with "Recognition of the Need" as the first step. The need is organized by using a BICD requirement list and a corresponding checklist based on engineering design requirement list [12]. A checklist for a BICD requirement list is given in Table 2 with examples.

Table 2. Checklist for a BICD requirement list

Main Headings		Examples
Biological System Name (if mentioned)		The name of the creature if mentioned by customers
Biological System Type		Animal/Plant/Both
Morphology (Form and Structure) of the Final Product		Dimensions, weights, number of the links, desired vision
Desired Function of the Final Product	**Motoric**	Locomotion, grasping, drilling
	Sensoric	Vision, audition, touch, smell, taste
	Cognitive	Cognitive, adaptive, autonom
Flow of the Final Product	**Material**	Flow materials, prescribed materials
	Energy	Flow of energy, efficiency, friction
	Signal	Inputs and outputs, control equipment
Operational Environment		Surface roughness, operational temperature
Production and Assembly		Preferred production methods, number of the desired products, standards
Cost		Maximum permissible manufacturing cost
Schedule		End date of development, delivery date

In Table 2, the first two rows include information about the biological system to be bioinspired. These two rows clear whether the design approach is SB or PB. If the specific name of a biological system is given, the design approach is a SB-BID approach, otherwise a PB-BID approach. The third row displays information about the form (size, shape, etc.) and structure (number of the links, joint details, etc) of the desired bioinspired product.

Bioinspired robots being as mechatronics products have three sub-systems; motoric, sensoric, and cognitive. Motoric sub-systems are related with actuators and they express the motion of the robot; such as walking, climbing, and drilling. Sensoric sub-systems include vision, audition, touch, smell, and taste sensors which are inspired from biological systems. Cognitive sub-systems cover adaptive mechanisms, such as; learning, evolution, and control architecture. Thus, the desired function row includes these three sub-systems. The requirements of flow (material, signal, and energy), operational environment, and information about the production, cost, and schedule of the product are collected in a BICD requirement list table.

The second step in our BICD approach is the “Problem Definition”. The output of BICD problem definition is a problem statement including the goal, constraints, and criteria collected in the requirement list. The goal describes the desired product with its main functions. Constraints define the boundaries of allowable solution space [16] (engineering limitations on the operational environment and size of the product). During problem, the criteria are stated as to achieve quantifiable objectives.

The next step in engineering domain is to “Establish Functions and Behavioral Model”. This well-known engineering step is only valid for PB-BICD approach. In this step, the overall function of the problem is decomposed into sub-functions and a behavioral model of the engineering problem is established.

The first step of the biological domain is “Select Biological System(s) Alternatives (if required)”. This is a matching step and uses a current database [17] to find biological systems based on some keywords collected from the previous stages. If the desired biological system is known, this step is skipped.

The “Analysis of the Biological System(s) Alternatives” is the next step in which selected biological systems are analyzed to answer the questions of “what does it do?” and “how does it do?”. For this reason, biological systems are decomposed into components of *morphology* (form and structure), *function*, and *behavior*. Function-Behavior-Structure (FBS) knowledge representation was developed by Gero [18]. In the present study, semantic network of biorobots has been developed for representation of conceptual interrelationships and as a result necessity of morphology-function-behavior structure was justified. Detailed explanation on the semantic network is given in [19].

The morphological information includes dimensions (length, shape, etc.), weights and body structure (number of the links, joint details, etc). The forms of biological systems perform vital functions economically [20]. The function decomposition component supplies a function structure, mathematical models for desired kinematic data, and performance (dynamic data) of the biological systems. The behavioral model gives the information about how the biological system achieves the desired function.

Mainly, two methods are discussed to obtain these decomposition components. This first method is a method of “consulting biologists and using literature survey”. The second method is an empirical one and it includes observation and measurements.
The next step is “Evaluating Biological System Alternatives”. If a designer is concerned with multiple biological systems, this stage is used to generate combinations of them to provide the overall function. Each combination represents a hybrid biological system.
In the “Bioinspired Transformation” stage, transformation can be done by matching between sub-functions of biological domain and engineering domain. For example, “store chemical energy” (a biological domain sub-function) can be matched with the “store electrical energy” (an engineering domain function). In this step, the terminology of Pahl et al. [12] is used to describe engineering domain functions.
The last two steps are “Generating Alternatives” and “Evaluating Alternatives” in engineering domain. During these stages, firstly, the components for each sub-function are generated and then, they are combined and evaluated. The following section introduces a case study to illustrate the complete process flow for the BICD approach.

3 CONCEPTUAL DESIGN OF A GRASSHOPPER-LIKE JUMPING MECHANISM

The mentioned BICD procedure is illustrated on conceptual design of a grasshopper-like jumping mechanism. A single biological system for a SB-BICD approach is selected for this example. This example is only used to show an application of the suggested BICD procedure and the work is under development. In this case study, it is assumed that the customer need is a grasshopper-like jumping mechanism.

3.1 Recognition of the Need

Requirements of the desired mechanism are collected and summarized in Table 3. Name of the inspired biological system is known, so the design approach is a SB-BICD. Therefore, design is based on SB-BICD steps.

Table 3. A requirement list of a grasshopper-like jumping mechanism

Main Headings		Requirement List
Biological System Name (if mentioned)		Grasshopper
Biological System Type		Animal (Insect)
Morphology (Form and Structure) of the Final Product		Grasshopper-like Max. 2 kg. Max. 2 cm^3
Desired Function of the Final Product	**Motoric**	Jumping
	Sensoric	-
	Cognitive	Autonomous
Flow of the Final Product	**Material**	-
	Energy	Power consumption $\leq$ 5 kW/ 380V
	Signal	-
Operational Environment		Temp: between -10°C and 40°C Surface roughness is 200 Ra
Production and Assembly		Standard parts and Modular
Cost		10,000 TL
Schedule		1 year

3.2 Problem Definition

In this step, the problem is defined by using information in the requirement list. Three main parts of the problem statement are given as follows;
Goal: Design an autonomous grasshopper-like jumping mechanism which will operate on a surface whose roughness is 200 Ra.

Constraints: Between -10°C and 40°C
Surface roughness is 200 Ra
Max. 2 kg
Max. 2 cm^3
Power ≤ 5 kW/ 380V

Design Criteria: Design criteria and their weight factors are listed in Table 4. These criteria will be used to evaluate combinations of components in engineering domain.

Table 4. Design criteria of the grasshopper-like jumping mechanism

Design Criteria	Condition
Use of standard parts	If the parts depend on TSE (Turkish Standards Institution)
	Otherwise
Modularity	A variable number of parts ≥ 8
	≤ 8
Break-resistance	σ ≥ 200 Pa
	200 Pa> σ > 50 Pa
	σ ≤ 50 Pa
Appearance (look like a grasshopper)	High fidelity (creature-like)
	Low fidelity (mechatronic system like)

3.3 Select Biological System Alternatives (if required)

The biological system, grasshopper for the function of jumping is clear, so this step is omitted.

3.4 Analysis of biological systems alternatives

The grasshopper should be analyzed only for the selected jumping function. To obtain decomposition components of the grasshopper, literature survey method is preferred. Previous research on morphology, function [21], and behavioral model [22] of the grasshopper are used for this case study.

3.4.1 Morphology (Form and Structure)

The related literature [23], [24] shows that grasshoppers jump by using their hind legs powered with flexor and tensor muscles as well as the storage energy in a special cuticle. Thus, the form and the structure of the grasshoppers' hind legs are analyzed. Figure 2 shows that the leg has five distinct segments; coxa, trochanter, femur, tibia and tarsus. The hind femur is the enlarged jumping spring of the hind legs; it includes flexor, extensor muscles and semi-lunar process (a special cuticle) inside the exoskeleton (hard shell). Average dimensions and weight of the grasshopper are tabulated in Table 5.

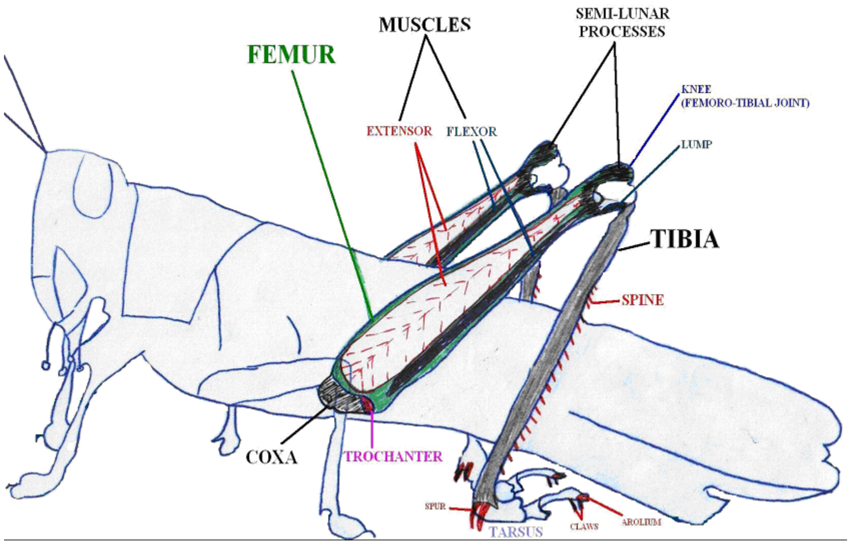

Figure 2. A hind leg morphology of a grasshopper [21]

Table 5. Average dimensions and weight of the grasshopper [23]

Body Structure	Total body mass (M)	415 mg
	Hind leg tibia length (L_{tibia})	15.6 mm
	Hind leg femur length (L_{femur})	17.1 mm
	Hind leg femur max.-min. diameter (D_1- D_2)	3.2-0.8 mm
	Tibia tubular construction diameter (D_3)	0.6 mm
	Extensor muscle occupying a cross-sectional area	4.4 mm^2
	Flexor muscle occupying a cross-sectional area	1.08 mm^2
	Angle of rotation of tibia	165°

3.4.2 Function

The grasshopper jumping goes through a set of routine activity (a motor program) before it actually takes off [24] as listed below:

- Initial flexion (contraction of flexor muscle): A jump begins with a forward rotation of the hind legs at their body-coxa joints and a flexion of the tibia about the femur.
- Co-activation: Flexor and extensor muscles contract together. The contraction of the flexor muscle keeps the tibia in the fully flexed position, so that the simultaneous contraction of the extensor muscle bends semi-lunar shaped region.
- Trigger relaxation of flexor: The flexor muscle is released suddenly using the energy stored in the cuticle spring when the extensor muscle continues contraction.

By using jumping steps, functional structure of the grasshopper jump is constructed as given in Figure 3. Jumping performance data obtained from mathematical models [21] are tabulated in Table 6.

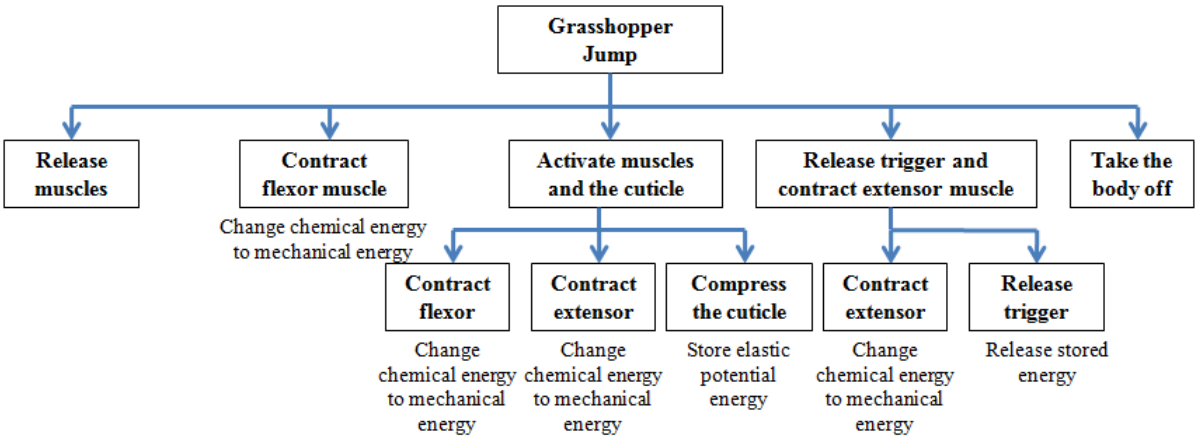

Figure 3. Functional structure tree of a grasshopper-like jumping

Table 6. Jumping performance data of Pholidoptera motion [21]

	Air resistance is ignored	Force is constant with air resistance	Adams Simulation Solution
Take-off velocity (m/s)	1.79	2	Input data (1.79)
Take-off time (s)	-	-	0.203
Take-off acceleration (m/s^2)	48.99	61.2	-
Peak acceleration (m/s^2)	97.98	122.32	-
Take-off force (mN)	20.3	25.6	-
Extension time (ms)	36.5	30	-
Horizontal distance (mm)	Input data (302)	Input data (302)	301.861
Height gained until take-off(mm)	4.92	4.92	-
Kinetic Energy (μJ)	614.74	768.43	664.1
Min. energy requirement (μJ)	634.74	788.43	684.1
Power (μW)	36.3	51.2	-

3.4.3 Behavior

An abstract level Coloured Petri Net model (called CPN_Jump) for the grasshopper's jumping behavior is developed [22] and its graphical simulation is done using CPN Tools© software package [25]. Coloured Petri Nets (CP-nets or CPNs) [26; 27] is a graphical oriented language for design, specification, simulation and verification of systems. A CPN model of a system describes the states of a system and events (transitions) that can cause the system to change its states. By making simulations of the CPN model, it is possible to investigate different scenarios and explore behaviours of the system.

The graphical representation of the CPN model of a grasshopper's jumping behavior is illustrated in Figure 4. The states of the motor program for jumping are modeled by seven places represented as ellipses in the model. The data value (token colour) assigned to each of these places is defined as STRINGxSTRING. This type of data value contains all pairs where each of the two elements is a text string. In the presented CPN model, basic function-flow definitions of engineering design [12] are used and two variables are defined. The first variable is "func" that represents function and the second one is "flow" for modeling the flowing item through the system. It is assumed that any event in the system occurs as a result of "SENSING" a "SIGNAL".

Variables "func" and "flow" are bound to the values "SENSE" and "SIGNAL" during the simulation of the model. Number of tokens deposited in a place is represented in a small circle next to the places. Events that take place in the system are modeled by five transitions shown as rectangles. Each of the events represents start of the corresponding action. The initial marking in Figure 4 represents an initial state. In the initial state, a grasshopper is at rest (represented by the place "Resting") and senses a signal (represented by a token in place "Resting" with the specified colour). In this initial marking M0, "contraction of flexor" transition is enabled and it occurs resulting in "the initial flexion" state, in which the grasshopper's flexor muscle is contracted fully. In this state, hind legs' knees are close to the ground, so grasshopper prepares to jump, and this is represented by the token in the "Knee position ready" place. During "the initial flexion" state, "Contraction of extensor" transition is enabled and its occurrence results in "the co-contraction" state, in which two muscles contract and the cuticle spring is ready to be bent.

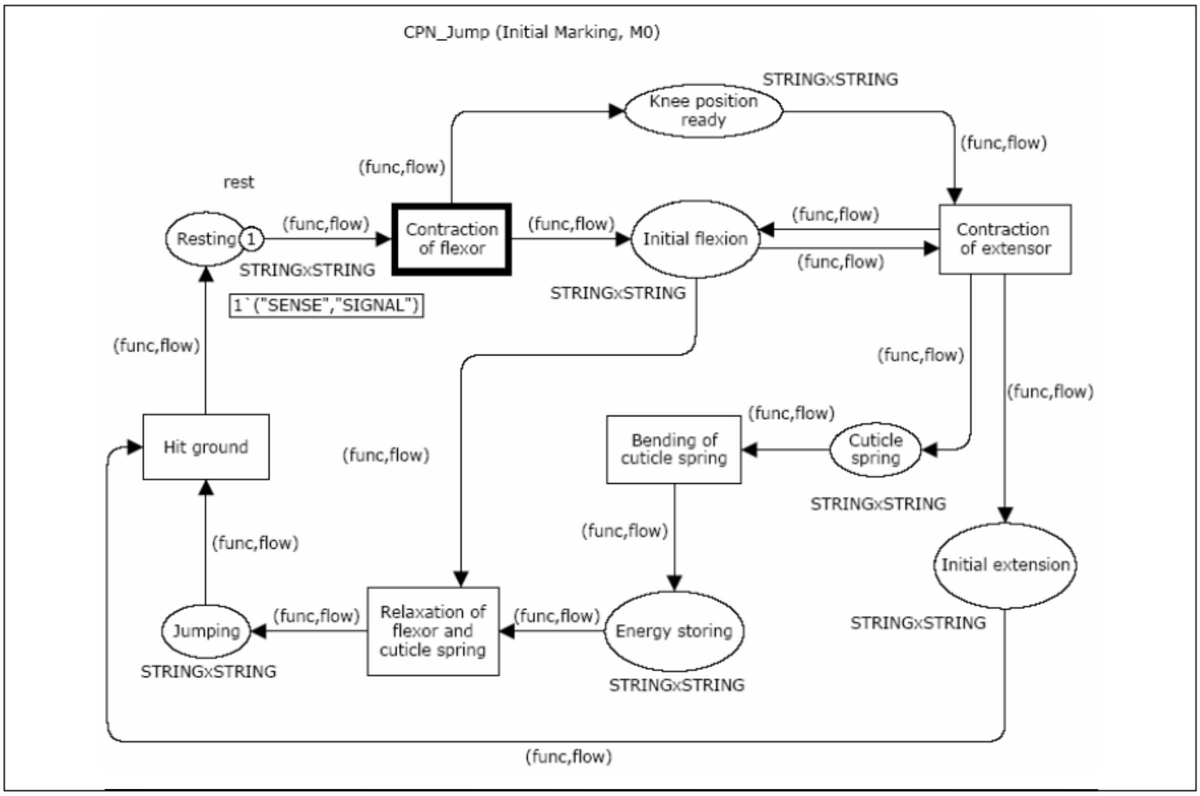

Figure 4. The CPN model of the jumping mechanism of a grasshopper [22]

Occurrence of the transition "Bending of cuticle spring" which is the only enabled transition in "the co-contraction" state, results in a new state. After the bending of cuticle spring, nearly half of the jumping energy is stored in the cuticle spring structure, and this is represented by a token deposited in the "Energy storing" place. After this state, preparation for jumping is completed, the jumping action starts, and this is represented by the enabled transition "Relaxation of flexor and cuticle spring". Occurrence of "Relaxation of flexor and cuticle spring" transition represents that the grasshopper releases the flexor muscle and cuticle spring suddenly, using the energy stored previously. This marking represents the jumping state. The only enabled transition in this marking is "Hit ground" and when this transition occurs, the grasshopper returns back to the initial state, and the jumping cycle is completed. Graphical representation of the complete simulation is given in [22].

3.5 Evaluating Biological System(s) Alternatives

For a desired function, only a biological system is discussed in this case study, so there is no combination which is generated by multiple biological systems.

3.6 Bioinspired Transformation

As mentioned before, the overall function of the design which is the grasshopper jump has five sub-functions. These biological domain sub-functions are "release muscles", "contract flexor muscle", "activate muscles and the cuticle (co-activate)", "release trigger and contract extensor muscle", and "take the body off". In addition, co-activation and trigger relaxation have second level sub-functions. The transformation is a matching between these biological domain sub-functions and engineering domain functions using a standard terminology as suggested by Pahl et al. [12]. Different levels contract flexor and contract extensor sub-functions have the same process; "change chemical energy to mechanical energy", so they can be matched with the same engineering domain function, "change energy". The other engineering domain steps are "store energy" and "connect energy". The processes for each engineering function related with biological processes, such as "change electrical energy to mechanical energy" are also shown in Figure 5.

3.7 Generating Alternatives

The components which conform to the engineering domain functions are generated in this stage. A few component examples for each function are given in Figure 5. These components are collected manually by using different literature. While these components are selected, the design criteria and the body structure and performance data of the grasshopper are considered.

3.8 Evaluating Alternatives

Components from each engineering domain function are collected to generate combinations. Combinations of components are represented as C_is in Figure 5. For instance, C_1 is the combination of a servo motor (to change energy in different parts of the robot), a torsion spring (to store energy), and a locking mechanism (to release the stored elastic potential energy). The number of combinations depends on the number of functions and the number of components for each function. An appropriate combination can be selected by using an evaluation method. The selected combination represents the conceptual design of the grasshopper-like jump mechanism.

A weighted design criteria F(C) where C; $\{C_1, C_2, ... C_N\}$ may guide the designer to select the "best" design alternative among the available designs. This study is in progress and will be published later.

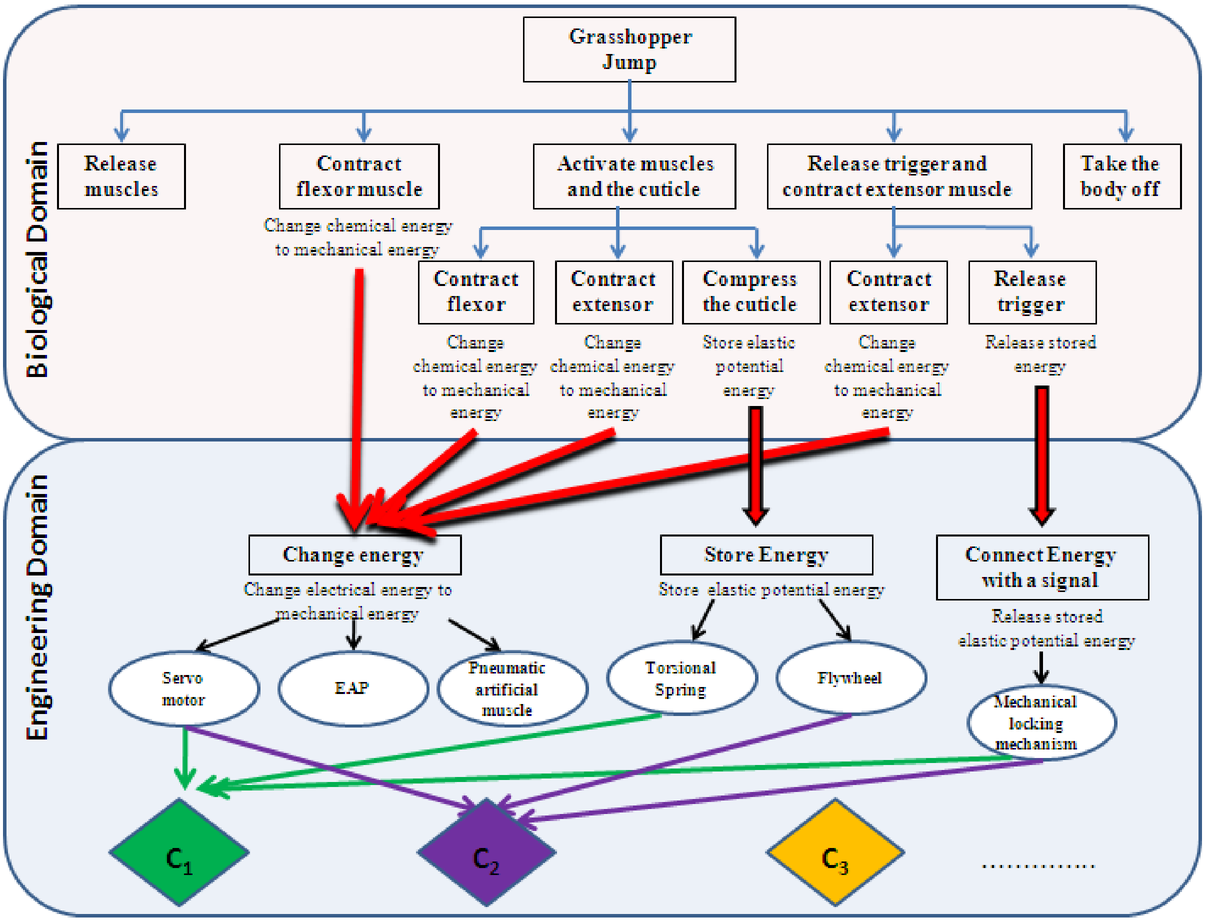

Figure 5. An illustration of the BICD transformation and last engineering steps of a grasshopper jump via grasshopper-like jumping mechanism

4 SUMMARY, DISCUSSION, AND FUTURE WORK

Inspiring from functions, behaviors, structures, materials, and, form of biological systems is a challenging process for engineers and designers and this process encourages creative designs. However, it is not a straight forward engineering process; it requires a high level balanced expertise on both domains. Moreover, biologists and engineers use different terminologies so that there is always difficulty when biological systems are translated into engineering domain. Many studies focus on constructing a BID methodology to eliminate these disadvantages and help designers to develop creative and innovative products. This paper presents a new conceptual BID study for hybrid bioinspired robots which can be inspired from either one biological system or from multiple biological systems. This new BICD procedure has some advantages as listed below.

- Well-known engineering steps and associated methodology are used in the procedure.
- Similar to the other engineering designs, the BICD procedure starts with a need in engineering domain.
- Most of the steps in both PB and SB approaches are identical.
- Multiple biological systems can be used for a bioinspired product, if necessary.
- The transformation step is clear and simple.
- The problems due to the different terminology between biologists and engineers are reduced.
- The analysis of biological systems step is abstracted.

Research still continues on the suggested BICD approach. Future work will be mainly directed towards;

- Obtaining decomposition components in the analysis step, the observation and measurement method (empirical method) should be progressed. A high speed camera will be used to obtain morphology, function, and behavioral components.

- In the step of the generating alternatives in engineering domain, limited number of design alternatives is generated manually for demonstration. These engineering components should be easily accessible. An automated approach for this step is under progress.
- Case studies on multiple biological systems are part of future work.

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